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FINAL MILESTONE REPORT

PROGRAMME	Mechanise Mining Systems	**WORK PACKAGE**	MMS23WP3 Mechanical Rock Breaking Technical Design Phase 2
MILESTONE	Milestone 9: Final Report		

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REF NO:	MMS23WP3-9v2

science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

CSIR
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1 EXECUTIVE SUMMARY

This project is part of the range of topics on rapid access development, and focuses on the establishment of design optimisation guidelines to improve development advance rates.

The objective of the current project phase is to establish a set of testing data of the important geotechnical parameters for PGM and gold hard rock tabular mines. This is required for the detailed design of mechanical rock breaking systems. The previous phase was a review the historic geotechnical studies done for mechanical rock breaking equipment for narrow reef hard rock (NRHR) gold and PGM mines, with the focus on identifying key geotechnical requirements and parameters. This current phase was used to assign tested values to the identified parameters.

Based on the previous phase, it was found that significant interest exists from OEMs, tool designers and the South African mining and tunnelling contractors, in the use of mechanised cutting technology in the South African mining industry. The technology has however not transcended the barriers and hurdles posed by the South African mining industry. A number of projects related to mechanical rock breaking has been conducted without the widespread adoption of the technology. Some of the factors contributing to this are the disparity of costs, when compared to conventional methods, difficulty of integrating aspects, such as cleaning with the rock cutting, thereby limiting the advance rates and the tunnel profile. Difficulties also arise due to the significant variability in rockmass conditions. Another major hurdle is the flexibility provided by the current mining layout and conventional mining practices limiting the mechanical equipment applications.

The objective of the current project phase is to develop a geotechnical database which is required for the detailed design of mechanical rock breaking equipment. The establishment of a rock parameter database will assist future mechanical design for more effective rock cutting equipment. This will enable the geotechnical design of a mechanised rock cutting machine and will have beneficial value in learning and understanding of the design principles.

To enable the capturing of historical rock sample data relevant to the parameter requirements being filed at the CSIR premises, the CSIR requested additional funding from the project funding in order to fund the employment of a person to analyse and capture the archived test data.

A number of other learnings from the project and project outcomes are listed below:

- Should future collaboration be required/demanded; there is a need to align and streamline the contractual processes between parties for example the CSIR and EUP.
- The South African mining companies are, typically not conducting testing on rock samples. The majority of laboratory test work conducted originates from projects in

Africa. Very few companies in the NRHR environment seems to be testing rock samples.

- The CSIR initiated the digital capturing of laboratory testing data and created a central database of rock test data during the 1980s. Currently there is no indication of the actual existence of such a database, while the person responsible for the database passed away.
- The current project included the creation of a new version of a rock test database. The database is now available and accessible to all to add their data.
- A major consideration, when considering the data required for optimally designing a rock cutting machine, is a full suite of test results. From the discussions, it is clear that very little of the existing testing data consisted of the full suite of tests required.

The establishment of the parameter database will be able to benefit the entire industry and will enable the geotechnical design of a mechanised rock cutting machine. This work also has the benefit of creating an understanding of the design principles. As a further extension of this project, some of the basic principles of fracture mechanics was investigated by conducting a literature review.

In summary, this project was an important stepping stone for future work related to mechanical cutting of rock. Progress was made by establishing a rock parameter database and the collection of rock testing data. This has been neglected in South Africa in the narrow reef hard rock environment for many decades.

2 AIM OF RESEARCH PROGRAMME

It was envisaged that this project would be a collaborative approach from industry representatives and research partners to establish a database of rock property information.

The main aim is the collection of relevant rock characteristics and population of a database that would enable the execution of a full technical study for effective mechanical cutting in PGM, chrome and gold narrow reef hard rock mines.

3 METHODOLOGY USED

The collection of rock testing data and the creation of a parameter database was conducted by searching for and approaching interested parties. Following the initial outreach and discussions, agreements and contracts were finalised. The major collaborator, the CSIR, possessed hard copies of test data in a store room in Pretoria. The files were transferred to the CSIR premises at Carlow road where it was digitised and used to populate an offline database. This required significant effort. To supplement the digitised data, some of the other collaborators allowed the project team access to relevant testing data.

Additional testing was also commissioned at a recognised laboratory. The team was fortunate as one of the collaborators assisted by providing rock samples. The samples consisted of a number of different rock types and was of such a nature and quality that 4 sets of testing were completed on all the identified parameters. Two rock types were additionally tested, although not the full spectrum of tests could be performed. As mechanical rock breaking is fundamentally governed by fracture mechanics, this phase of the study was used to bolster the past studies by completing a literature review of Fracture Mechanics. This was submitted as a standalone report.

4 RESEARCH FINDINGS

Introduction

Tunnel Boring Machines (TBMs) have been cutting through different rock lithologies for the past few decades. Tunnels with a range of dimensions have been developed. In contrast, underground tunnel development in the South African mining industry, has been dominated by conventional drill and blast methods. These methods have been applied to both stoping and development ends.

Historically, TBMs have been tested by a number of operations (Figure 1) while DeBeers successfully applied mechanised cutting on some of their diamond mines. More recently, TBMs with a smaller turning radius have been introduced to assist with the development of underground excavations in South Africa, some of the platinum mines have tested the cutting machine with a smaller turning radius with some success. Other projects using borehole drilling technology was used in the gold mining sector besides the large scale on-reef testing that was done in the platinum mining sector.

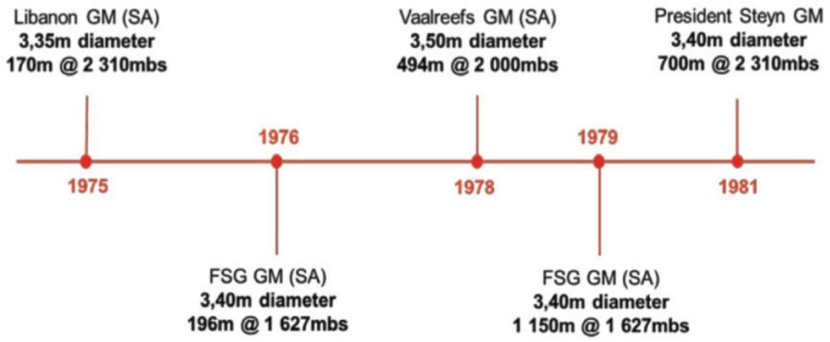


Figure 1: Early tunnel boring trails in South African mines (after Gouws S.C., 2015)

One such example of early mechanised tunnelling, not included in the project shown in Figure 1, is a project of a 4 m diameter tunnel planned for a 6 km length at a depth of 3000 m on East Driefontein (Figure 2).

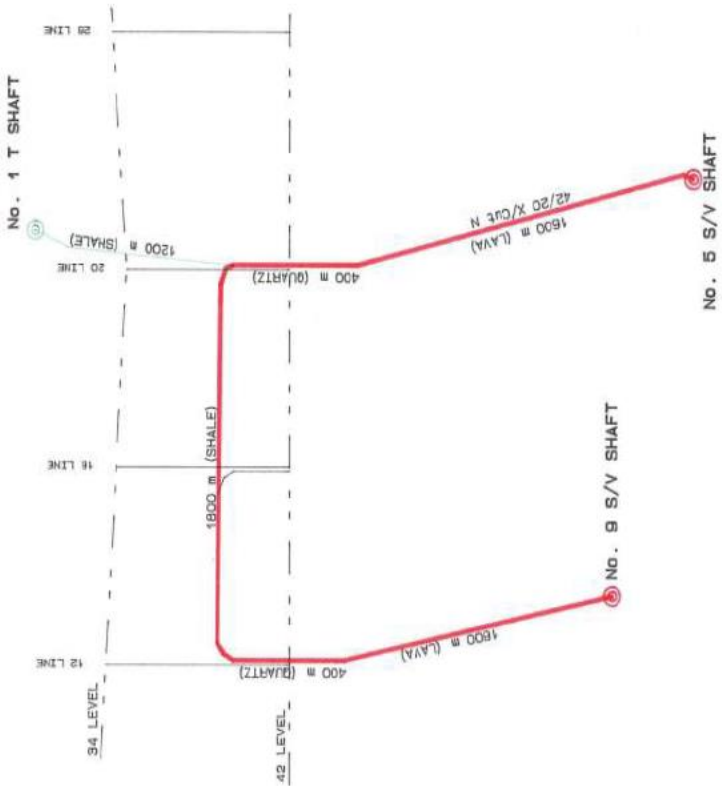


Figure 2: Image of a plan for a mechanical cut tunnel at East Driefontein (BBE Consulting internal report)

The mechanical rock cutting projects have unfortunately not yet resulted in a commercially viable option that can replace the conventional mining methods. Some of the challenges that are typically experienced with the mechanised mining efforts in the South African context, are the rock stress conditions, cost of the operation, hardness of the rock, the turning radius of the machine and the orientation and geometry of the orebody.

