Mineralogical impact on the compaction of residual gabbro soils in the construction of Platinum Tailings Storage Facilities

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ABSTRACT:

Over the past decade, there have been 45 tailings storage facility (TSF) disasters worldwide, resulting in fatalities, serious environmental damage, and the destruction of entire ecosystems. These failures often stem from substandard design or operational practices. Many TSFs are constructed in regions associated with intrusive mafic rocks such as gabbro, norite, pyroxenite, and anorthosite, which are commonly found alongside platinum group metals in areas like the Bushveld Igneous Complex in South Africa and the Great Dyke in Zimbabwe. The stability of these structures can be significantly influenced by the residual soils present at the construction sites. Residual soils, both cohesive and non-cohesive, contain varying quantities of different minerals, which can impact the compaction characteristics and, consequently, the stability of the TSF foundations. Cohesive soils rich in clay minerals, such as kaolinite and smectite, exhibit properties that can hinder effective soil compaction. The expansive nature of smectite due to its ability to absorb large amounts of water and host free exchangeable cations, counteracts the compaction process, reducing soil stability. Soil compaction is a complex process influenced by several factors, including compaction effort, method, water content, particle size distribution, and mineralogy. This study aimed to analyse these factors using a series of laboratory tests, including foundation indicators, MOD AASHTO compaction testing, and X-ray diffraction analysis, on residual soils from two TSF construction sites. The findings revealed that soils with high clay content tend to retain more water and have a higher optimum water content, adversely affecting their compaction properties. This study highlights the critical need to consider the mineralogical composition and weathering effects of residual soils in the design and construction of TSFs. By improving our understanding of these factors, we can enhance the stability of TSF foundations, reducing the likelihood of future failures. The insights gained from this research highlight the importance of thorough geotechnical assessments in the successful design and maintenance of TSF’s.

KEYWORDS:

TSF; soil compaction; residual gabbro; mineralogy; Great Dyke; Bushveld Igneous Complex

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1. Introduction

Tailings storage facilities (TSFs) are a vital part of many mining operations around the world as they provide a means of storing processed waste material that could be detrimental to the environment. Tailings are the waste products produced when extracting valuable minerals or metals from rock ore such as platinum, copper, gold, and uranium to name a few. Mechanical and chemical processes are used to break down ore into a fine sand to extract these valuable commodities. All the unrecoverable and uneconomic remnants (gangue) from this process are waste, and they include chemicals such as cyanide, mercury and arsenic, as well as finely ground rock particles and contaminated water (Araya et al., 2020). A recent study conducted by Piciullo et al. (2022), presented a statistical analysis of tailings dam failures since 1915. Through their research, they determined the leading causes of tailings dam failures globally (**Figure 1**).

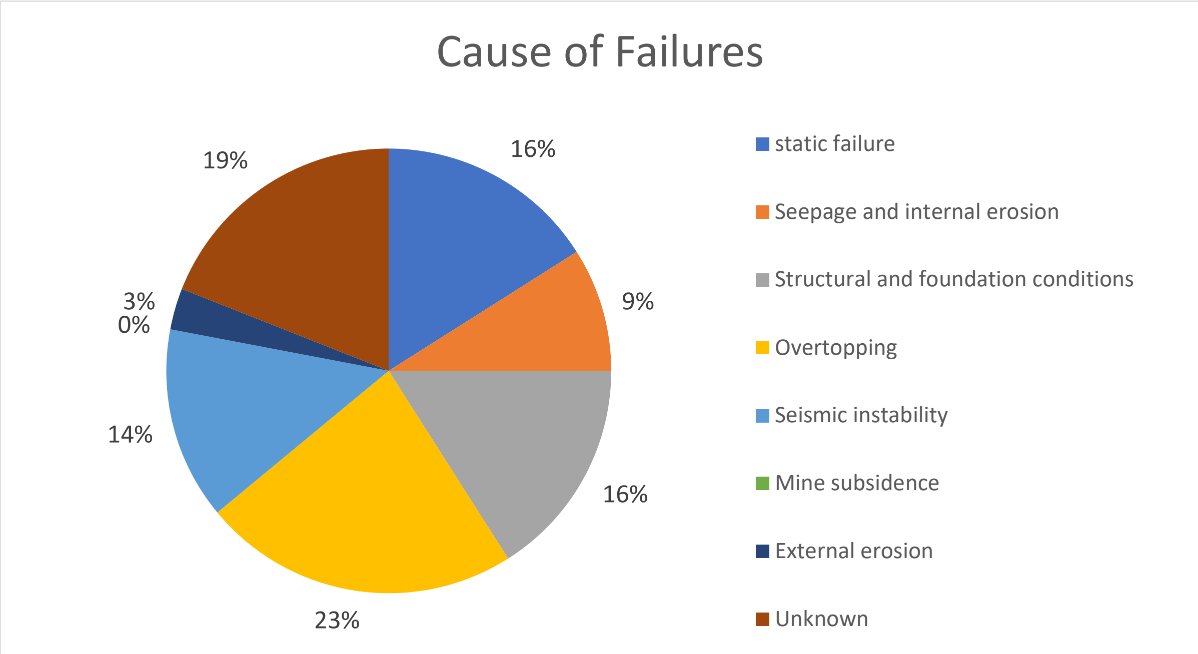

Figure 1 Causes of tailings dam failures since 1915 (Piciullo et al., 2022)

Historically, foundation failures are one of the leading causes of tailings dam catastrophes around the world accounting for at least 16% of all failures recorded. Compaction of in situ material to its maximum dry density is imperative to ensure the foundation stability of these mega structures. The construction of tailings dam foundations is a complex and expensive process that includes the preparation of in situ ground material, the construction of drains and stability bunds, and the placement of high-density polyethylene (HDPE) liner to prevent the contaminated water from infiltrating into the groundwater system.

To lower the costs during construction, in situ material is often used as aggregate for concrete or fill for foundations and earth structures. Rocks such as gabbro and anorthosite, and their residual soils are often used in the construction of these super structures, and as such the importance of understanding these geological units and their engineering properties are important in assuring their stability.

Platinum (Pt) is a dense, malleable, precious metal that is inert and is regarded as a noble metal due to its exceptional corrosion resistance. It forms part of the platinum group metals (PGMs) together with palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir), and osmium (Os). Platinum is one of the most valuable metals on Earth, and it is an important economic mineral that is utilised in various industries such as dentistry, jewellery manufacturing, catalytic converters, and the manufacturing of various medications to treat cancer. Five countries account for approximately 97% of total global platinum production (Sousa, 2017). Table 1 shows the known distribution of platinum reserves across the world.

Table 1 World platinum reserves (Sousa, 2017)

Country:	Reserves (metric tonnes)	World total reserves:
South Africa	110 000	68%
Russia	25 000	16%
Zimbabwe	11 000	7%
Canada	7 200	4%
United States	3 650	2%
Total of All Other Countries	3 800	2%
World Total	**161 000**	**100%**

Due to the abundance of platinum-group metals (PGMs) in intrusive mafic rocks located in places like Zimbabwe's Great Dyke and South Africa's Bushveld Igneous Complex, mining operations have extracted large amounts of material from the ground, creating waste and necessitating the construction of more tailings storage facilities.

The investigation presented here is a study of the importance of mineralogy with specific reference to its effect on the compaction of residual soils derived from gabbroic parent material during the construction of TSF foundations on two platinum-producing mines located in South Africa and Zimbabwe. The research can be used to aid both the design and construction sections of the Global Industry Standard on Tailings Management (GISTM) requirements.

1.1. Hypothesis

The mineralogical composition of residual gabbro soils has a considerable impact on their compaction properties, which in turn affects the stability of Platinum Tailings Storage Facilities (TSFs). Changes in the percentage of cohesive materials within residual gabbro soils will result in measurable variances in maximum dry density and optimal moisture content, ultimately affecting compactability. Understanding these connections will allow for more precise engineering techniques for developing and maintaining the foundations of TSFs, potentially increasing their durability and lowering the danger of structural failure.

1.2. Aims

This research consists of the following aims:

- To analyse and characterize the mineral content and composition of residual gabbro soils

to understand their properties better.
- To study how the mineralogical composition influences the compaction properties of these soils, specifically focusing on maximum dry density and optimal moisture content.
- To identify and quantify the relationships between the soil's mineralogical composition, its compaction characteristics, and overall compactability.

1.3. **Objectives**

To achieve the aims of this research, the following objectives have been outlined:

- Collect representative samples from different sites and conduct an in depth literature review of the hypothesis.
- Characterize Residual Gabbro Soils by conducting mineralogical analyses to determine their composition.
- Identify and quantify the different mineral components present in these soils.
- Measure the maximum dry density and optimal moisture content of residual gabbro soils.
- Perform laboratory tests to evaluate the compaction properties of the different soils with varying mineralogical compositions.
- Investigate how changes in the percentage of cohesive materials (e.g., clay content) within the soils affect compaction characteristics.
- Determine the relationship between cohesive material content and soil compactability.

2. Literature Review

2.1. **Overview**

In the last decade, approximately forty-five (45) TSF failures have been recorded across the world and the number of failures is increasing (Piciullo, et al., 2022). Failures occur due to various reasons, including poor construction or operation errors resulting in loss of life, major environmental degradation, and the destruction of entire ecosystems (Zongjie et al., 2019). **Figure 2** shows the number of recorded tailings dam failures for each prevailing decade.

