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Kimberlite durability: geotechnical input into Jwaneng underground mining studies

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Abstract

Jwaneng D/K2 mine has started its transition into an underground mine through development of twin declines that started in May 2024. First carats production from the underground mine is expected around 2036. Block caving, sublevel caving and other caving-related methods are being studied for potential use in the exploitation of the Jwaneng underground resource.

Jwaneng mine initiated analysis of swelling clays as part of geotechnical inputs into mining studies. Relationships between occurrence of swelling clays and rock durability/strength are a widely known phenomenon in mining and construction industries. The presence of swelling clays of various proportions in kimberlite rocks poses several technical and operational issues that need to be managed in an underground mine. Understanding intricacies between the rock swelling behaviour and strength, and overall deformation in response to excavation, is critical as an input into the kimberlite underground mine design and operation.

Jwaneng mine determined the presence of swelling clays (smectite group) in various kimberlite facies (volcaniclastic kimberlite and pyroclastic kimberlite) using the X-ray diffraction methodology. The swelling clay results were then compared to known durability tests – field weathering test, Slake Durability Index and accelerated weathering index – in an endeavour to determine the impact of swelling clay on durability. Kimberlite durability is an important consideration of both design and operation caving mines on such aspects as oredrive design, ground support design, rehabilitation strategies, draw control strategies and mud rush risks.

This paper summarises the work undertaken to date in characterising the Jwaneng D/K2 kimberlites, with a specific focus on swelling clays proportions and expected behaviour.

Keywords: *volcaniclastic, pyroclastic, smectite, X-ray diffraction, durability, squeezing ground*

1 Introduction

The Jwaneng D/K2 mine has been operating since 1982 and currently has two active open pit cuts. Cut 8 is active on the eastern wall of the pit and will be depleted by 2029. Cut 9 (the latest cut) was started during 2019, is mining the western wall and will be depleted by 2036. Following the depletion of Cut 9, Jwaneng mine will be transitioned to an underground mine as Cut 10 was found to be unviable. This transition is being studied by the Jwaneng underground project. The Jwaneng underground mine is scheduled to exploit ore from three kimberlite pipes named North, Centre and South. These pipes comprise volcaniclastic and pyroclastic kimberlites and associated kimberlite/country rock breccia facies as shown in Figure 1. The volcaniclastic and pyroclastic kimberlites facies are defined as follows: (S) – South pipe, (C) – Centre pipe, (N) – North pipe, VK – volcaniclastic kimberlite, AVK – autolithic volcaniclastic kimberlite, QVK – quartz-rich volcaniclastic kimberlite, PK – pyroclastic kimberlite, CRBQS – country rock breccia-quartzitic shale, CRBDM – country rock breccia-dolomite and KBWDM – kimberlite breccia-dolomite.

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This paper summarises swelling clay behaviours of Jwaneng kimberlites as observed from the X-ray diffraction (XRD) testing and analysis conducted over time at the mine. The paper also compares the XRD results to other kimberlite durability test results within the Jwaneng mine database for further understanding of the behaviour of swelling clays within the kimberlites. These swelling clays may pose problems for infrastructure development in kimberlite due to their poor strength, high compressibility, sensitivity to water and high volumetric fluctuations (swelling).