The use of TBMs for tunnelling in civil engineering projects has been very popular worldwide, with numerous projects currently underway. These tunnels are occasionally difficult to extract owing to changing rock lithology. As the rock excavation process is, however, not dependent on the mineral value of the ore, tunnelling for civil engineering projects, allows for a more controlled process.

A change in rock lithology can occur for both civil engineering excavations as well as mining. This typically require the expertise and ongoing analysis of conditions by a geotechnical engineer to ensure that optimal cutting of the TBM is achieved. For the civil engineering application of TBMs, the ground conditions along the planned tunnel route are usually pre-determined to a high level of accuracy, owing to the nature of the project. Should the TBM intersect an un-anticipated change in ground conditions, a group of engineers, including a geotechnical engineer, are utilized to ensure that the machine can operate safely and effectively.

To implement an acceptable mechanical cutting methodology on a South African hard rock mine is challenging, the *"sweet spot needs to be hit"* for the solution to be feasible as shown in Figure 3. The challenges in the mining environment ranges from environmental conditions such as dust and temperature to logistics, further complications such as utilisation, support, ground water and unpredictable ground conditions.

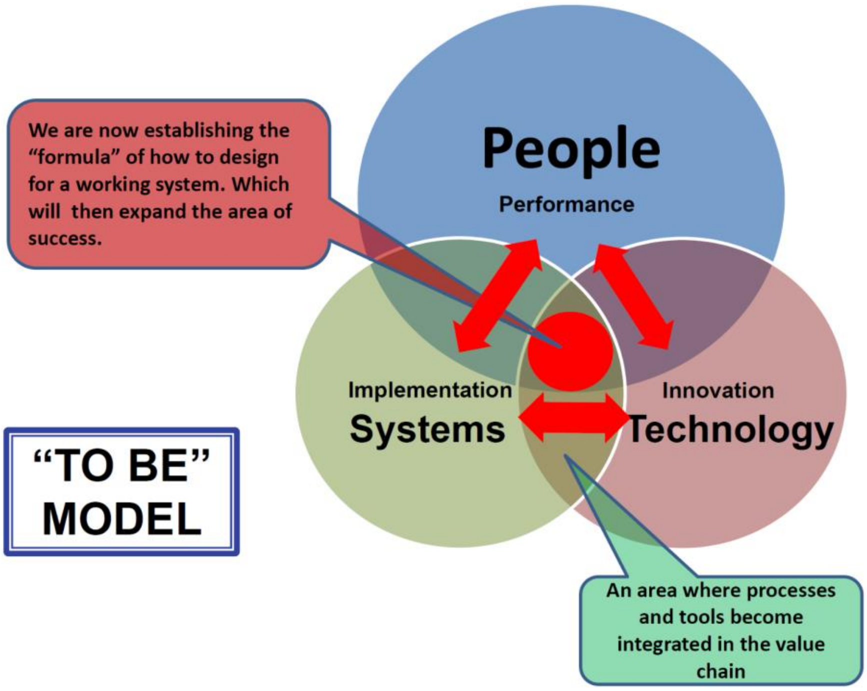


Figure 3: The integration of man, machine and systems (after Pickering, 2013)

The OEMs do have the technology and skill to overcome challenges and obstacles presented by hard rock mining (Figure 4). The efforts to date, their successes and learnings are typically not freely available by means of well documented publications in the public domain.

Figure 4: Sandvik Narrow reef hard rock stoper (after Sandvik, 2013)

One reason why companies might not be very eager to record and share their efforts is the significant costs involved with planning, sampling, testing and designing mechanised cutting solutions, the typical cost of a trial at this point in time for lateral development is close to a Million rand a meter, compared to an international high-rate development crew that is planned at a rate of R 250 000 per meter compared a conventional mining crew planned at R 65 000 per meter.

Mechanised rock cutting machine selection and design

Mechanical excavation can be defined as using machines to transfer energy from cutting instruments to the rock and thereby creating concentrated strains resulting in rock failure, whilst the scientific study of the relationship between the cutting tool and the rock is known as rock-cutting mechanics. In addition to planning and estimating excavation performance, building and choosing mechanised miners rock-cutting mechanics are a fine balance between physical rock properties and system requirements. The rock cutting design process is shown in Figure 5.

Some of the earlier study phases, emphasized the value of comprehensive geotechnical data and how essential it is to the use of mechanical rock cutting techniques. It was also demonstrated that geotechnical analysis is crucial to the design process when thinking about mechanical rock cutting for uses in underground mining.

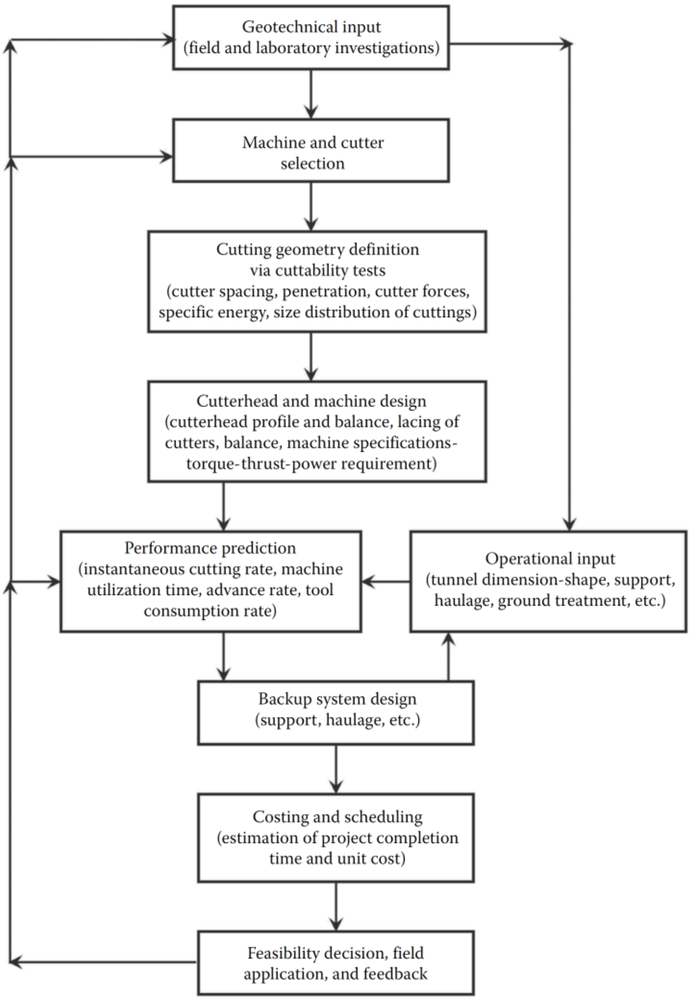


Figure 5: Generalised mechanised rock-cutting development methodology (after Copur, H. 1999)

Development Earmarks

The main development objectives of the study are large scale inter-region tunnels between shafts, main access haulage development from the shaft infrastructure, reef access development, such as crosscuts, and lastly on-reef development. On-reef development presents a significantly more challenging working environment as the reef is generally inclined and narrow (less than 2.5 m in mining height). The focus of this current project is on the horizontal off-reef excavations.