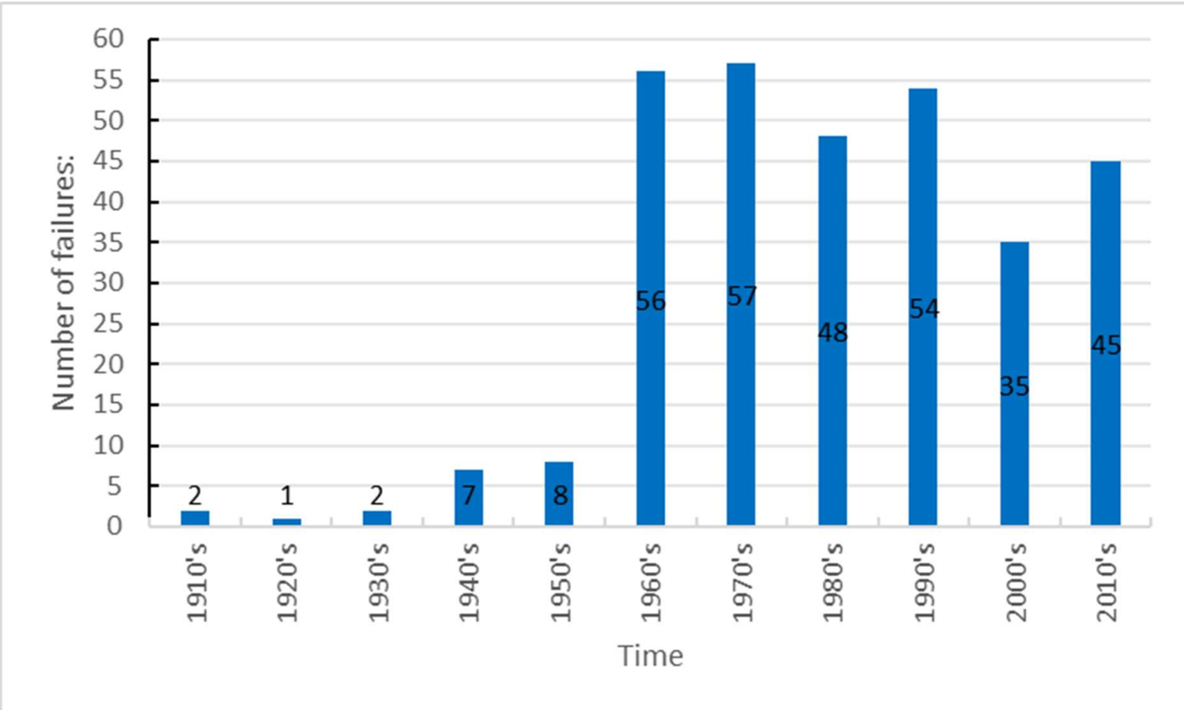

Figure 2 Tailings storage facility failures to date (Zongjie et al., 2019)

TSF failures can result in toxic waste material travelling hundreds of kilometres, contaminating rivers and lakes, and killing flora and fauna by flooding land with poisonous slurry. The 2019 collapse of the Brumadinho Dam in Mina Córrego do Feijo (Minas Gerais, Brazil) is an example of how disastrous such occurrences may be. Around 10 000 000 m^3 (ten million cubic meters) of mine waste were spilled into the valley due to the incident. As the slurry moved downstream, it killed 270 people and severely harmed the environment, other ecosystems, and nearby communities (**Figure 3**) (Piciullo et al., 2022).

Following the failure of the tailings storage facility at Vales Corrego de Feijao Mine in Brumadinho, the Global Industry Standard on Tailings Management (GISTM) was launched on 5 August 2022. A significant tailings storage facility breach might have a cost of between $750 million and $56 billion (social and environmental) (Piciullo et al., 2022).

Figure 3 Collapse of the Brumadinho dam in Mina Córrego do Feijo (Piciullo et al., 2022)

There is a significant risk posed by tailings facility failures to the environment and communities. A dataset including 1743 tailings facilities provided insight into, for instance, construction method, stability, fault consequences, and stored volumes. 10% of tailings report notable stability failure or concerns sometime in their history. It showed distinct trends according to construction method, governance, age, height, volume, and seismic hazard. Upstream construction method facilities report a higher incidence of stability issues. In-pit/natural and dry-stack facilities, on the other hand, report lower stability issues. All these instabilities are still significant by engineering standards (2%) necessitating careful facility management and governance (Piciullo et al., 2022).

Point III of the GISTM in **Figure 4** calls for an improvement in the requirements during the design, construction, operation, and monitoring of tailings storage facilities around the world (ICMM, 2022).

Figure 4 Global industry standard on tailings management (ICMM, 2022)

Closer to home, South Africa has approximately 200 active tailings dams McRobert, C. (2018). Various departments including the department of mineral affairs have regulations in place for the monitoring of these superstructures stability. A recent failure of the Jagersfontein TSF on 11 September 2022 resulted in catastrophic downstream flooding, destroying homes, infrastructure, and farmland, and causing significant loss of life and property. The dam failed primarily due to critical foundation problems. Poor geological conditions, including weak rock formations and high water pressure, undermined the stability of the dam's foundation. Inadequate site investigation and faulty construction practices further exacerbated these issues, leading to the seepage of water beneath the structure. This erosion weakened the foundation over time, ultimately causing the dam to collapse. (Motsau, B, et al, 2022).

TSFs pose global risks to the environment and communities and limited data is available about global risk distribution of facility characteristics that are needed for proper governance. A study conducted by the Church of England found that 687 of a total of 1,700 tailings dams (±40%) investigated were deemed high risk (Warburton et al., 2020). They found that the construction method is important because it can be indicative of a dam’s level of risk. Their findings are that:

- Upstream facilities pose a higher incidence of stability issues that are elevated in highly built governance settings.
- A lower incidence of stability issues occurs in pit/natural landform and dry-stack facilities,

but still significant by engineering standard, so it is important for facility management and governance.

Figure 5 shows the distribution of construction methods for the above-mentioned tailings storage facilities.

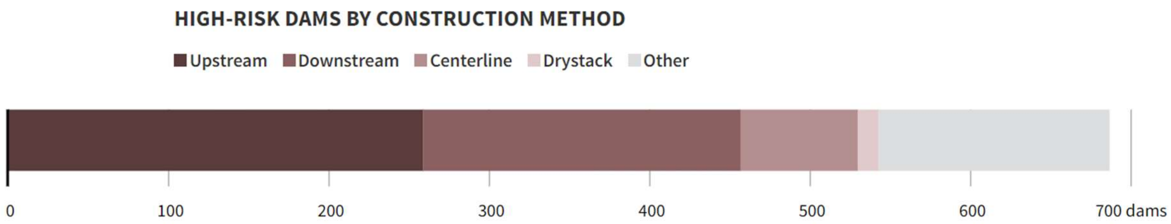

Figure 5 High risk tailings dams by construction method (Warburton et al., 2020).

2.2. Construction

The construction of tailings storage facilities is a complex and expensive process. These facilities are some of the largest earth structures that geotechnical engineers design. Due to their vastness, and instead of constructing a fully operational facility with a greater capacity, intermediary retaining embankments are often built utilizing the coarse fraction of the tailings further increasing the dam's height and therefore capacity (Warburton et al., 2020). Once the initial foundation is completed there are three ways to raise the embankments, namely upstream construction method, downstream construction method, and centreline construction method (**Figure 6**). The type of construction used in designing tailings dams is influenced by a variety of factors, including site-specific conditions, safety considerations, cost, and regulatory requirements (Lumbroso et al., 2020).

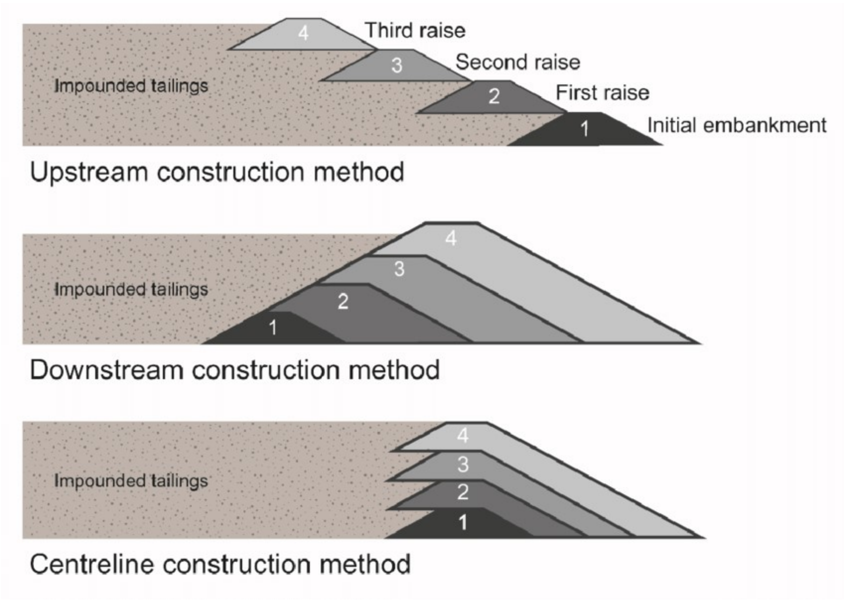

Figure 6 Tailings dam embankment construction methods (Lumbroso et al., 2020)

2.2.1. *Upstream Construction*

This is the least costly method of construction due to the minimal amount of material needed for both the initial construction and succeeding raises. The decrease in cost is however at the cost of stability as more of the embankment is underlain by fine tailings as the dam rises. They are extremely vulnerable to liquefaction when the tailings behind the dam wall become saturated with water. The liquid mixture slowly erodes the structure of the dam wall and increases the likelihood of a rupture (Lumbroso et al., 2020).

2.2.2. Downstream construction

This method decreases the chance of failure due to breaching as it is more structurally stable because no wet tailings are stored below the embankment. It is also the costliest construction method due to the increased footprint size and amount of material required for construction (Lumbroso et al., 2020).