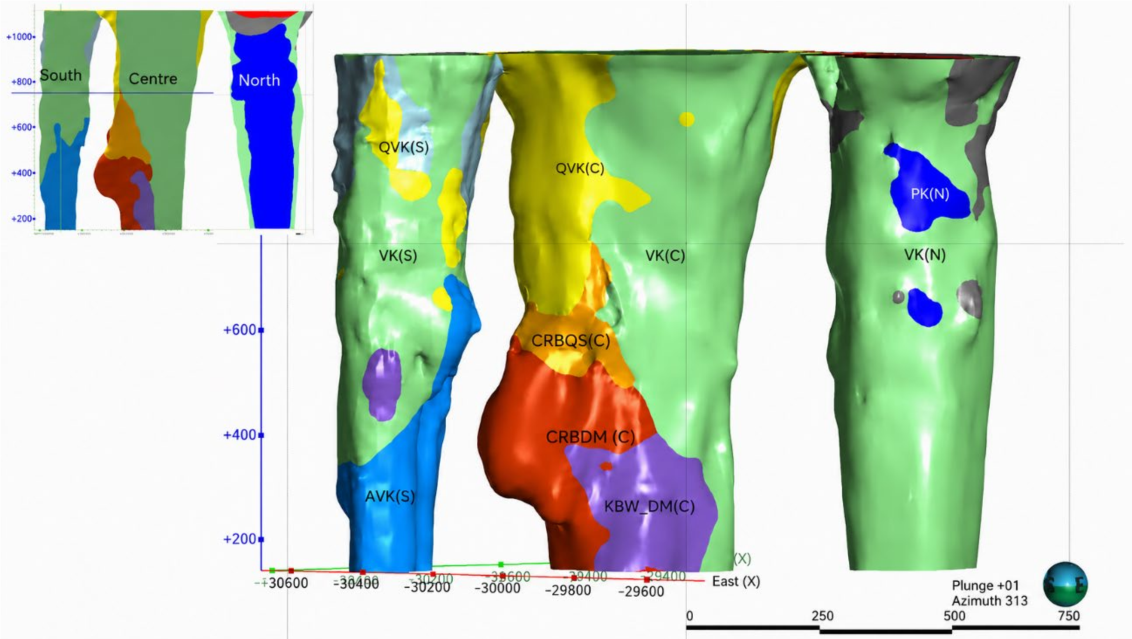

Figure 1 The Jwaneng D/K2 kimberlite showing key geological facies

Clay minerals in kimberlites form primarily through the alteration of the original minerals within the kimberlite rock itself, particularly the breakdown of serpentine and other silicate minerals in the presence of water and aqueous solutions (Bartlett & Nesbitt 2000). Kimberlites contain minerals like olivine, phlogopite, carbonates, spinels, monticellite, and other accessory minerals that are prone to weathering and alteration into clay minerals such as smectites (Figure 2).

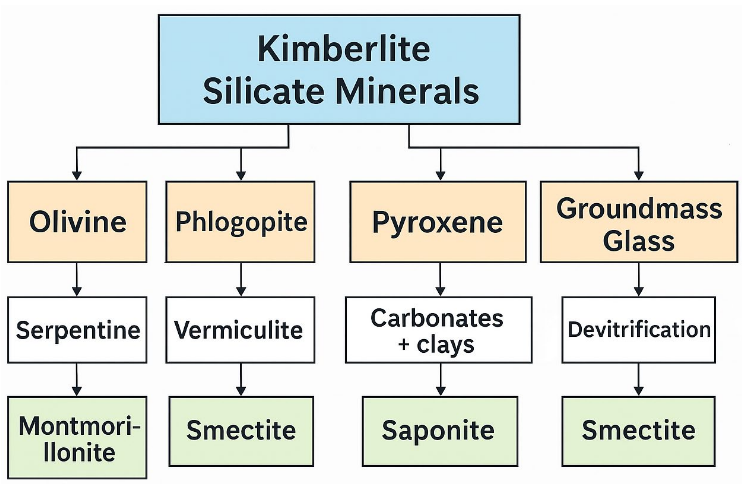

Figure 2 Alteration pathways of silicate minerals forming swelling clays in kimberlite

2 Impact of swelling clays

Swelling clays – especially smectite-rich minerals such as montmorillonite – pose significant engineering challenges because of their ability to absorb water and expand, generating high swelling pressures, rapid strength loss and structural degradation. This behaviour leads to foundation heave, pavement deformation, slope instability and tunnel lining distress in civil engineering settings, as well as bench failures, haul road degradation, drilling problems, and time-dependent deformation in open pit and underground mining. The mechanisms driving these issues are well documented: smectite can expand up to several times its volume due to crystalline and osmotic hydration (Chipera et al. 2019), producing substantial internal stresses and promoting mudrock breakdown. Specific to kimberlite, Morkel & Vermaak (2006) and Morkel (2006) studied their smectite content and swelling behaviour focusing on weatherability and concluded that increasing smectite in kimberlite increases weatherability. For the Jwaneng kimberlite, the smectite and subsequent weathering behaviour will have an impact on the underground tunnels and present mining-related challenges.

2.1 Tunnels in kimberlite

The presence of swelling clays presents the following challenges for sublevel retreat/sublevel caving drives and block caving production undercut and extraction levels:

- squeezing ground when exposed to water, requiring dry drilling and good overall water management
- deterioration of the kimberlite rock mass requiring a thin skin liner to prevent this from occurring
- a generally weaker rock mass depending on the proportion of swelling clays present that will deform under mining-induced loading.