Considering the PGM mining sector, the large scale, inter-regional tunnels, main access tunnels and reef access tunnels will be developed through different types of igneous rocks, including anorthosite, magnetite, norite, chromite and pyroxenite (Figure 6 and Figure 7). Dykes that can be encountered and vary in type from dolerite, diabase, syenite to lamprophyre.

The development of tunnels in the gold sector will mostly be in dolomites, quartzites, lavas and occasionally in shale host rock, depending on the depth below the surface. Dyke material and fault material like mylonite or psuedo-tachylite will also occasionally be present as the geological features are traversed.

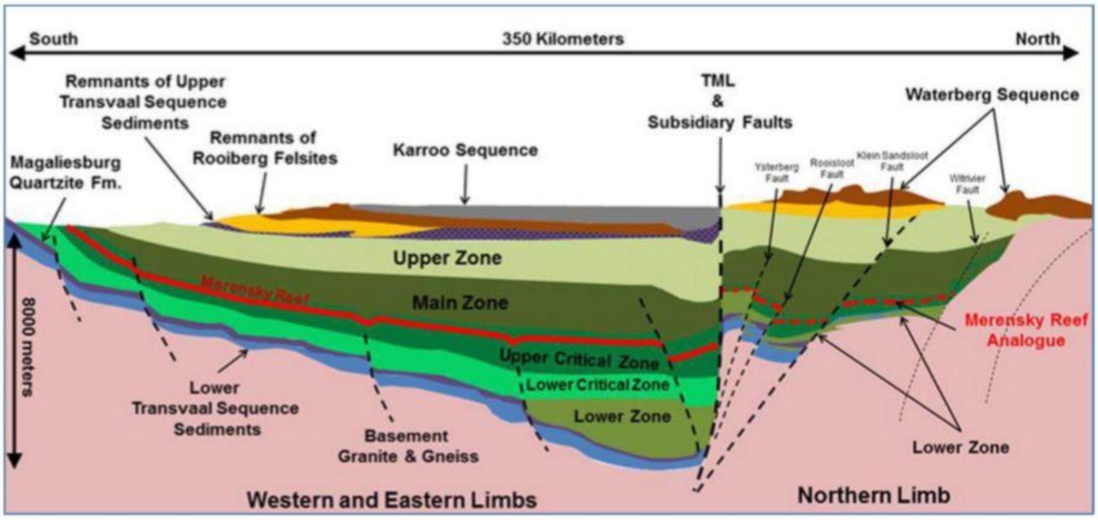


Figure 6: Bushveld Complex cross section showing the PGM bearing Merensky reef, Upper Critical Zone and Platreef (after Kruger, 2005)

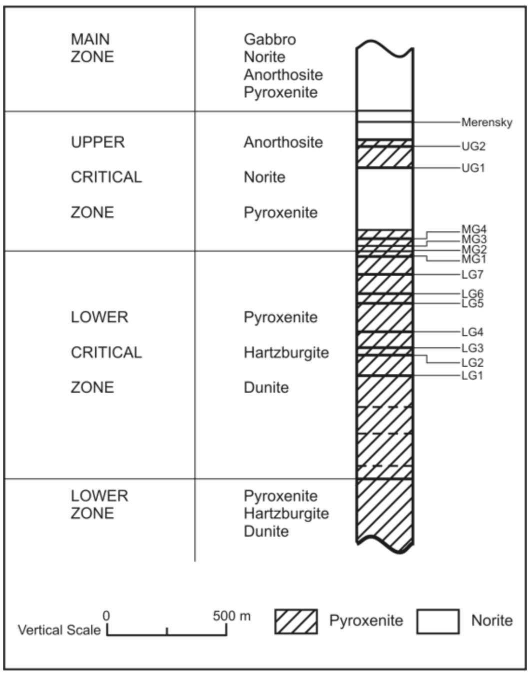


Figure 7: Stratigraphic column showing position of significant chromitite seams (after Schürmann et al., 1998)

Geotechnical Laboratory Testing

To design the correct mechanical rock cutting equipment, the work site needs to be described and characterised. A site investigation for mechanical excavation purposes would need to define the rock mass condition, forming part of the geotechnical study framework. This will involve geological, geotechnical, and other information about the area. Wrong parameters will lead to an incorrect design, increased costs and a number of unwanted or non-deal outcomes.

It should, however, be noted that even if all the rock parameters are tested, it would not guarantee the success of mechanical cutting as the interaction and behaviour of all the rock types would not necessarily be determined, while burned (altered) or transitional materials, may not be well understood. Rapid changes in rock strength will also be detrimental to the performance of a rock cutting machine.

The design of a Mechanised rock cutting machine is dependent on a number of parameters and indices. In order to accurately design such a machine, it was found that a significant number of tests needs to be conducted. The test code and expected outcome are listed in Table 1.

Table 1: Required sample test and expected outcome

Test Code	**Output**
UCM	UCS, Elastic modulus and poisons ratio
UTB	Brazilian Tensile strength
NTH	Norwegian rock boreability tests
SBT	Sievers miniature drill tests
AI	Rock abrasiveness tests
DRI	Boreability tests
CAI	CHERCHAR hardness index tests
SHO	Shore Scleroscope hardness tests
STI	Rock cohesion and friction angle tests

Laboratory testing of rock samples

In order to ensure that a full suite of rock tests is performed, as part of this study phase, a significant number of samples are required. Between the CSIR and the stakeholders some samples were secured and transported to a laboratory that is capable of testing all the required parameters.

Figure 8: Samples secured and transported by the CSIR

As the test results was captured in a database, which also forms part of the outcomes of the current project, the details such as location coordinates are also known and available. Sufficient samples were obtained to conduct testing on Norite, Pyroxenite, Anorthosite and UG2. Another two types of rocks were tested, but unfortunately only a portion of the suite of tests were performed. Figures 9 and 10 indicates some typical pre- and post-testing photos of the prepared rock samples, while Figures 11 to 12 is some of the results obtained from the tests conducted at this point in time.

Figure 9: Prepared samples ready for testing

Figure 10: Sample after UCM testing

Table 2: Results of UCM testing

Rocklab Specimen No	Sample ID	Rock Type	Failure Load	Strength (UCS)	Tangent Elastic Modulus @ 50% UCS	Secant Elastic Modulus @ 50% UCS	Poisson's Ratio Tangent @ 50% UCS
9485-			kN	MPa	GPa	GPa	
UCM-01A	Norite 1	Norite	328.8	185.9	85.9	85.8	0.29
UCM-01B	Norite 6	Norite	416.3	234.5	96.5	96.1	0.33
UCM-01C	Norite 29	Norite	393.2	222.6	78.3	58.9	0.38
UCM-02A	FPYX01		326.6	188.9	117.0	119.0	0.28
UCM-02B	FPYX06		303.2	173.5	106.0	111.0	0.31
UCM-02C	FPYX02		349.3	202.6	115.0	118.0	0.27
UCM-03A	Granite 02	Granite	585.8	330.2	69.4	67.5	0.26
UCM-03B	Granite 06	Granite	350.3	200.3	56.7	45.7	0.37
UCM-03C	Granite 03	Granite	483.2	272.6	73.7	68.3	0.32

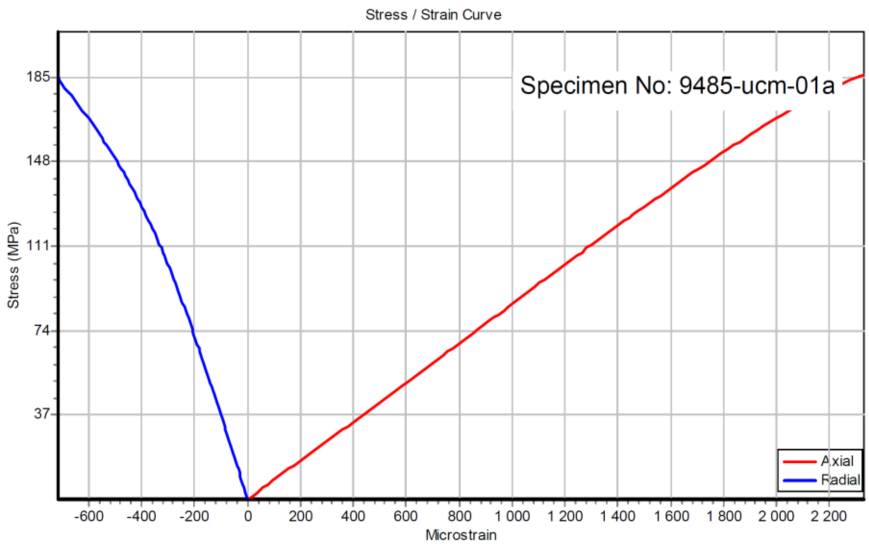


Figure 12: Typical graph produced following UCM testing

Laboratory test data from collaborators

A number of people were contacted and discussions held in order to determine possible collaborators. Some of the major and most prominent contacts are listed in the table below:

Table 3: Prominent contacts

No.	Company	Response	Comments
1	Knight Piesoldt	Interactions can be described as negative.	Of the viewpoint that the data is privileged information.
2	Bear Geo Consultants	Open to discussions, waiting on a written response.	Indicated that the data can be provided with client's permission.
3	Jones and Wagner	No response.	
4	CSIR	Relocated physical archive. Person employed to analyse and digitize the information.	The archive was partially digitised and captured.
5	DRA	Open to discussions, the type of data does not seem to fit this projects requirements.	Indicated that the data can be provided with client's permission.
6	Geo Pioneers	No response	
7	Rocklab	The initial response can be described as hesitant and negative. Later discussions and clarifications led to a response where data can be made available based on client permission.	Indicated that the data can be provided with client's permission.
8	Anglo American	Open to discussions, waiting on a written response.	Indicated that the data can be provided if acceptable database management and custodianship is put in place.
9	Impala platinum	Open to discussions, waiting on a written response.	Indicated that the data can be provided if acceptable database management and custodianship is put in place.
10	Raisbore drilling contractors	Open discussion did not result in any commitment, companies do not capture clients data in a separate database.	No additional data secured

A number of discussions were held with the testing laboratory in order to gain access to the data at source, this was however met with a myriad of red tape and opposition. Some of the large clients were approached in order to obtain permission to access the data and agreements to view the data were obtained. The clients were also kind enough to supply the project test data of internal rock cutting projects. The data can however be described as very sparse.

Considering the similarities in laboratory test work when planning a raise bore hole when compared to the mechanised mining machine, the companies involved with shaft sinking and raise boring were contacted with a detailed list of data requirements unfortunately none of the companies captured the rock data of past projects in a central database while client privilege were also a concern. Fortunately the mining houses indicated that they are willing to share their full test databases under certain circumstances, the data was secured and incorporated into the digital database.

Other sources of geotechnical laboratory test data

A final source of information would be the historic test data as produced by the CSIR. It is believed that Jhon Ryder started a digital database containing test data in the early 1990s, unfortunately the database could not be traced or found.

Fortunately, some of the physical records, contained in several filing cabinets were available and some funding were made available to transport and capture the test records. Some of the records originated between about 1953 and 1990 as part of the Rock Mechanics Research Programmes and thus the rock testing laboratory was part of the "National Mechanical Engineering Research Institute - NMERI". While other reports were created between 1991 and 1996 by the "CSIR Division for Earth, Marine and Atmospheric Science and Technology – EMATEK".

The CSIR worked through the cabinets, capturing and digitizing the information contained in eight cabinets that were purely rock test data. Figures 13 to 17 indicates the physical cabinets, the contained documents as well as some of the data as captured by the CSIR.

Figure 13: Image showing some of the cabinets that was transported back to the CSIR based at Carol road

Delivery 8A

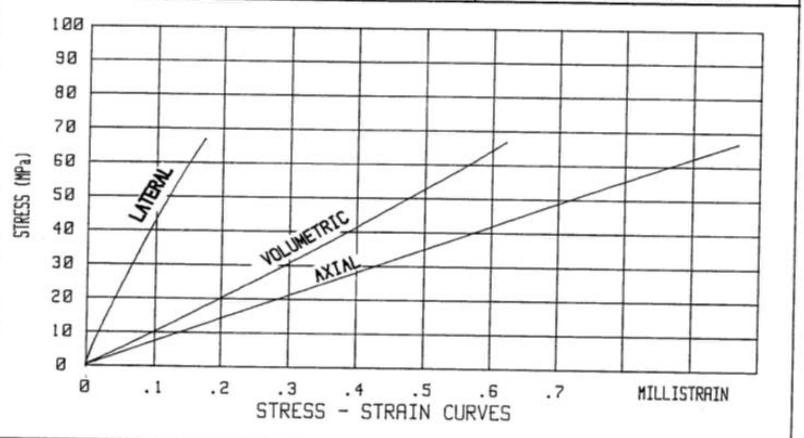
TABLE 8.1.1: UNIAXIAL COMPRESSIVE STRENGTH TESTS

Specimen No 1324-	Depth m	Rock type	Dia. mm	Height mm	Mass g	Density kg/m^3	Failure load kN	Strength UCS MPa	Tangent @ 50% UCS Poisson's ratio –	Tangent @ 50% UCS Deformation modulus GPa	Tangent @ 50% UCS Transducer modulus GPa
KVR 101-UCM-129	0,09/ 1,01	Highly amygd Basalt	54,1	135,5	839,56	2700	373	162,3	0,266	59,5	–
KVR 102-UCM-130	0,20/ 1,20	Highly amygd Basalt	54,2	135,4	849,63	2720	327	141,7	0,256	54,1	–
KVR 102-UCM-131	0,20/ 1,20	Highly amygd Basalt	54,4	135,2	854,10	2720	324	139,4	0,221	57,1	–
KVR 102-UCM-132	0,20/ 1,20	Highly amygd Basalt	54,2	135,3	849,57	2720	313	135,7	0,253	48,7	–

Figure 14: Image showing some example data as per the physical test records

GEOMECHANICS RESEARCH SERVICES
EMATEK - CSIR

UNIAXIAL COMPRESSION TEST
WITH DEFORMABILITY MEASUREMENTS
BY MEANS OF STRAIN GAUGES



STRESS - STRAIN CURVES

STRESS - STRAIN DATA

POINT No	STRESS (MPa)	MICROSTRAIN AXIAL	MICROSTRAIN LATERAL
1	.4	1	-0
6	.5	1	-0
11	.8	3	1
16	1.4	12	1
21	3.4	41	5
26	6.2	79	10
31	8.7	116	16
36	11.1	150	21
41	13.3	183	26
46	15.7	217	32
51	18.2	253	38
56	20.6	288	43
61	23.0	323	49
66	25.7	361	56
71	28.2	398	62
76	30.7	434	68
81	33.2	470	75
86	35.7	506	81
91	38.2	543	87
96	40.7	580	94
101	43.2	616	101
106	45.9	653	108
111	48.4	690	115
116	51.1	729	123
121	53.7	769	131
126	56.1	804	138
131	58.9	846	146
136	61.4	883	154
141	64.2	924	163
146	67.0	966	172

SPECIMEN DETAILS

ROCK TYPE : QUARTZITE
NUMBER : 1355-FW/17/1-CRP-01
DIAMETER : 43.3 mm
LENGTH : 91.8 mm
MASS : 367.54 g
DENSITY : 2720 kg/m^3

TEST DETAILS

DATE : 1989/09/ 1 TIME : 09:55:30
TEST MACHINE : AMSLER RANGE : 200 kN
FAILURE LOAD : 104 kN TESTER : UWV

CALCULATED DATA

METHOD AT STRESS (MPa)	E (GPa)	P.RATIO
TAN AT 30 % UCS = 21.1	69.3	.173*
TAN AT 50 % UCS = 35.3	68.2	.165*
SEC AT 30 % UCS = 21.1	71.4	.150
SEC AT 50 % UCS = 35.3	70.5	.150