2.2.3. Centreline construction

In terms of output and price, this is a middle-range solution. With this technique, as the tailings dam is raised, the centre lines of the embankments coincide (Lumbroso et al., 2020).

Due to the continually increasing capacity of the tailings dam, it is imperative that the foundation be constructed appropriately to sustain the ever-increasing load exerted from the expanding dam above. Soil compaction is utilized to increase the bearing capacity and shear strength of the TSF's foundation and initial embankments to increase its stability (Lumbroso et al., 2020).

2.3. **Soil compaction**

Soil compaction is the mechanical densification of soil that involves pressing soil particles together and removing the air between them. It is critical in the broad science of geotechnical engineering, and it plays an important role in all types of geotechnical investigations. Compacted soils are widely used in the construction of geotechnical and geo-environmental structures, and their durability and stability are directly related to proper soil compaction. The principal soil properties affected by compaction include settlement, shearing resistance, water movement and volume change (Ghosh, 2012).

It is an essential activity in civil engineering as it is utilised to create a stable work surface for various construction operations by increasing the shear strength of the underlying geological media. Compaction is commonly used in various projects such as:

- Foundations for buildings
- Roads (base, subbase, subgrade, embankments)
- Pavements
- Waste storage and earth dams
- Trenches and backfills.

Soil compaction can be defined as the process of densification and void ratio reduction in a geological medium that changes hydromechanical properties such as permeability, strength, and porosity (Nawaz et al., 2013). When soil is required to be subjected to a load, soil compaction is generally employed to reduce any potential settlement, and compaction can result in increased shear strength, bearing capacity, void space reduction, permeability reduction, and, ultimately, increased stability (Namdar, 2011).

2.4. History of compaction

Prior to 1830 road construction consisted of merely laying down material and pavers, followed by minimal compaction. The invention of a horse-drawn roller in France in the 1830s revolutionized road construction and brought the first use of mechanical compaction. Steam rollers were introduced in the 1860s, enabling greater degrees of compaction (Croney et al., 1997). These advancements in mechanized compaction made it possible to achieve higher degrees of compaction during the construction of highways, TSF's, dams, and the footprints of structures to prevent settling.

During the 1920s and early 1930s, a study conducted by the California Highway Department revealed that differential settlement owing to uneven amounts of compaction was the leading cause of road failure. This study resulted in the development of the Proctor compaction curves (**Figure 7**) for compaction specification (Proctor, 1933) and the California Bearing Ratio (CBR) (**Figure 8**) which are still being used in laboratory testing today (Croney et al., 1997).

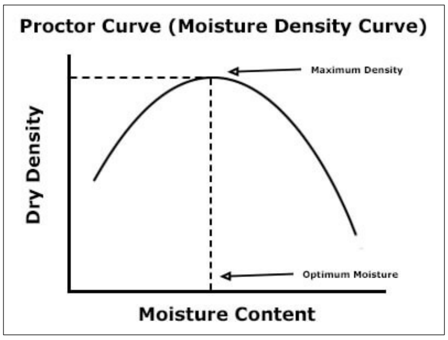

Figure 7 Proctor compaction curves (Kalantari, 2012).

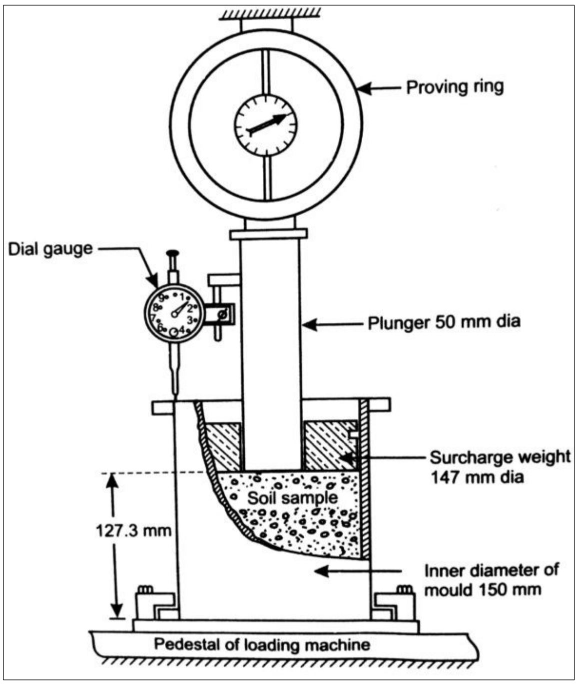

Figure 8 CBR set up (CementConcrete.org, 2021)

Various methods have been devised in the past to determine the level of compaction obtained in the field as well as the maximum dry density and optimal moisture content of a soil under laboratory conditions. These laboratory tests serve as benchmarks against which in-situ test results can be compared to ensure that the material has been compacted properly. This chapter will give an overview of the possible laboratory and field experiments that could be used to determine compaction.

2.5. **Laboratory testing**

The Standard Proctor Test (ASTM D698) is a lab-based moisture-density relationship test. It serves as a benchmark against which field testing can be evaluated, with all field results represented as a percentage of laboratory results. This makes it easy for a designer to specify what is needed for compaction and to determine whether the material being compacted requires more water or less water to achieve its optimal moisture content (OMC) and, as a result, its maximum dry density (MDD) (Patel, 2019).

The Modified Proctor Test (ASTM D1557) was developed following the need for higher weights to be accommodated on roadways and foundations as technology advanced. This allowed for a larger compaction effort while maintaining a lower OMC as the test methods for a modified proctor are identical to those for a proctor, but with slight differences that result in a higher compaction effort being utilised. The approach chosen is determined by the project's requirements and specifications. **Figure 9** shows the general setup for both a standard and modified proctor test (ASTM, 2021).

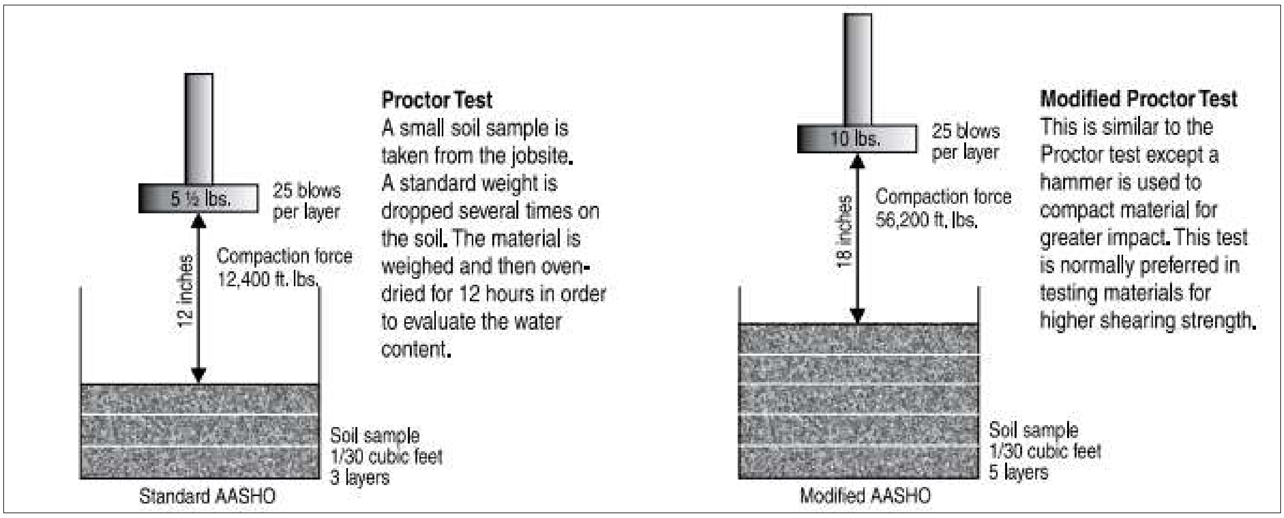

Figure 9 Standard Proctor Test vs Modified Proctor Test (CementConcrete.org, 2021)

2.6. In-situ Testing

There are several methods for determining the density and moisture content of soil in situ of which the sand replacement method and Troxler tests are the most utilized tests. The sand replacement setup is shown in **Figure 10** where a small, cylindrical pit is dug in the compacted material to be tested. The soil is removed and weighed, then dried, and weighed again to determine its moisture content as shown in Eq. 1 where M_W = water mass (kg), M_{TOTAL} = total mass (kg) and M_S = soil mass (kg) (SANS, 2013).