2.2 Mining issues

When mining there are several issues that will impact on operational practices and effectiveness. These include:

- drilling difficulties with hole closures
- 'sticky' ore which can cause hang-ups in ore passes and difficulties on conveyors
- secondary fragmentation effects with more fines being produced
- the increased potential for fines generation increases the mud rush risk.

2.3 Mitigation of swelling clay issues

The issues noted above can be mitigated to some extent by understanding the proportions of swelling clays present in different kimberlite facies and which facies are likely to be more problematic, and then ultimately developing an understanding of the swelling clay distribution with different facies.

A better understanding of these factors will allow for improved ground support design, planning and scheduling, and budgeting, and the planning of rehabilitation activities.

3 Assessment methodology

The XRD testing methodology was used for the determination of presence/absence of clays within the Jwaneng kimberlites. Over 400 samples across the three kimberlite pipes were analysed through established laboratories. The analysis methodology followed for the XRD testing is based on Morkel et al. (2006) and is summarised as follows:

- An inventory of samples as received is crosschecked and naming conversion confirmed between the client (Debswana) and the testing laboratory.
- All received samples are opened and photographed for record prior to any processing.

- Each sample is then crushed, pulverised and split using a rotary splitter to obtain representative subsamples for major element bulk chemical assays, clay XRD and quantitative XRD studies.
- Major elements' bulk analysis is determined on the pulverised portion of all samples using inductively coupled plasma optical emission spectrometry. This method has a detection limit of ~0.05 wt %.
- For clay XRD analysis a McCrone mill is used to micronise a representative portion of the sample. This is done to obtain a homogeneous size distribution of all minerals present. The sample is also run on a Bruker D8 Advance X-ray diffractometer over the full 2 theta range of 3–80°.
- If clays are observed from the XRD analysis, to continue into quantitative XRD studies, after micronising the samples:
  - Glycolate the sample overnight and then run an XRD pattern to examine the impact of the experiment on the suspected clay peak, as per the United States Geological Survey (USGS) method detailed in Poppe et al. (2001).
  - Heat the sample in an oven to 400°C for at least half an hour and then run an XRD pattern to examine the impact of the experiment on the suspected clay peak, as per the USGS method.
  - Heat the sample in an oven to 550°C for at least half an hour and then run an XRD pattern to examine the impact of the experiment on the suspected clay peak, as per the USGS method.

The swelling clay results were then compared to other kimberlite durability test results within the Jwaneng mine database. These durability tests were selected for comparison because they all entail the wetting and drying of kimberlite samples under variable conditions. There is an expected reaction which could be linked to the intensity/concentration of swelling clays within a kimberlite facies.

The durability tests results used for comparison are the Field weathering test (FWT), Slake Durability Index (SDI), accelerated weathering index (AWI) and Duncan swell index. A summary of pertinent aspects of these durability tests is shown in Table 1. These tests are undertaken as per the established International Society for Rock Mechanics and Rock Engineering standards (ISRM), edited by Ulusay & Hudson (2007).

Table 1 Summary of the salient aspects of various durability tests

Feature	Slake durability index	Accelerated weathering index	Field weathering test
Purpose	Quick durability screening	Predict long-term durability	Observe real-world weathering
Location	Laboratory	Laboratory	Field
Time required	Short	Short to medium	Long
Weathering simulated	Physical (wetting/drying)	Physical and chemical	Physical and natural
Control conditions	High	Very high	Low
Output	Slake durability index	Strength, weight loss, chemical alteration	Observed rock degradation over time

4 X-ray diffraction results and discussions

Over 400 kimberlite samples, shown spatially in Figure 3, were tested for swelling clay through the XRD testing process. The XRD test sample statistics are shown in Table 2, with the highest sampling in the VK(C). Sampling density is a function of ongoing data collection programs. Smectites were found to be the predominant, and in most cases the only available, swelling clay within the Jwaneng kimberlites.