UNIAXIAL COMPRESSIVE STRENGTH (UCS) : 70.6 MPa

FIG. A4.1 TEST RESULTS OF SPECIMEN No : 1355-FW/17/1-CRP-01

Figure 15: Image showing an example test record as per the physical test records

Specimen No 1324-	Depth m	Rock type	Diameter mm	Height mm	Mass g	Density kg/m^3	Failure load kN	Strength UCS MPa	Tangent @ 50% UCS		
									Poisson's ratio -	Deformation modulus GPa	Transducer modulus GPa
KVR 101-UCM-129	0.09/1.01	Highly amygd Basalt	54.1	135.5	839.56	2700	373	162.3	0.266	59.5	-
KVR 102-UCM-130	0.20/1.20	Highly amygd Basalt	54.2	135.4	849.63	2720	327	141.7	0.256	54.1	-
KVR 102-UCM-131	0.20/1.20	Highly amygd Basalt	54.4	135.2	854.1	2720	324	139.4	0.221	57.1	-
KVR 102-UCM-132	0.20/1.20	Highl amygd Basalt	54.2	135.3	849.57	2720	313	135.7	0.253	48.7	-
KVR 101-UCM-172	1.48/2.29	Highly amygd Basalt	60.2	150.1	1135.6	2660	491	172.5	0.286	60.1	-
KVR 101-UCM-173	1.48/2.29	Highly amygd Basalt	60.2	147	1104.9	2640	485	170.4	0.242	58	58.1
KVR 102-UCM-174	1.39/2.40	Highly amygd Basalt	60.2	150.6	1122.8	2620	427	150	0.217	50.5	-
KVR 102-UCM-175	1.39/2.40	Highly amygd Basalt	60.2	150.4	1111.6	2600	415	145.8	0.23	53.5	-

Figure 16: Extract from the digitized data as captured by the CSIR during 2023

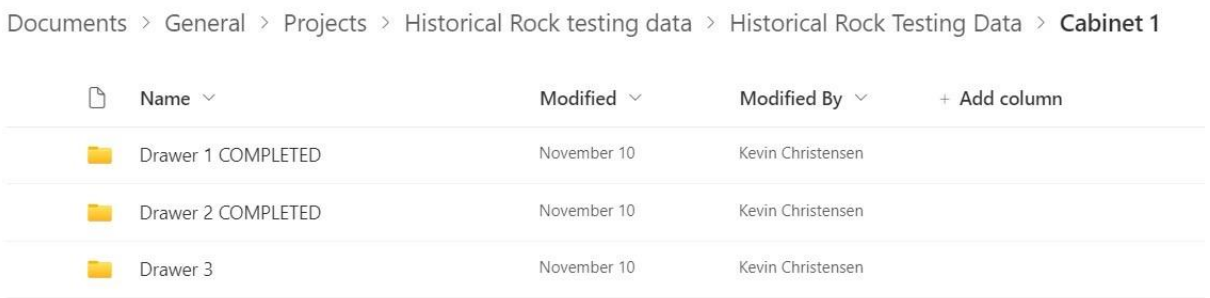


Figure 17: Image showing an example of the digital filing system as captured by the CSIR during 2023

The contents of the 9 cabinets were digitised and captured in the digital database. Hence a major stride in terms of retaining geotechnical knowledge by making it available for use by practitioners.

Geotechnical Database

An offline database has been created with the aim of storing rock test data. The data sources have been discussed as part of this report.

The database was set up to enable the capturing of the bore hole coordinates (Figure 18). The capturing of the client, site and other details would not only enable the user to analyse the data for specific areas but also enable the administrator to limit access to certain data should the stakeholder require it.

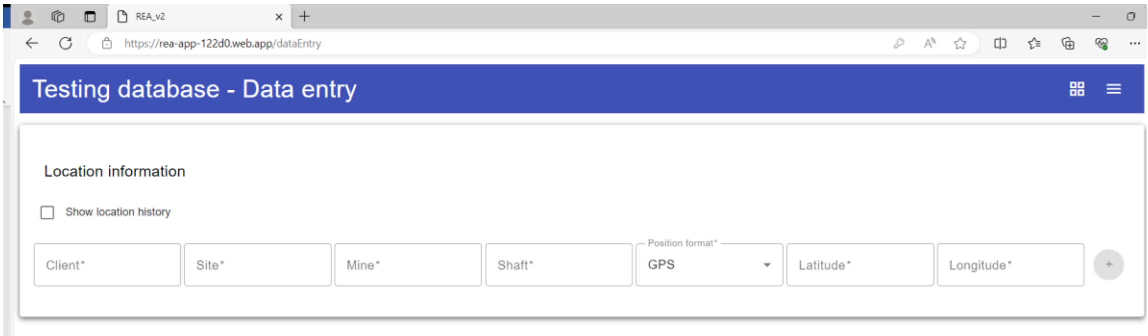


Figure 18: Location information as entered into the database

A significant number of test parameters can be captured, this would ensure that none of the test data are lost whilst also allowing for the complete range of tests required to accurately classify the rock types, Figure 19.

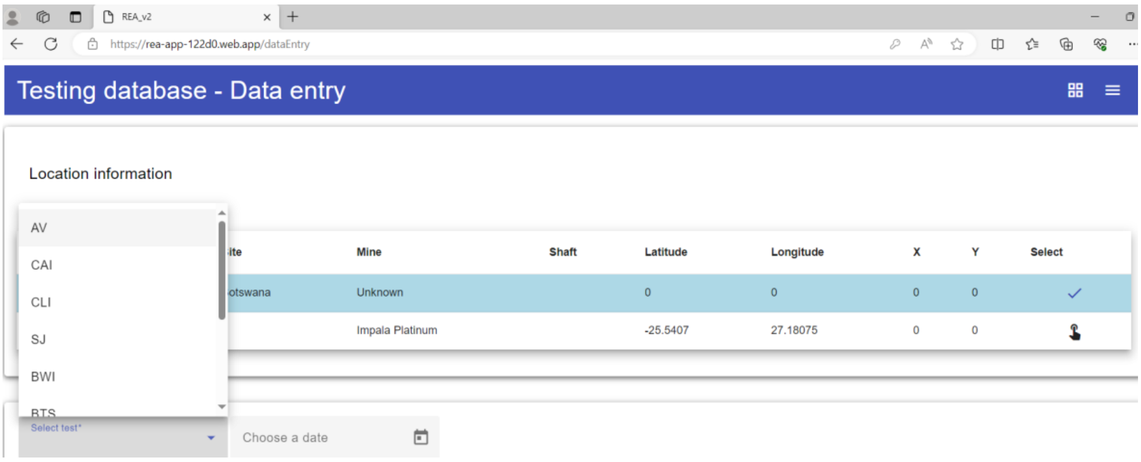


Figure 19: Test types selection for data entry

The data capturing process entails entering data into fields, the fields has been set up for each test type and in accordance to the typical format in which test results are presented. Figures 20 and 21 indicates the capturing format of a few different tests.