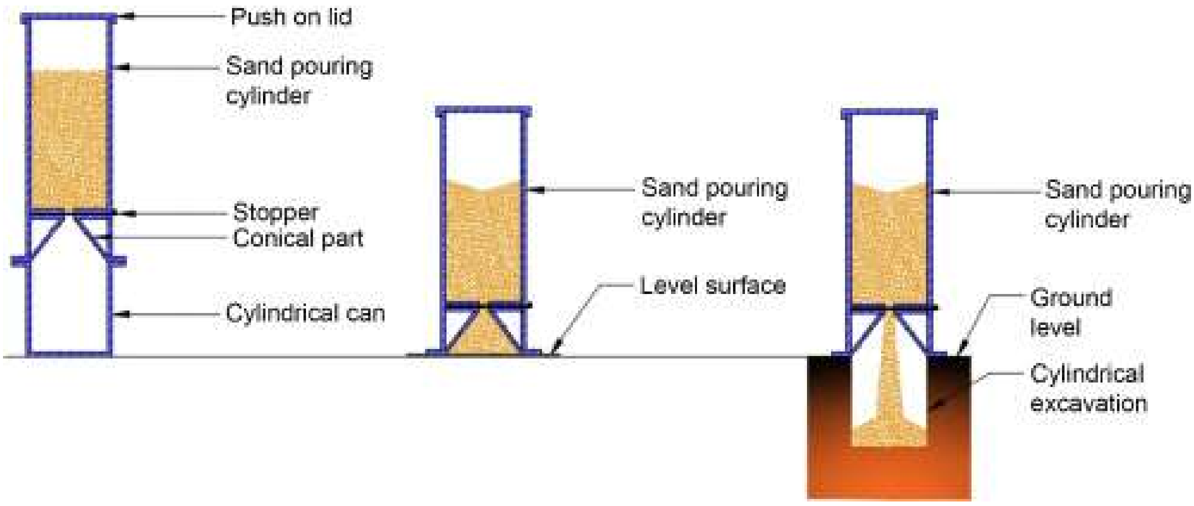

Figure 10 Sand replacement setup (SANS, 2013)

$$M_w = M_{total} - M_s \tag{1}$$

A soil's moisture is presented as a percentage of its total mass. The specific volume of the pit is determined by filling it with dry sand of a predetermined density, and the dry weight of the soil removed is divided by the volume of the pit to determine the density of the in-situ soil where γ = dry weight (kg/L), M_S = soil mass (kg) and V_S = volume of pit (L) (Eq. 2).

$$\gamma = \frac{M_S}{V_{pit}} \tag{2}$$

This density and moisture content are compared to the maximum dry density and optimal moisture content calculated prior in a lab, which gives us the relative density and moisture content of the material (South Africa National Road Agency, 2013).

Nuclear Density meters are a relatively accurate and fast way of determining density and moisture content (**Figure 11**). The device uses a radioactive isotope source caesium 137 at the soil surface in the backscatter method, or from a probe placed into the soil in the direct transmission method). The isotope source releases photons as Gamma rays which radiate back to the detectors on the underside of the unit. Dense soil will absorb greater amounts of radiation than loose soil and the readings are computed to show overall density (ASTM, 2023). Water content can also be determined, but a moisture correction test is usually required for correlation (Patel, 2019).

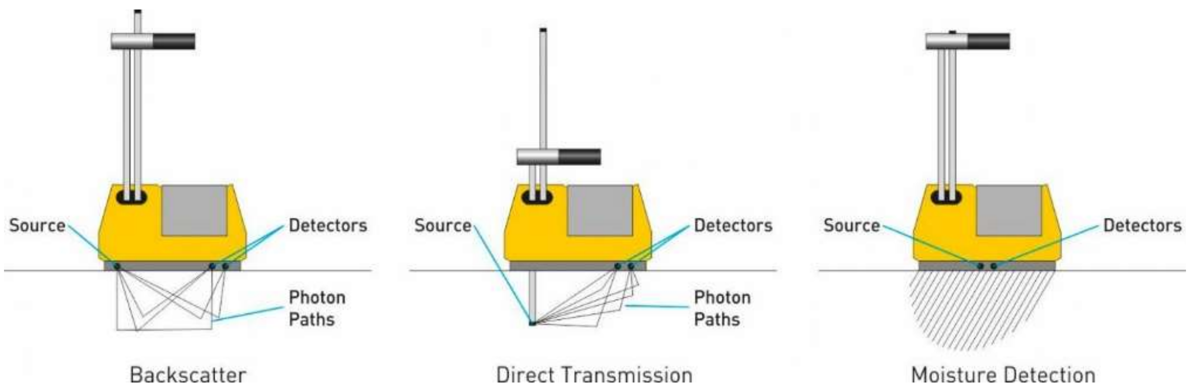

Figure 11 Nuclear density gauge setup (Utest, 2022)

2.7. Factors affecting Compaction

The controlling elements that influence soil compaction can be separated into various internal and external factors. Factors affecting the compaction properties are complex and numerous, including grain composition, aggregate shape, moisture content, rolling technology, and compaction power. However, it is difficult to analyse each factor and understand its mechanism individually (Harris, 1971).

The following factors are addressed, noting that mineralogy will not influence external factors such as the compaction effort and compaction method (Das et al., 2014):

- Compaction effort
- Compaction method
- Water content
- Particle size distribution
- Mineralogy.

2.7.1. Compaction effort

Increased compaction effort raises the soil's maximum dry density, and as the soil becomes more compacted, the rate of compaction decreases. As the soil densifies soil particles are forced into a denser packing configuration and the porosity decreases, resulting in a lower moisture content as the water dissipates out of the pores. The compaction curves shift to the top left of the graph as the compaction effort increases as shown in **Figure 12**. Increasing compaction effort allows a soil to be compacted to its MDD at a lower OMC, and only when the water content reaches its OMC does this effect of increased compaction become evident. After this the air void volume becomes constant, and the effect of increased compaction effort is not significant (Das et al., 2014).

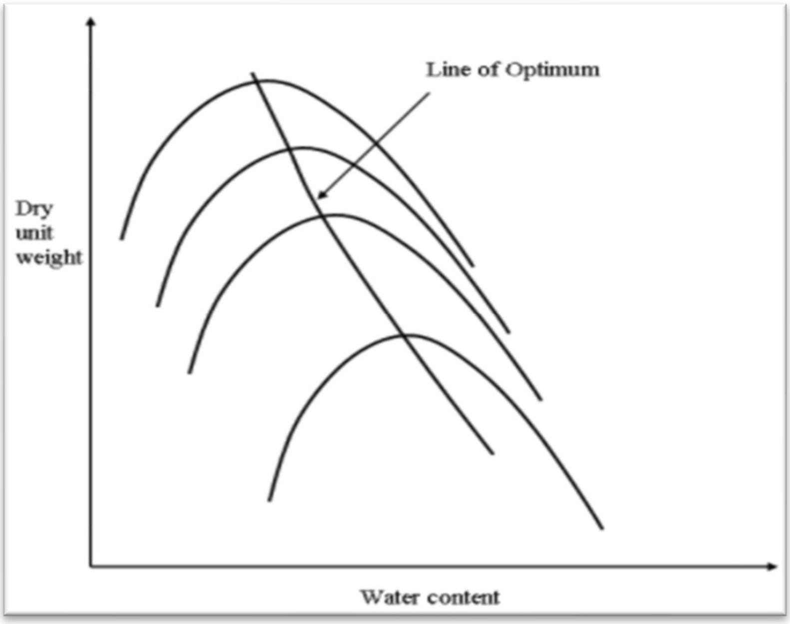

Figure 12 Effect of compaction effort (The Constructor, 2021)

2.7.2. Method of compaction

The method of compaction has an impact on the shape of the compaction curves that are created. Factors such as contact pressure, rolling speed, number of passes, and layer thickness will all affect the compaction effort achieved independent of the machinery used to compact a soil (Suryakanta, 2023). Machinery that should be utilised for different soil types is provided in Table 2(Harris, 1971).

Table 2 Machinery used for different soil types (Harris, 1971)

Type of soil	Suggested equipment / machinery
Crushed rock, gravelly sand	Smooth wheel roller
Gravels, sand	Rubber tyred roller
Sands, gravel, silty soil, clayey soils	Pneumatic tyred roller
Silty soil, clayey soil	Sheep foot roller
Soils in confined zone	Rammer
Sands	Vibratory roller

2.7.3. Water content

Water content plays a significant role in compaction characteristics of soil. At low water contents (below OMC), soil is stiff and has a higher resistance to compaction. As the water content increases a film of water forms around soil particles and acts as a lubricant allowing particles to slide past one another. This results in the soil being compacted with more ease into a dense packing configuration (**Figure 13**). At optimum moisture content (OMC) soil reaches its maximum unit weight, and with further addition of water it displaces the soil particles and lowers its ability to be compacted. This results in a decrease in unit weight as the water particles replacing the soil particles have a lower unit weight and negatively affect the sample's ability to be compacted (Di Sante et al., 2016).

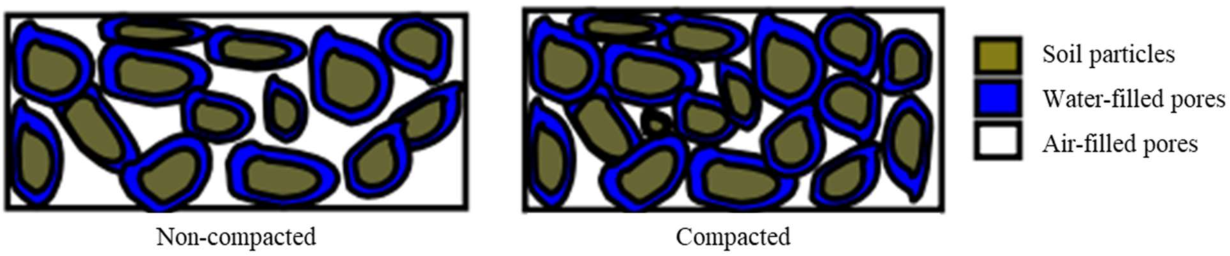

Figure 13 Water content of compacted vs non-compacted soil (Dejong-Hughes et al., 2001)

Water-holding capacity is controlled predominantly by soil texture and the presence of organic matter. Soils with smaller particles (silt and clay) have larger surface areas than those with larger particles (sand and gravel), and a large surface area allows a soil to hold more water due to increased adhesion. This means that soils with higher levels of organic material and higher silt and clay fractions have a higher affinity to water and therefore have a higher water-holding capacity (Rousseva et al., 2017).

Soil texture influences water holding capacity, and the type of clay also affects the soil's water holding capacity. 1:1 layered silicate minerals such as kaolinite (**Figure 14**a) have one tetrahedral sheet of silica bonded to one octahedral sheet of alumina. The bond between the tetrahedral sheet and octahedral sheet forms through hydrogen bonding and is relatively strong. 2:1 layered minerals can be separated into two different categories, namely 2:1 non-expanding clays such as illite (**Figure 14**b), and 2:1 expanding clays such as montmorillonite (**Figure 14**c) which are known for their interlayer expansion which happens during their swelling behaviour when they are wet (Al-Atroush et al., 2021).