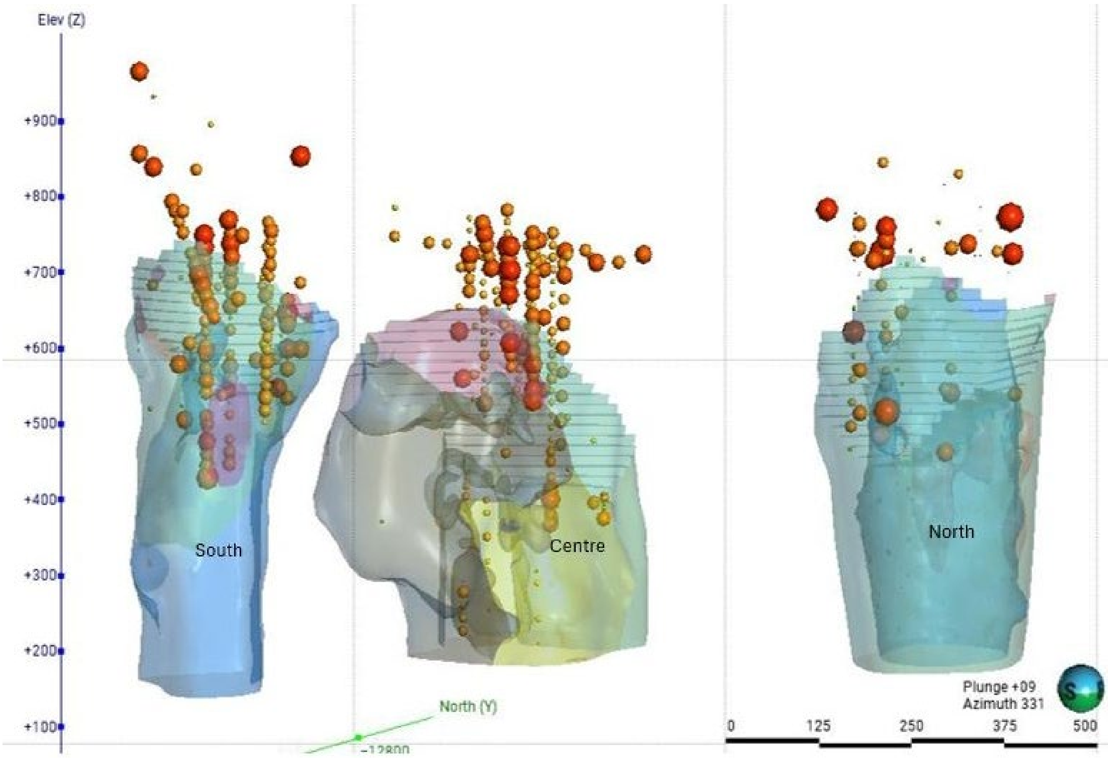

Figure 3 Spatial visualisation of X-ray diffraction samples within kimberlite. Dot size indicates relative smectite content

Table 2 Summary statistics of smectite content (%) for the Jwaneng key rock types

Kimberlite facies	Count	Min	Max	Mean	STD	cv
Autolithic Volcaniclastic kimberlite (S)	47	2.5	55.8	32.5	11.7	0.4
Volcaniclastic Kimberlite (S)	72	7.7	50.4	32.7	10.2	0.3
Pyroclastic Kimberlite (N)	90	0	66.1	7.1	13.2	1.9
Volcaniclastic Kimberlite (N)	41	0	66.4	26.3	18.1	0.7
Volcaniclastic Kimberlite (C)	156	0	55.1	26.0	11.9	0.5
Kimberlite Breccia-Dolomite (C)	33	0	30	10.6	8.2	0.8
Country Rock Breccia-Quartzitic Shale (C)	20	0	43.4	8.9	15.3	1.7
Country Rock Breccia-Dolomite (C)	30	0	45.5	2.4	8.5	3.6

STD – standard deviation; CV – coefficient of variation; (S) – south pipe, (C) – centre pipe, (N) – north pipe

Comprehensive statistical and graphical analyses were conducted on smectite content and smectite rating across all geological facies. Outputs include violin and boxplots, kernel density estimation (KDE)-style distributions, stacked rating profiles and pairwise statistical tests. These collectively define smectite variability, lithological controls and alteration zoning. Prior to analysis, the smectite content was classified according to the Morkel (2006) classification scheme to allow for qualitative intensity analysis as summarised below and in Figure 4. The following summary is derived from smectite content intensity analysis:

- VK(C), VK(N), VK(S) and AVK(S) exhibit high proportions of intermediate, major and predominant smectite ratings.
- CRBDM, CRBQS(C) and PK(N) are overwhelmingly trace or minor, confirming weak clay alteration.
- KBWDM(C) shows a mixed but generally moderate profile.