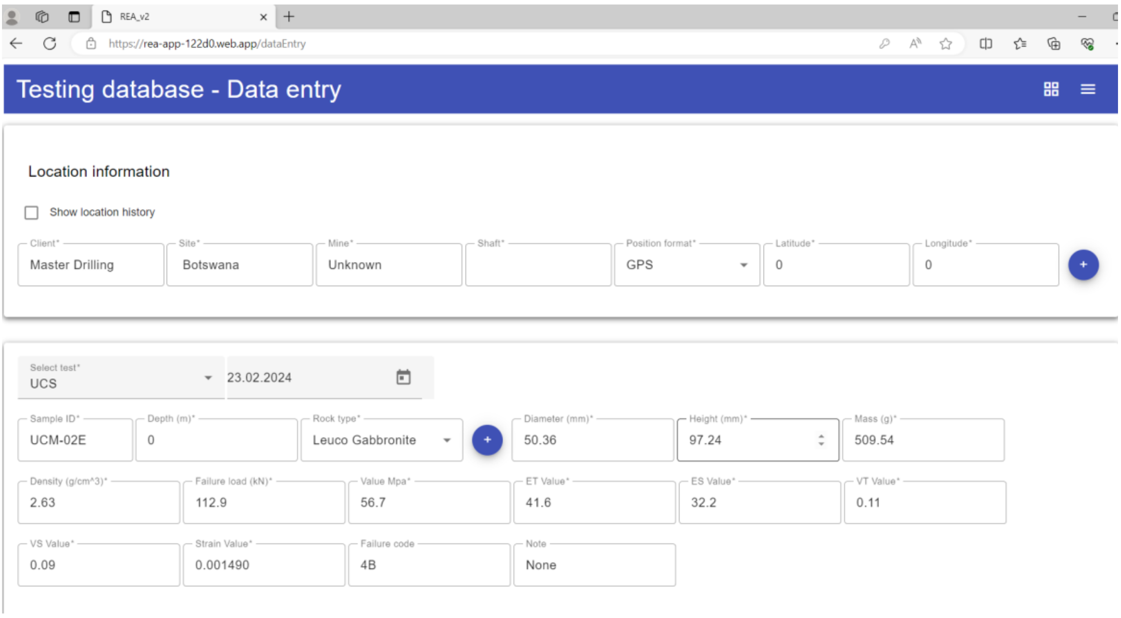


Figure 20: Data entry fields for UCS strength tests

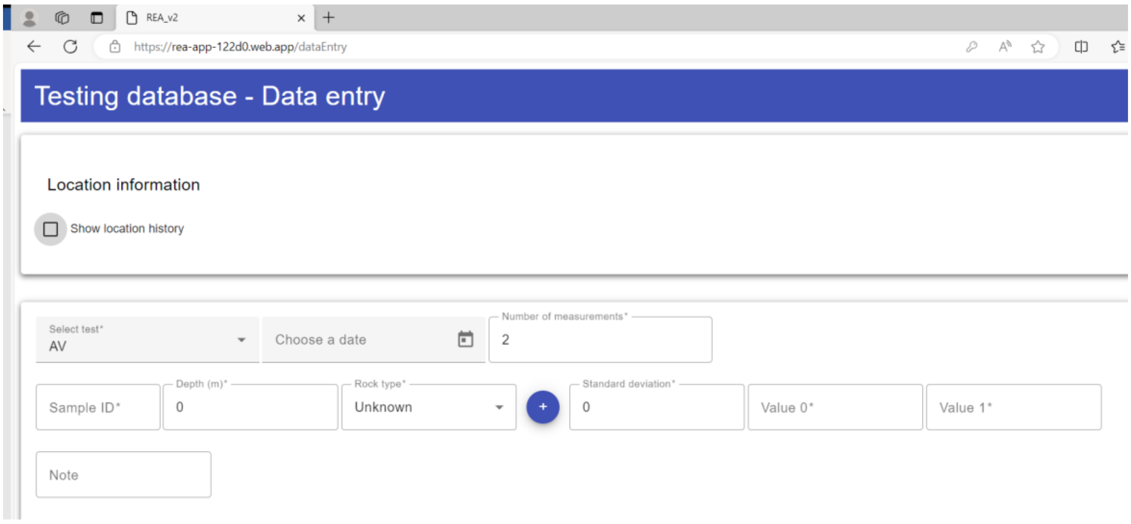


Figure 21: Data entry fields for abrasiveness testing

The database functionality includes a search function, Figure 22, whereby the data can be filtered by a host of attributes such as test type, rock type and depth to name a few.

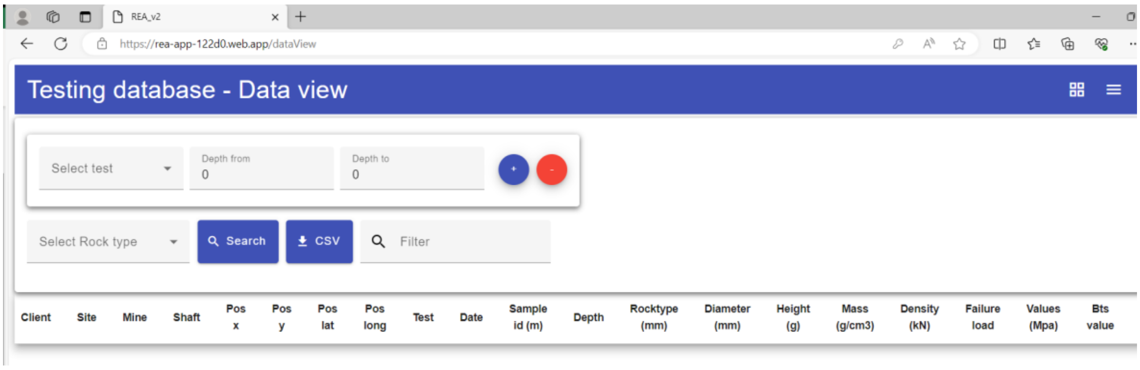


Figure 22: Data search function

The functionality of the search function in the offline database is shown in Figure 23, while Figure 24 indicates the ability of the database to export the data for further analysis.

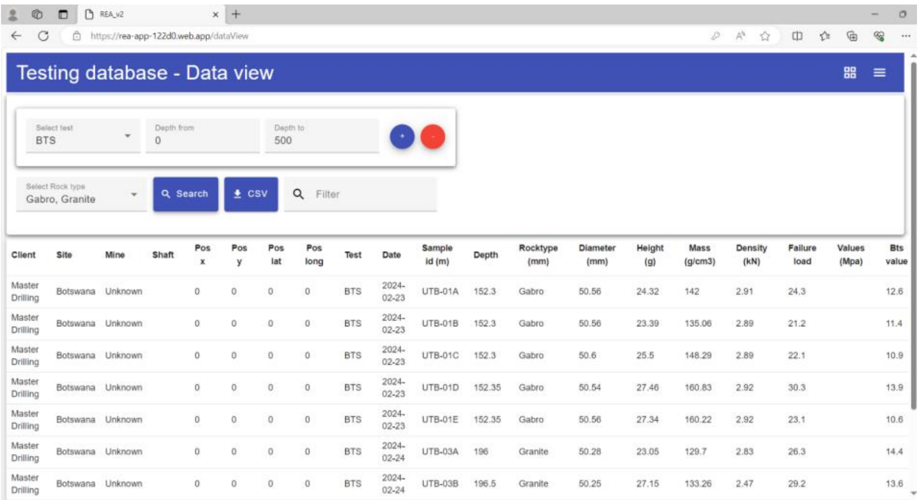


Figure 23: Display of captured data in database.

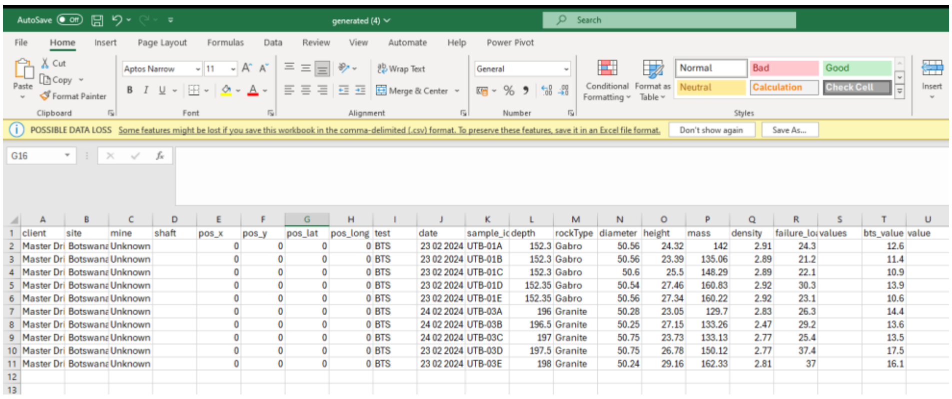


Figure 24: Export of captured data.

Rock test data summary

Considering the significant number of tests that are required to make up a full set of testing very few of the participants have data that can be called complete and representative, Figure 25 indicates typical values of only one of the parameters as found in the literature.