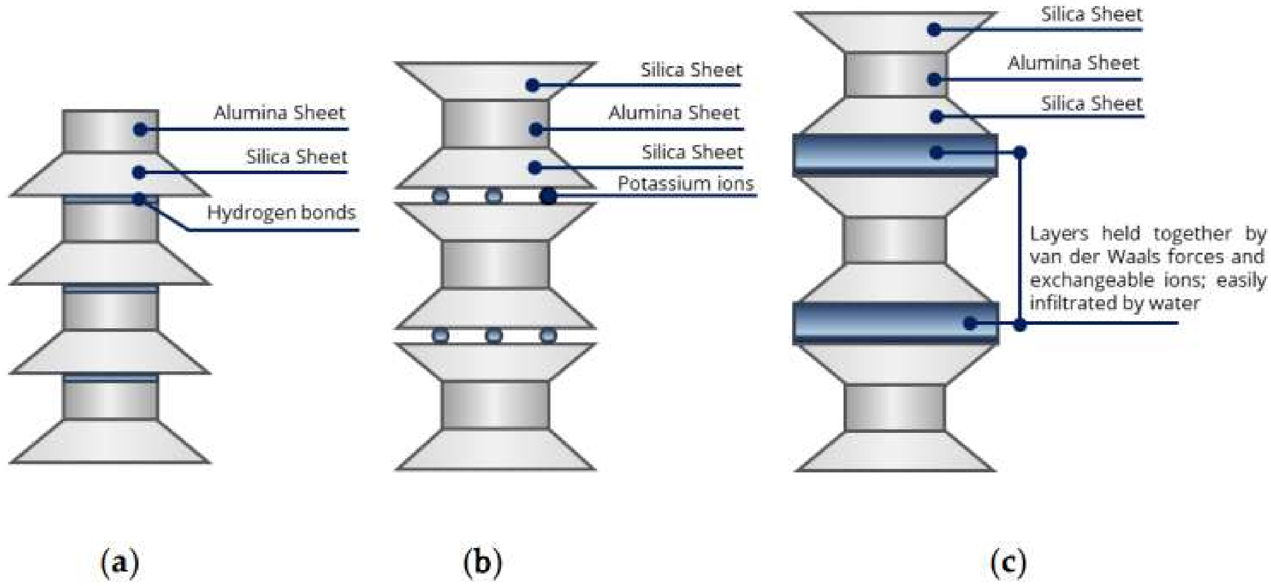

Figure 14 (a) 1:1 clay minerals such as kaolinite, (b) 2:1 clay minerals such as illite and (c) 2:1 clay minerals prone to expansive behaviour such as montmorillonite (Al-Atroush et al., 2021)

These layered silicates consist of one octahedral sheet sandwiched in between two tetrahedral sheets. Oxygen atoms occur on the top and bottom of the tetrahedral sheets of two adjacent units exhibit a slight attraction to one another. As a result, there is a variable space between the layers that is occupied by water and exchangeable cations held together by Van der Waals forces, causing water and exchangeable cations to readily enter the interlayer gap, and layers to expand. Paired with the greater surface area of clay minerals, this interaction can result in swelling and increased pore pressure that further detriments compaction. The ideal structure of kaolinite has no charge resulting in a fixed structure and very little to no swelling when interacting with water. The presence of 1:1 layered silicate minerals in a soil will result in a higher OMC due to the smaller particle size, and therefore greater surface area for atmospheric water to bond (Kumari et al., 2021).

2.7.4. Particle size distribution

The compaction of a soil is strongly influenced by its composition. There are implicit relationships between the particle size distribution (PSD) and the physical and mechanical properties of granular materials, even though these qualities are exceedingly complex and challenging to ascertain (Chen et al., 2018). Coarse-grained soils can be compacted to a higher dry density than the fine-grained soils, and if the quantity of fines is raised above what is required to fill voids in coarse-grained soils, the maximum dry density drops, and therefore a well-graded soil has a significantly higher dry density than a poorly graded soil. Cohesive soils, such as heavy clays, clays, and silts, are more resistant to compaction because their maximum dry density is lower.

Sandy soils and gravelly soils have little cohesion and are susceptible to easier levels of compaction. The varying shape of minerals present in a soil will affect its ability to be compacted into its densest packing formation and can therefore affect its maximum dry density. The effect of the gravel content of a soil together with soil grading and index properties play a vital role in the soil's ability to be compacted. The increasing gravel content in a sample will also increase its maximum dry density and lower its OMC (Alcott, 1970).

2.8. Weathering

Weathering refers to the physical disintegration and chemical decomposition of rocks and minerals on the Earth's surface (Aloni et al., 2020). Bowen's reaction series describes the sequence of mineral crystallization from a cooling magma. Minerals that form at higher temperatures, such as olivine and pyroxene, are less stable at the Earth's surface and more susceptible to weathering compared to minerals that crystallize at lower temperatures, such as quartz and muscovite (GeologyHub, 2023). **Figure 15** below depicts a basic annotation of Bowen's reaction series.

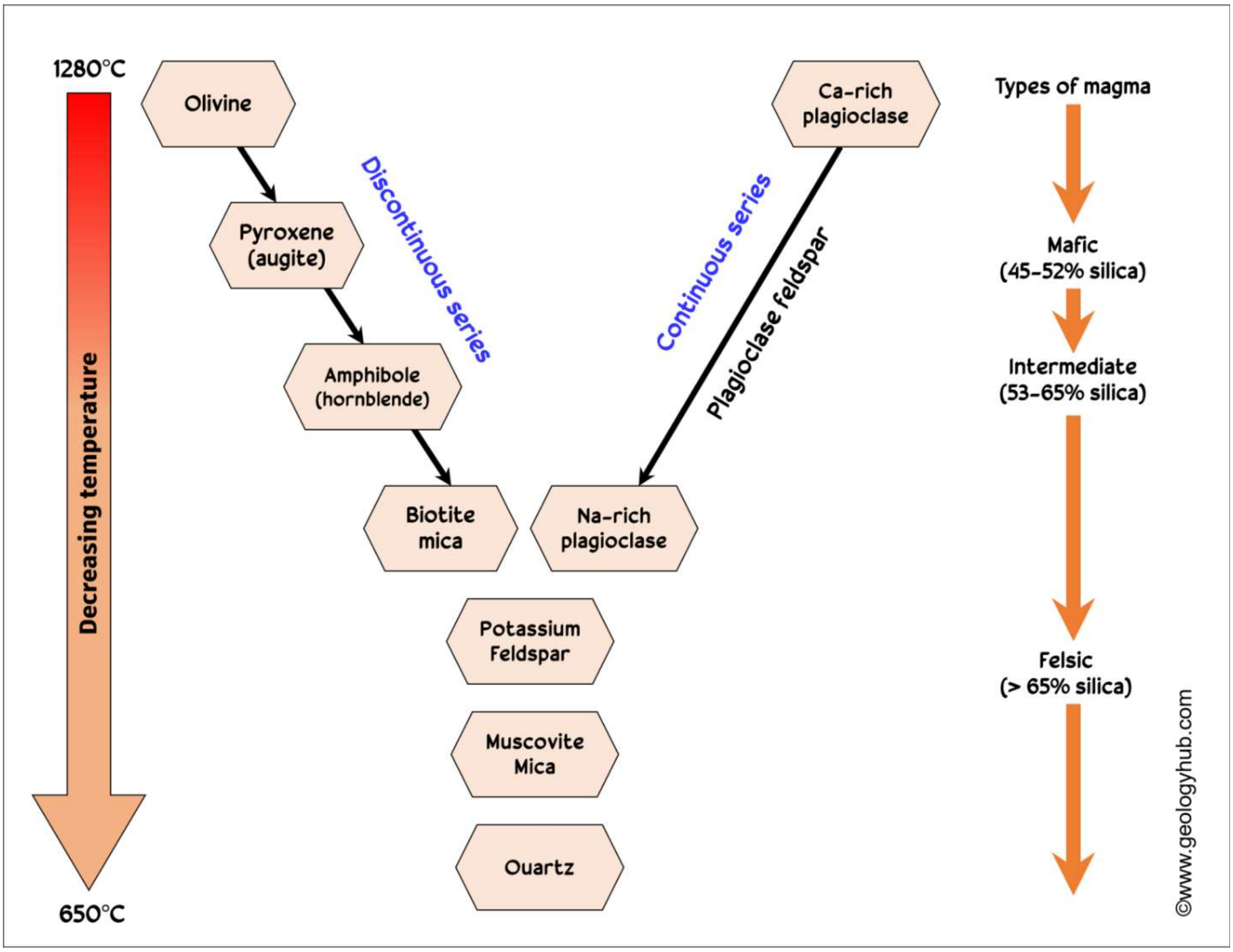

Figure 15 Bowens reaction series (GeologyHub, 2023)

This stability sequence plays a significant role in the weathering behaviour of basic igneous rocks. According to Berner (1985), the sequence of mineral decomposition during weathering of basic igneous rocks can be broken down into three stages:

- Initial Breakdown: Olivine and pyroxene, being high-temperature minerals, are the first to weather. Hydrolysis and oxidation break these minerals down into iron oxides and secondary clays like smectite.
- Intermediate Stage: Plagioclase feldspar weathers next, with calcium and sodium being leached out. This results in the formation of secondary clays such as kaolinite and additional

smectite, depending on the local pH and drainage conditions.

- Advanced Weathering: Continued weathering leads to the formation of stable secondary minerals. In acidic environments, kaolinite predominates, while in more alkaline environments, smectite and other 2:1 clay minerals are more common.