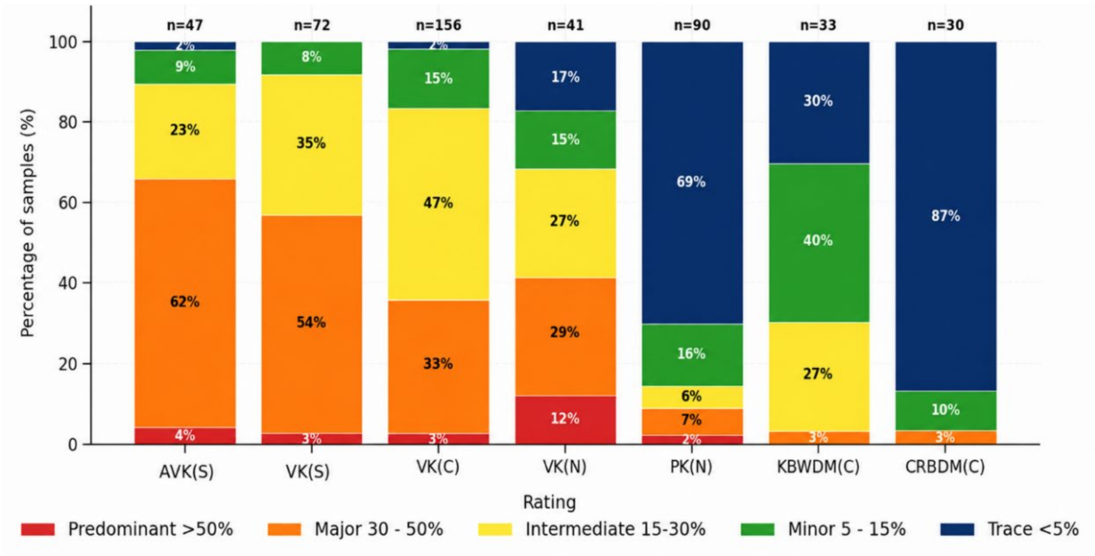

Figure 4 Stacked plot of Jwaneng mine percentage swelling clay per kimberlite facies within a kimberlite pipe (rating after Morkel 2006)

Across the facies, smectite exhibits distinctly non-normal, multimodal distributions, confirmed visually via KDE envelopes, and a combined violin/box overlay (Figure 5). Key observations are:

- VK(C), VK(N), VK(S) and AVK(S) show broad, high-intensity smectite distributions with medians commonly between ~25–40%.
- CRBDM, CRBQS(C), PK(N) are consistently low-smectite units, often dominated by < 5% smectite.
- KBWDM(C) is a kimberlite-rich breccia and sits in the intermediate range, with moderate variability.

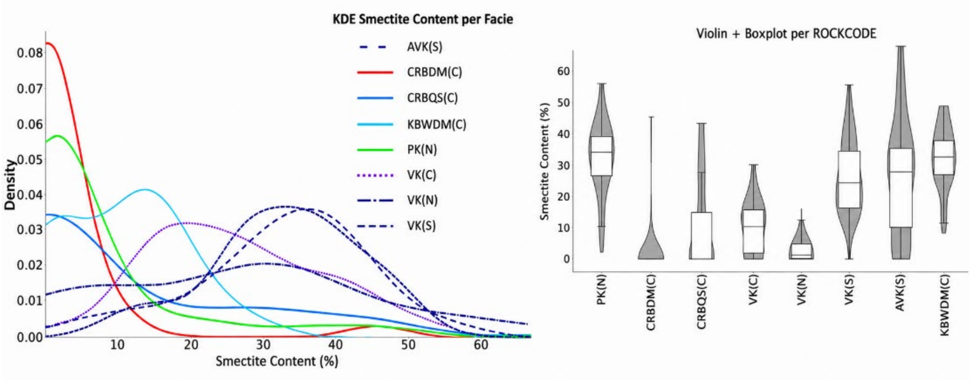

Figure 5 Smectite content in kernel density estimation plots, and combined violin and boxplot per facies

Using the Mann-Whitney U test for the smectite content and chi-square test for the rating, only the South pipe AVK(S) and VK(S) are demonstrated to be statistically equivalent, with p-values of 0.898 and 0.524 for the two tests, respectively. The close genetic relationship between these units has been demonstrated before using indicator mineral chemistry and microdiamond size frequency distribution data (Mmualefe 2014; Ferreira 2014).