Table 4: Typical rock strengths for rocks associated with the PGM mining environment (after Clark-Mostert, 2007)

Rock Type	UCS (MPa)		
	Minimum	Maximum	Average
Anorthosite	174.63	234.17	207.43
Leuco Norite	151.35	155.72	154.02
Norite	235.18	275.50	256.29
Lamprophyre	52.86	68.77	58.36
IRUP	95.07	149.59	115.28
Pyroxenite	138.56	170.36	159.04
Merensky Reef	79.48	113.06	92.05
UG2 Chromitite	56.91	68.13	62.19

In order to visualise the data in the database Figures 26 to 28 is an example of the typical values of a limited set of parameters and data. An appendix with a more complete overview of the rock test data will be made available.

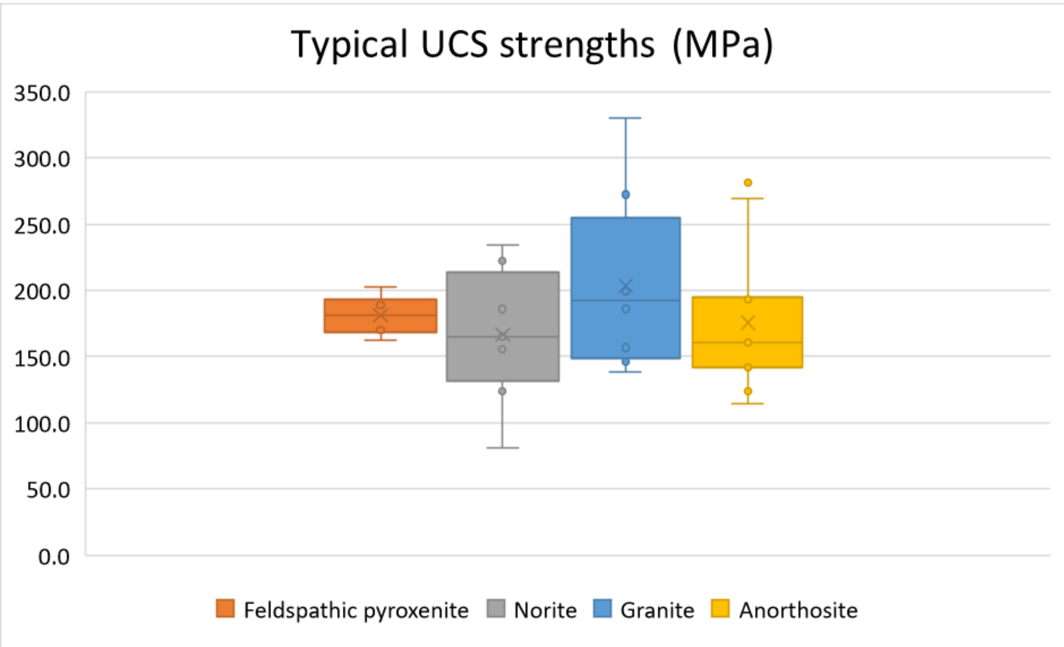


Figure 26: Typical rock strengths for common rock types in the South African PGM NRHR mining sector

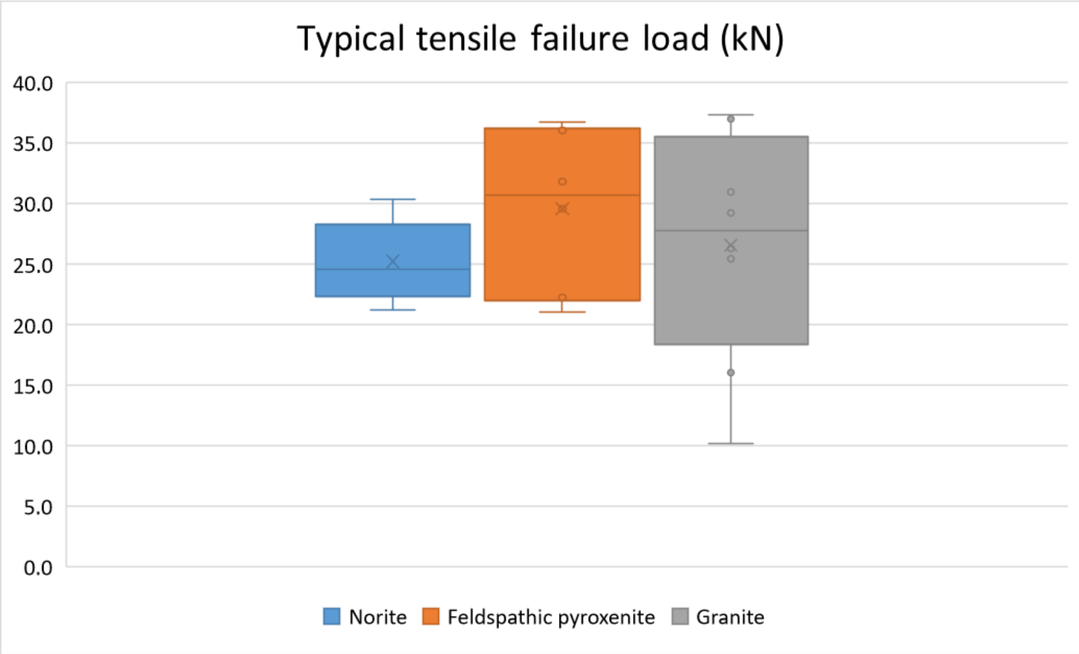
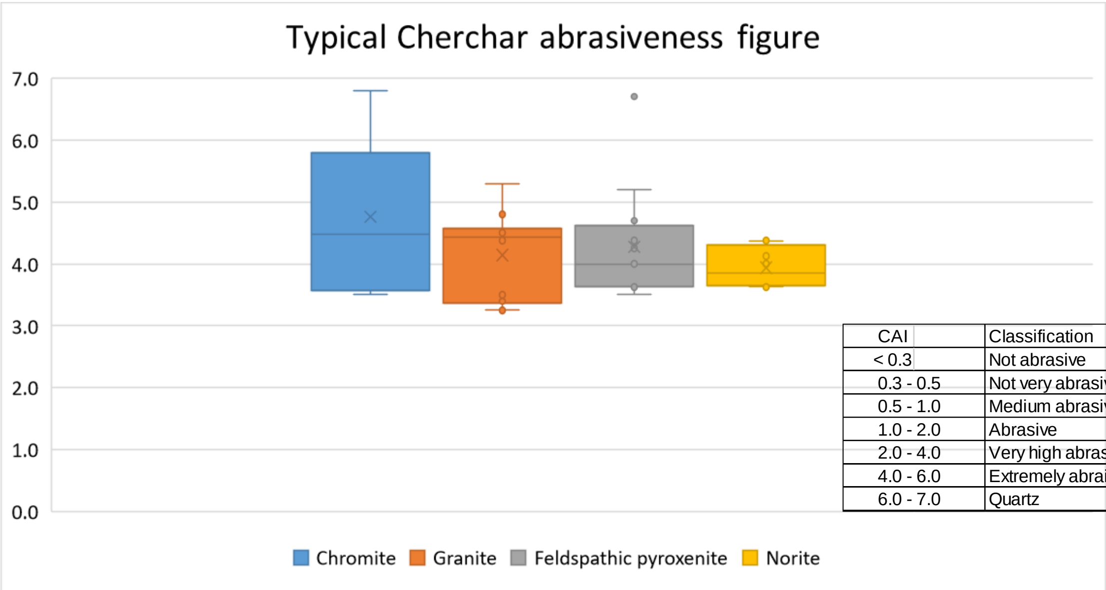


Figure 27: Typical tensile failure load for common rock types in the South African PGM NRHR mining sector



CAI	Classification
< 0.3	Not abrasive
0.3 - 0.5	Not very abrasive
0.5 - 1.0	Medium abrasive
1.0 - 2.0	Abrasive
2.0 - 4.0	Very high abrasive
4.0 - 6.0	Extremely abraisve
6.0 - 7.0	Quartz

Figure 28: Typical rock abrasiveness values for common rock types in the South African PGM NRHR mining sector

Considering the rock test data that was provided with the aim of mechanical rock cutting, it can be concluded that the rock strengths are high some samples exceeding 330 MPa, while chrome had the lowest compressive strength at 90 to 130 MPa.