The process of weathering is complex and is influenced by several factors, which are elaborated below:

2.8.1. Mineral Composition

The mineralogical composition of igneous rocks predominantly consists of mafic minerals such as olivine, pyroxene, and plagioclase feldspar. Olivine and pyroxene, which are rich in iron and magnesium, are more susceptible to chemical weathering processes like hydrolysis and oxidation. These processes result in the formation of secondary minerals and oxides. For instance, olivine typically alters to a mixture of clay minerals, iron oxides, and ferrihydrites. Plagioclase feldspar undergoes hydrolysis, leading to the production of clay minerals such as kaolinite and smectite, which play a significant role in soil formation (Aloni et al., 2020).

2.8.2. Climate

The climate of a region depicts the temperatures and precipitation that facilitate weathering. Higher temperatures accelerate the chemical reactions essential for mineral breakdown. Precipitation provides the water necessary for hydrolysis, dissolution, and other chemical weathering mechanisms (Derry, 2009).

2.8.3. Biological Activity

Biological activity contributes to both physical and chemical weathering. Plant roots can penetrate fissures and crevices within rock formations, exerting physical forces that contribute to mechanical breakdown. Additionally, microbial activity, through the metabolic actions of microorganisms, produces organic acids as metabolic byproducts. These acids actively participate in mineral dissolution, thereby accelerating the chemical alteration of rocks and minerals (Aloni et al., 2020).

2.8.4. Time

The duration of exposure to weathering processes is a crucial factor. Extended exposure allows for more extensive weathering and the formation of advanced secondary minerals (White et al., 2003).

2.8.5. Topography

Topography influences weathering in several ways. Steep slopes can enhance physical weathering by enabling gravitational forces to cause rockfalls, leading to the disintegration of rocks. Conversely, more gradual or flat surfaces can retain water, increasing the likelihood of chemical weathering (Spatial Post, 2023).

2.8.6. Typical Weathering Products

The weathering of basic igneous rocks produces secondary minerals and compounds, altering soil composition. The formation of clay minerals depends on the parent mineral and prevailing environmental conditions. Kaolinite forms from the weathering of feldspar minerals in acidic environments, while smectite results from the chemical breakdown of mafic minerals like pyroxene and olivine in alkaline conditions. Iron oxides and hydroxides, such as goethite and hematite, form from the oxidation of iron-bearing minerals. Secondary silicates like serpentine and chlorite emerge from the alteration of primary minerals such as olivine and pyroxene, with serpentine forming through hydration and chlorite through low-grade metamorphism. The interaction of basic igneous rocks with carbon dioxide and water leads to the formation of carbonate minerals like calcite and magnesite (Nelson, 2014).

In summary, weathering is governed by a variety of environmental factors. The parent material determines the initial minerals available for alteration, while the remaining factors influence the type of weathering processes that ultimately shape the mineralogy of the resulting soil.

2.9. **Mineralogy**

Mineralogy plays a crucial role in the compaction behaviour of soils, despite not always being highlighted as a primary influencing factor. While compaction is often discussed in terms of external factors like moisture content and particle size distribution, the underlying mineral composition of the soil exerts a significant influence on its compaction characteristics (Mungazi, et al., 2019). The mineralogy of the parent material directly impacts the composition of soils, determining which minerals are present and how they might alter over time through processes like weathering and diagenesis (Mile, et al., 2012). These alterations lead to the formation of secondary minerals, which in turn dictate the physical and chemical properties of the soil.

Clay minerals, in particular, hold significance in the context of compaction. Studies comparing the clay mineralogy of residual soils have shown a correlation between the clay fraction of a soil and its compaction behaviour. For instance, Alcott (1970) demonstrated through regression analysis that the fines fraction of a soil, often dominated by clay minerals, tends to negatively affect its compactability more than the coarse fraction. This negative impact can be attributed to the water-holding capacity of clay minerals and their tendency to reduce the Maximum Dry Density (MDD) of the soil. Phyllosilicates, a group of clay minerals, are commonly found in soils and exert a profound influence on various soil properties relevant to compaction. These minerals affect the physical, physical-chemical, water-physical, and physical-mechanical properties of soils. For instance, they contribute to properties such as plasticity, stickiness, swelling, shrinkage, cohesion, structure, and moisture retention.

The plasticity index of a soil, which measures its plasticity and thus its ability to undergo deformation without cracking, is significantly influenced by clay mineralogy. Soils rich in clay minerals tend to have higher plasticity indices, making them more prone to deformation under compaction efforts. Additionally, the presence of clay minerals can lead to the formation of soil aggregates, affecting the soil structure. Aggregates can either facilitate or impede compaction, depending on their size, shape, and arrangement. Well-aggregated soils generally exhibit better compaction characteristics due to improved particle packing and reduced void spaces.

Furthermore, the mineralogy of soils can influence their response to moisture content variations. Soils with substantial concentrations of certain clay minerals may exhibit high moisture retention capacities, making them less susceptible to compaction as moisture acts as a lubricant, reducing the friction between particles during compaction (Tiwari, et al., 2014).

In summary, the mineralogy of soils, particularly the presence of clay minerals, significantly impacts their compaction behaviour by influencing properties such as plasticity, structure, moisture retention, and particle aggregation. Understanding these relationships is essential for effectively predicting and managing soil compaction in various engineering and environmental applications.

3. Site Description

3.1. Site localities

Two sites were identified for this research project. The Mareesburg Tailings Storage Facility (MTSF) lies within the Der Brochen Project Area approximately 25 km south-west of the town of Steelpoort and 40 km west of the town of Mashishing in the Limpopo Province in South Africa. The Selous Metalogical Complex (SMC) TSF expansion site is located approximately 4 km northwest of the town of Selous in the Mashonaland West Province of Zimbabwe. The locality of both sites is shown in Figure **16**.

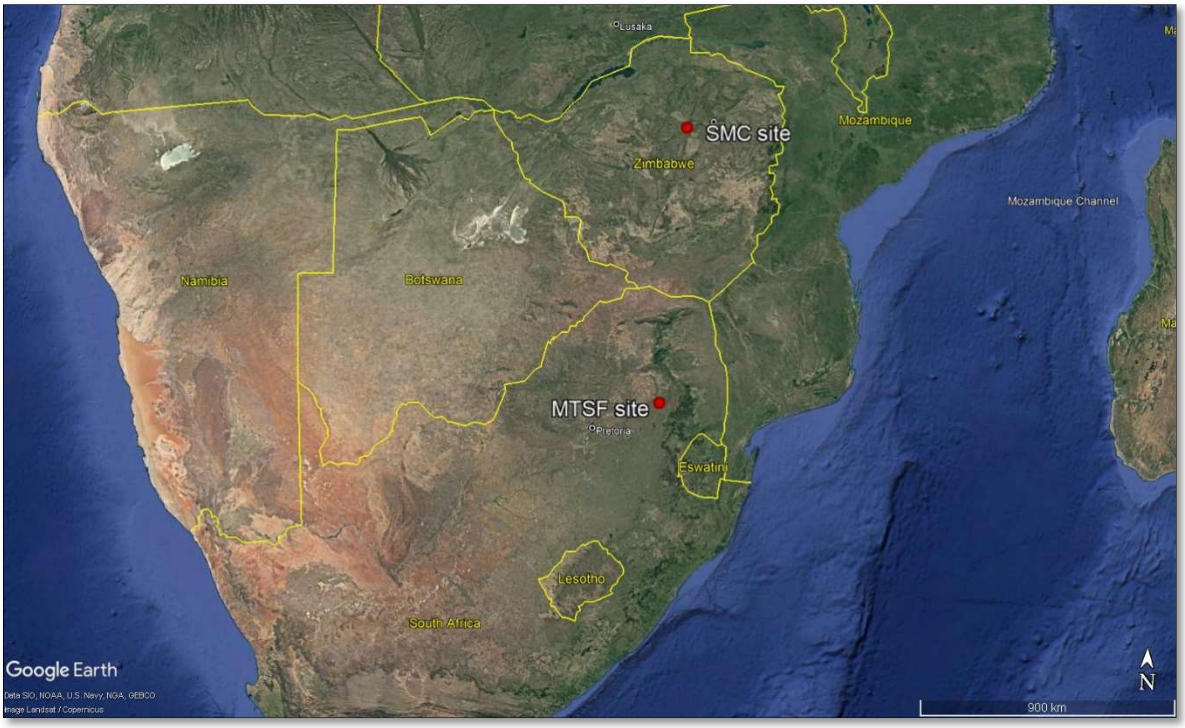

Figure 16 Site locality map (© Google Earth, 2022)

The data and information used for this study was obtained during fieldwork and reporting for the following SRK Consulting projects:

- Mareesburg Tailings Storage Facility – Phase 3 (Project number: 560333) (SRK Consulting, 2020)
- Mareesburg Tailings Storage Facility – Phase 4 Resource Estimation Report (Project number: 568263 (SRK Consulting, 2019)
- Selous Metallurgical Complex Tailings Storage Facility Expansion Geotechnical Investigation (Project number: 552477) (SRK Consulting, 2018)
- Selous Metallurgical Complex Tailings Storage Facility (TSF) Expansion (Project number:574365) (SRK Consulting, 2022).

The MTSF is being constructed in multiple phases. The purpose of the phased construction approach is to allow deposition of tailings in the Phase 1 area of the dam while construction continues of the following phases. **Figure 17** shows an aerial photograph of the MTSF with deposition occurring in the Phase 1 area (grey from tailings) while construction of Phase 2 and Phase 3 is ongoing.