In summary, the smectite content and rating in the dataset display clear lithological control and statistically robust differences between geological facies. The volcaniclastic units form a coherent high-smectite group, with AVK(S) representing the most intensely altered variant. Whilst the pyroclastic PK(N) kimberlite exhibits low smectite occurrences, there are zones within this unit that contain elevated smectite content.

4.1 Comparison of swelling clay results against selected durability tests

The dataset corresponding to the durability test is limited when compared to the swelling clay data, supporting visual analysis against the preferred detailed statistical comparison. Figure 6 is a stacked plot of slacking rating as observed on field weathering tests and associated sample counts per facie. A general observation is that facies with high clay content have a high slacking rating. This posits a directly linear relationship between an increased swelling clay percentage and increasing slacking rating.

It is observed that kimberlite facies which slakes easily (mud, flakes and chips) are in the order AVK(S) >VK(N)> VK(C) > VK(S) > PK(N). When compared to the swelling results from XRD testing shown in Figure 4, the trend of facies AVK > VK > PK is preserved. However, there are changes in the order of durability for the VK facies per pipe, and this may be attributed to low sample counts affecting the representativity in the field weathering test type.

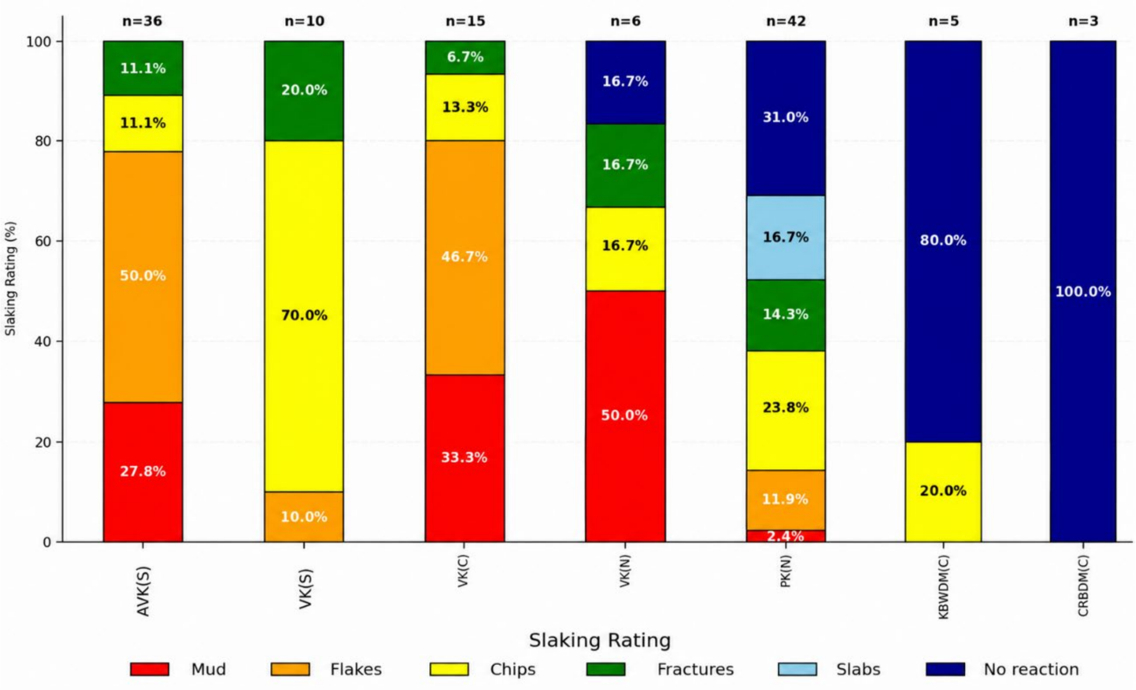

Figure 6 Stacked plot of Jwaneng mine for slaking rating from field weathering tests

Figure 7 is a stacked plot of combined SDI and AWI indices. A general observation is that facies with high clay content have a low durability rating, in agreement with observation from the limited data field durability test that shows a similar relationship.

The combined SDI and AWI rating shows the following order of reducing durability per kimberlite facies: VK(S) > AVK(S) > VK(C) > PK(N) >VK(N). Largely, the combined SDI and AWI results show a similar pattern where high clay facies have low durability although the VK(N) and PK(N) are interchanged. The disconnect between the PK(N) and VK(N) is likely a result of limited samples of the SDI and AWI test results. This durability test outcome suggests:

- AVK and VK kimberlite facies may have similar ranges of swelling clays as well as durability classes.
- PK(N) has pockets of low durability. These low durability portions can be related to the high smectite contents as seen in Figure 5.