The majority of the rock types tested (excluding chrome) fell into the highly to extremely abrasive category, and had Cherchar hardness rating well above the top scale limits of "very difficult". Looking at the other parameters the drill rate index was low, meaning slow penetration rates, low to medium cutter life index indicating frequent cutter disc changes and high operating costs.

The test date seems to be in line with the experienced advance rates and maintenance.

5 KEY CHALLENGES AND LESSONS LEARNED

Mechanical cutting of rock in the South African hard rock environment is a challenging endeavour on many fronts. The process should not only compete in terms of safety, price and quality but also be flexible enough to cater for the mining layouts, confined working areas and uncertain geology.

Tunnel shape was identified as an important consideration for mechanical cutting in mining. Round tunnels, such as those excavated using a TBM, generally excavate more material compared to a rectangular excavation with similar dimensions. Circular tunnels are only practical for vertical shafts and are deemed impractical for mining applications where trackless equipment is needed. There are different methods to make the circular excavation more practical for mining applications and these include backfilling the tunnel to create an even floor, cutting the corners at the bottom of the tunnel to create a flat floor or inserting an artificial floor structure using steel or other stiff material. These methods increase the excavation time and add to the capital expenditure and will ultimately impact on the feasibility of the project. Another alternative pursued by the tunnelling industry is the development of mining specific mechanical cutting systems that are capable of cutting rectangular excavations. These machines are still in the development and testing phases and are therefore not yet available on the market.

In general, there are notable differences between civil tunnelling, mining tunnelling and the key geotechnical parameters used in the equipment design. Civil tunnel projects are generally located in urban areas, which have a higher degree of sensitivity and therefore require a higher factor of safety in their design and support. Civil tunnelling projects tend to do more in-depth geotechnical studies before and during the project as these excavations have a long operational life. A detailed understanding of the rock mass is required for long term stability excavations with extensive geotechnical information collected, captured in Geotechnical Baseline Reports (GBR's) . These reports are used as the basis for tunnel design, support and cutting machine considerations.

Mining tunnels require a limited life of operation that is usually less than that of civil tunnels. These tunnels are also often deeper and not in as sensitive areas. Mining operations are cost sensitive and this affects the type of support installed. Extensive support is only installed in areas where extreme ground conditions are present. Mining tunnelling seems to focus on limited rock parameters and does not use the same comprehensive geotechnical study compared to the studies for civil engineering tunnels. It can be argued that the gap in quality and scale of the geotechnical studies between civil and mining projects may be one of the reasons why mechanical cutting applications in mining projects have not been successful. More in-depth studies of the various geotechnical parameters may be useful to improve the success rate of mechanical cutting in mining.

One of the possible machines that would be amenable and well suited to the to the current layouts and requirements of the South African narrow reef hard rock environment is the roadheader. Unfortunately, there are several major obstacles when using roadheaders in hard rock settings. These include the low proportion of cutting tools engaged at any given moment, face stability, excessive heat and sparks generated at the cutting interface, and lack of thrust with the boom configuration. In general, roadheaders operate at a maximum UCS of 150 to180 MPa. Using excessive thrust, in the presence of high strength rocks, the cutter head jumps around on the face as a result, while there are a limited number of cutters that are actively interacting with the face, on a cutter head, resulting in a system that is less effective than a TBM.

The rock face is also considered by some to be less stable when cutting smaller sections with a roadheader compared to the full engagement of the face by a TBM. When using picks with harder rock types, a large amount of heat and sparks are generated when the picks engage with the face. The hotter the tools are, the lower the cutting efficiency becomes and the higher the tool wear. This requires additional water sprays to actively cool the cutting interface. The sparks are risky for areas where gasses are present and are a source of ignition. One solution would be to use smart diamond composite picks that are able to manage heat generation more effectively. This will, however, not be able to solve the thrust force issue better than cutting harder rock with a roadheader.

Discussions regarding the current state of mechanisation in South African mines revealed a key issue concerning the lack of implementation success. It is suggested that the lack of implementation is not only due to labour concerns or union intervention, but is also largely due to current mining methods not being optimised for mechanical rock cutting systems. The successful implementation of mechanical rock cutting systems would require a review of current practices and a change in the method applied to extract the orebody. An example of a possible alternative to conventional board and pillar layouts would be to cut out the boundary of the orebody and then proceed with diagonal drives, which would potentially eliminate the issues with making 90 degree turns.

6 CONCLUSIONS

It is evident that very few, if any, of the available test databases contains all the desired rock tests. It is by now also well known that the rock test data is needed to ensure the design process are effective in achieving the set goals. The manufacturers, as a result of decades of experience, are able to factor in and account for some variability, whilst some of the typical rock properties (of international past projects) are beknown to them. Considering the uniqueness of the South African deposits, this project is thus valuable in setting and collating South African rock parameters and would enable the study to proceed to the next phase of this project.

A significant effort was made to obtain and capture relevant rock test data. The rock test data was obtained from collaborators, by conducting additional testing but also attained by capturing test results contained in old physical archives and creation of a database.

One of the findings of the project was that laboratory rock testing is not conducted as part of the ongoing processes of the South African mining industry, be it to confirm, verify or create a baseline. The lack of testing has a significant impact on the availability, capacity and ability of laboratory test facilities. As an example, there are a very limited number of laboratories that are equipped and able to test all the parameters required for this project, one of which indicated they are in the process of scaling down their operations and considering closing a full division. The effect and lack of testing was also realised when the fracture toughness testing could not be completed, this test was identified as a fundamental driver during the fracture mechanics review.

The rock test database that was created and partly populated are hosted at the CSIR and the system is available for all of the mining industry to make use of to capture their data. This represents a stride forward in the data and knowledge retention for the South African mining industry, while the project would be able to advance to the following project phase and allow mechanised rock cutting machines to be designed with greater confidence in the South African mining industry.

7 RECOMMENDATIONS and WAY FORWARD

In general the tunnel boring machines, with a round profile and large turning radius, are not well suited to the typical narrow reef, tabular layouts, equipment and designs as we currently know and apply it.

The typical TBM are designed & built for a fairly well defined "task", usually in the form of a "straight" service tunnel where environmental and social aspects are the driving factors rather than cost.

During the previous phases it has been shown that the current technology should be able to excavate the hard rock formations found in the SA mines. Unfortunately, the use of such equipment has not been adopted due to a number of reasons, ranging from logistics to operating cost.

The success of using mechanised cutting technology in the mining industry would greatly benefit and would have a significantly better chance of success if the mines are aware of the typical problems, downfalls and capabilities.

The following is recommended for future study phases:

- Draw up an outline containing the typical process when considering mechanised tunnel excavation, including a very brief overview of basic principles, machinery, and techniques. Such a document, summarising the study to date, would be useful for companies considering the technology in future.
- Create a checklist of key information and considerations in order to guide and assist future mechanised tunnelling efforts.
- Set out the minimum requirements in terms of Geotechnical studies (GBR) and testing prior to approaching equipment manufacturers.
- Draft an outline of a typical GBR report that would be suitable for the South African conditions.
- Create a simplistic system that can be used by a company to identify possible equipment that might be suitable to the identified conditions.
- Establish a set of past learnings and typical learnings from historic projects.
- Set out a workflow and outline the typical process from concept to realisation.

- In order to show the true value of applying, using and following the correct procedure and gathering sufficient data, it would be a great opportunity to use the ARM reef boring project as a case study.
- Conduct a desktop study on mining methods that would be more applicable to typical TBM capabilities; Introduce and study alternative mining layouts for the SA NRHR.
- Establish a cost model to evaluate the costs from; study, design, prototype testing, product manufacturing, testing and project execution.

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9 PATENTS, PROTOTYPES, TECHNOLOGY PACKAGES AND DEMONSTRATORS

This current phase of the project does not have any opportunity for patents or prototypes and the heading is thus not applicable to this project.

10 HUMAN CAPITAL DEVELOPMENT

There were no post-graduate students involved in the project. Mr Johann Esterhuyse is currently a PhD student at the University of Pretoria, his topic of study is not part of the scope of this current project.