Figure 17 Mareesburg TSF ongoing construction

The Selous Metallurgical Complex (SMC) currently processes ore from several different portals across the Great Dyke of Zimbabwe. This results in copious amounts of waste in the form of tailings that needs to be stored resulting in the existing TSF being near capacity (**Figure 18**). Construction of a new facility commenced in January 2022 to take over deposition when the existing dam is at capacity.

Figure 18 Selous metallurgical complex existing tailings dam

The MTSF site is characterised by an annual temperature ranging from 17 °C - 25 °C and an annual rainfall from 3mm - 131mm. The SMC site is characterised by an annual temperature ranging from 24 °C - 32 °C and an annual rainfall of 0mm - 163mm (Web & Media, 2022) as shown in **Figure 19** and **Figure 20** below. From the figures below, it is evident that the Selous Metalogical Complex TSF is generally exposed to greater annual temperatures with similar levels of precipitation to the Mareesburg TSF. Increased temperature and the presence of more water can directly affect the level of alteration the insitu soils will be exposed to due to chemical weathering.

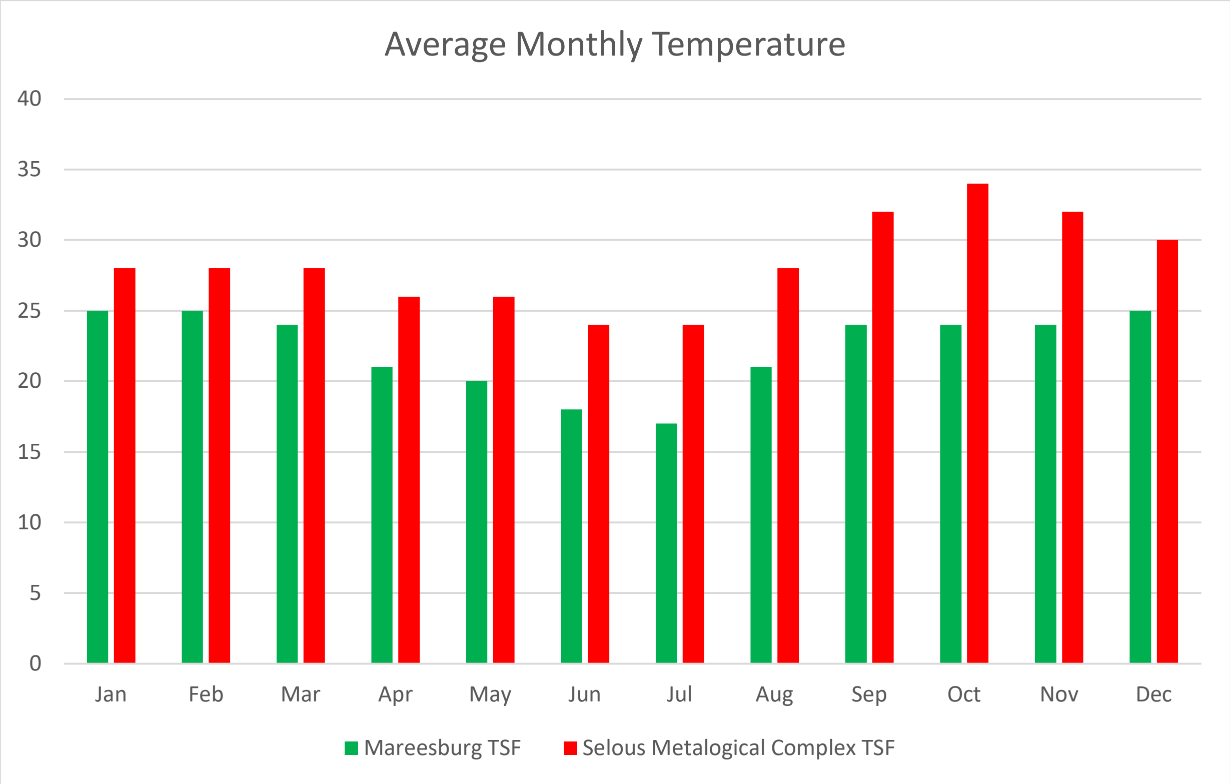

Figure 19 Average monthly temperature of sites

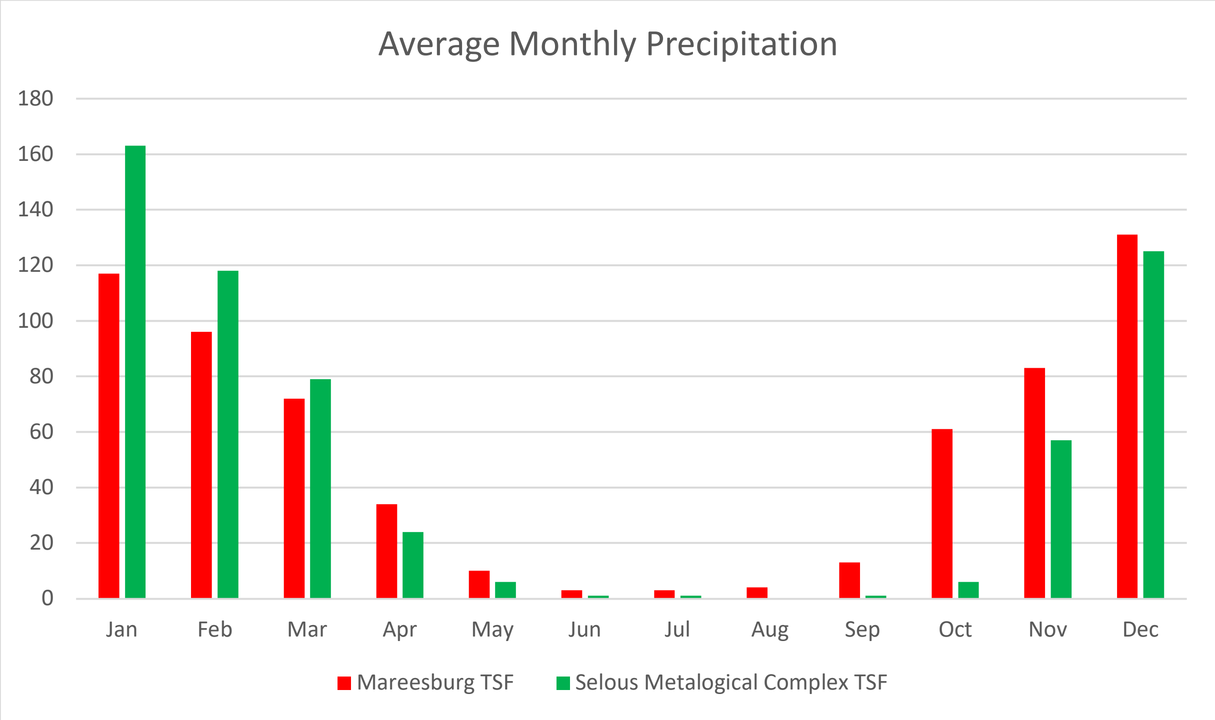

Figure 20 Average monthly precipitation of sites

3.2. **Geology**

The Bushveld Igneous Complex, which formed approximately 2.1 Ga (billion years) ago in northern South Africa, is the world's largest mafic layered intrusion and contains more than half of the world's known Platinum Group Metal (PGM) reserves. It is subdivided into, from the oldest to the youngest, the Rustenburg Layered Suite, the Lebowa Granite Suite, and the Rashoop Granophyre Suite. The Pretoria Group of the Transvaal Supergroup and the Rooiberg Group generally underlies it (Cawthorn et al., 2006). The Rustenburg Layered Suite contains mainly mafic rocks and is divided into several different stratigraphic units that are rich in PGMs that is associated with many mining operations. **Figure 21** shows various mining operations constructed across the Bushveld Igneous Complex for the extraction of these rare earth metals.

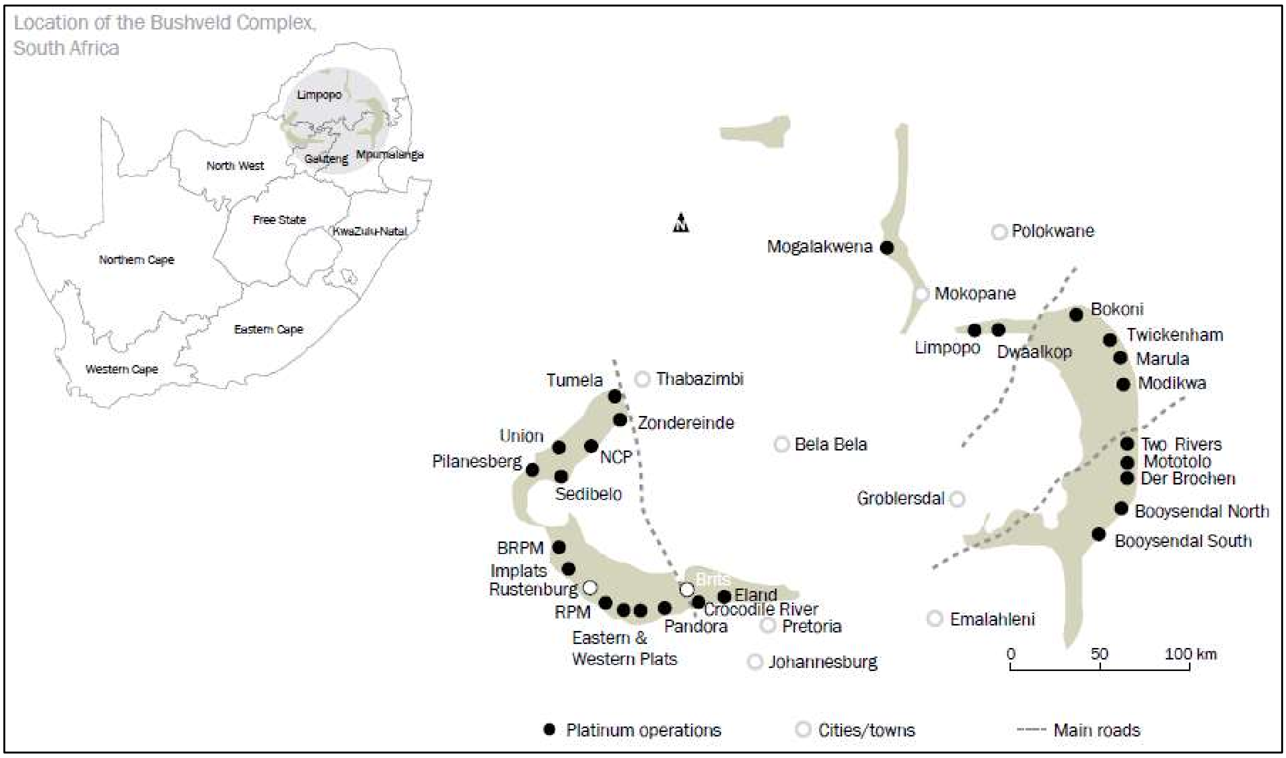

Figure 21 Platinum mining operations in South Africa (Cawthorn et al., 2006)