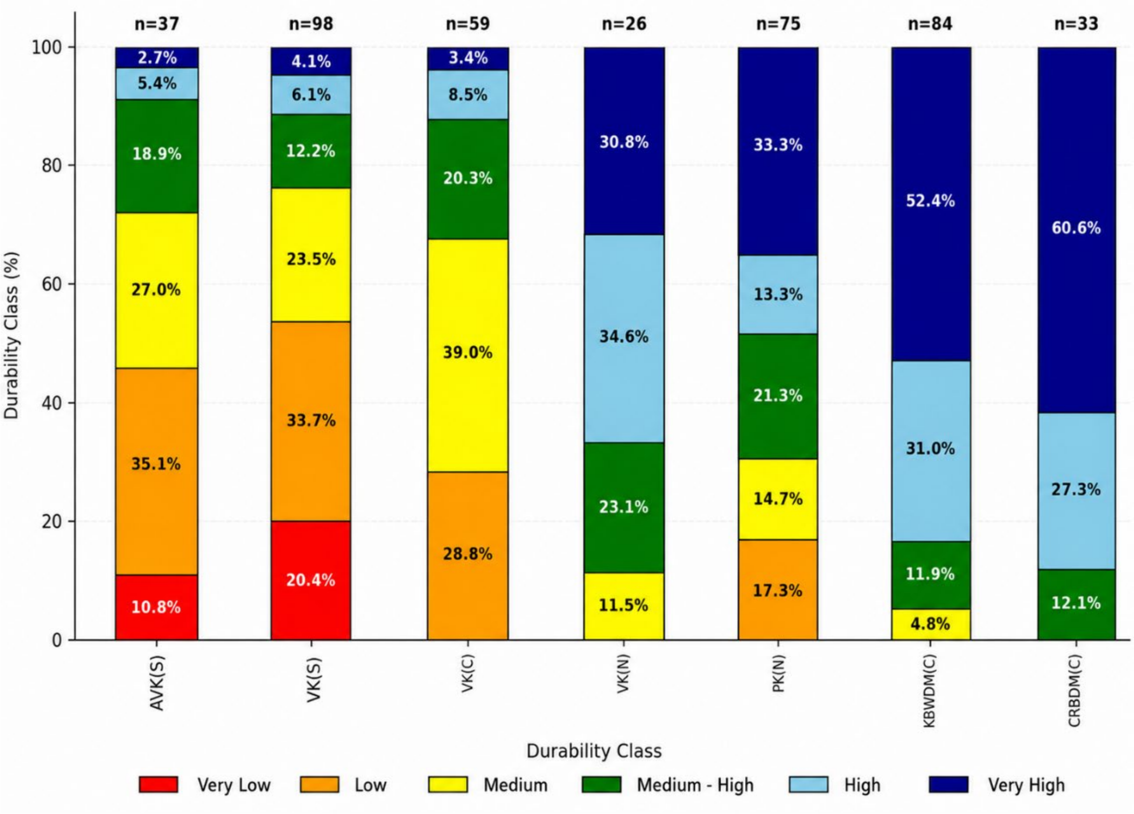

Figure 7 Stacked plot of Jwaneng mine for a combined Slake Durability Index and accelerated weathering index

5 Conclusion

This work sets a good base for understanding swelling clay impacts on the behaviour of different facies. Preliminarily, the general observation on swelling clay content (smectite) is autolithic volcaniclastic kimberlite (South pipe) > volcaniclastic kimberlite (South pipe) > volcaniclastic kimberlite (Centre pipe) > volcaniclastic kimberlite (North pipe) > pyroclastic kimberlite (North pipe). There are observed correlations between swelling clay potential and durability indices. This aligns with the Morkel & Vermaak (2006) study, which concluded that increased smectite content results in increased weatherability (loss of durability). An opportunity exists to increase the number of field durability tests and co-locating the durability and X-ray diffraction samples for better correlation.

Understanding the swelling clay proportions and spatial distribution is important for ground support design, scheduling and rehabilitation planning. It is also a valuable input into fragmentation assessments and for assessing mud rush potential and vulnerability.

The current XRD and durability indices work advanced our understanding and characterisation of the different kimberlite facies and allows ground support design, scheduling and rehabilitation decisions to be made per facies. Ultimately, a higher degree of spatial resolution would be desirable.

Acknowledgement

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