According to the 1:250 000 2530 Barberton geological map, the Mareesburg TSF area is underlain by alternating sequences of leucocratic and more melanocratic igneous rocks of the Dwarsrivier Subsuite (Vdr) and Shelter Norite (Vsn) of the Rustenburg Layered Suite of the Bushveld Igneous Complex (BIC) as shown in **Figure 22**. These rocks are characterised by medium grained anorthosite, norite, and gabbro, and they host the Merensky Reef pyroxenites, and Upper Group (UG) and Middle Group (MG) chromitite zones (Cawthorn et al., 2006).

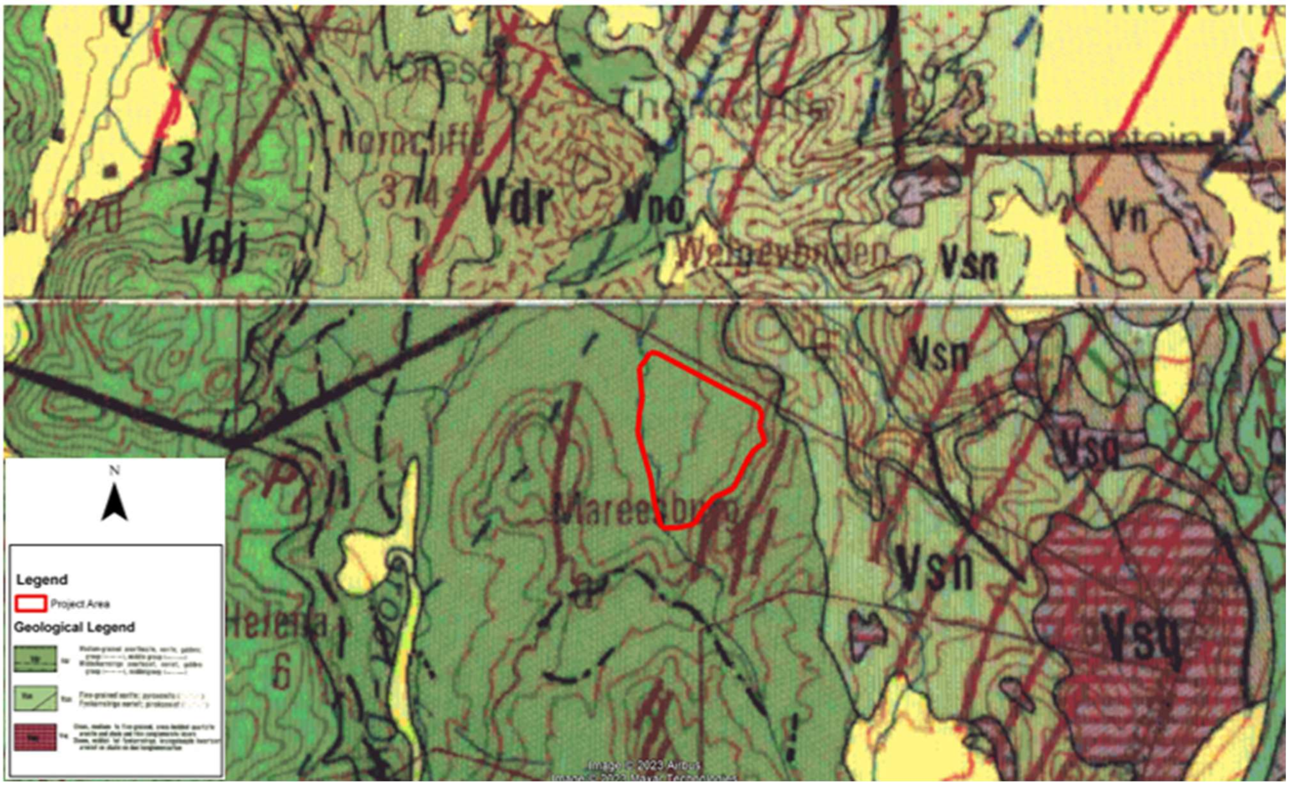

Figure 22 MTSF geology (1:250 000 2530 Barberton geological map) (Minerals Council of South Africa, 2022)

The Steenkampsberg Formation (Vsq) quartzite and subordinate shale (Pretoria Group, Transvaal Supergroup) is present in the far eastern regions of the area and occur along the intrusive contact between the older Transvaal Supergroup lithologies and the younger Bushveld Igneous Complex rocks (Minerals Council of South Africa, 2022).

The SMC TSF site lies on the Great Dyke of Zimbabwe (**Figure 23**) which is a layered mafic to ultra-mafic igneous intrusion into the surrounding Archean granites and greenstone belts of the Zimbabwe Craton. The dyke is composed of two major successions, namely a lower ultramafic succession (up to 2.2 km thick) dominated from the base up by cyclic repetitions of dunite, harzburgite, pyroxenite and chromitite, and an upper mafic sequence (up to 1.15 km thick) consisting mainly of gabbronorite and gabbro (Wilson, 1996).

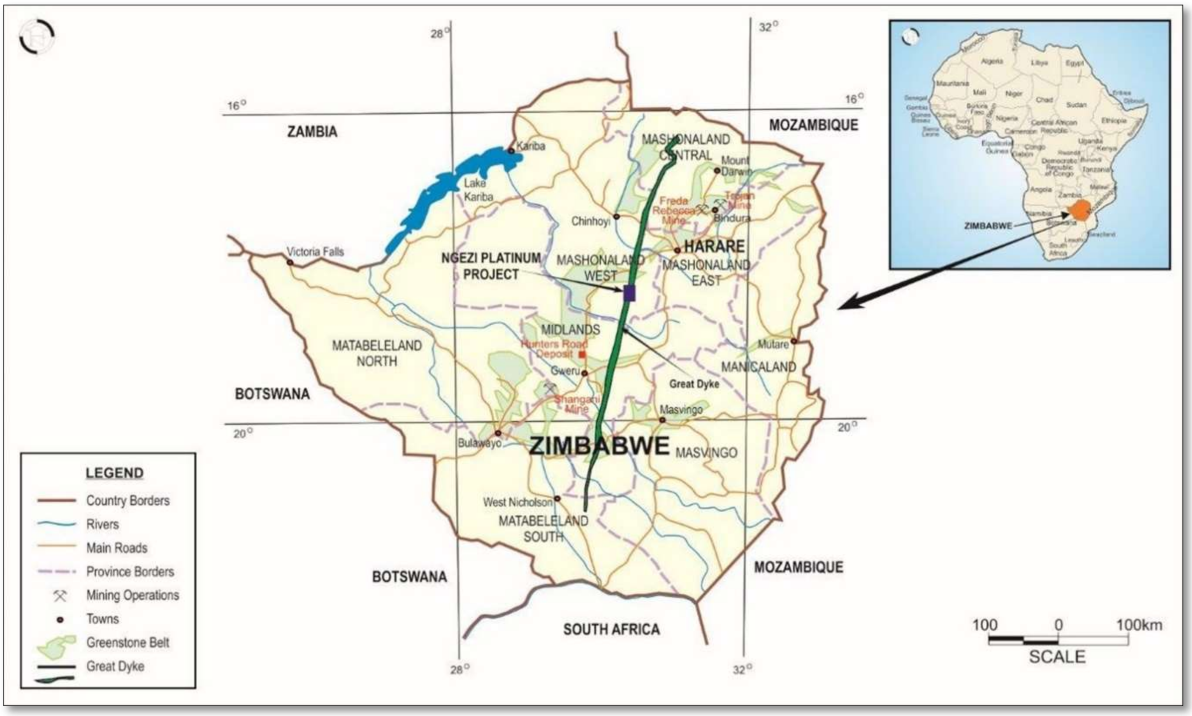

Figure 23 SMC site geology (Wilson, 1996)

The Great Dyke of Zimbabwe, which formed approximately 2.5 billion years ago, is unique among large, layered intrusions due to its highly elongate shape. The dyke formed due to the intrusion of a series of linked magma chambers into the surrounding granitoids, schists and gneisses of the Kaapvaal and Zimbabwe Cratons. During the filling process the intrusion began as a series of initially isolated chambers that became linked at progressively higher levels (Wilson, 1996). The Selous Metallurgical Complex where fieldwork and sampling were conducted is located on the old Hartley Complex site. **Figure 24** shows various mining operations constructed along the dyke for the extraction of rare earth metals. The Selous Metalogical Complex TSF is located at the Hartley platinum mine denoted on the figure below.

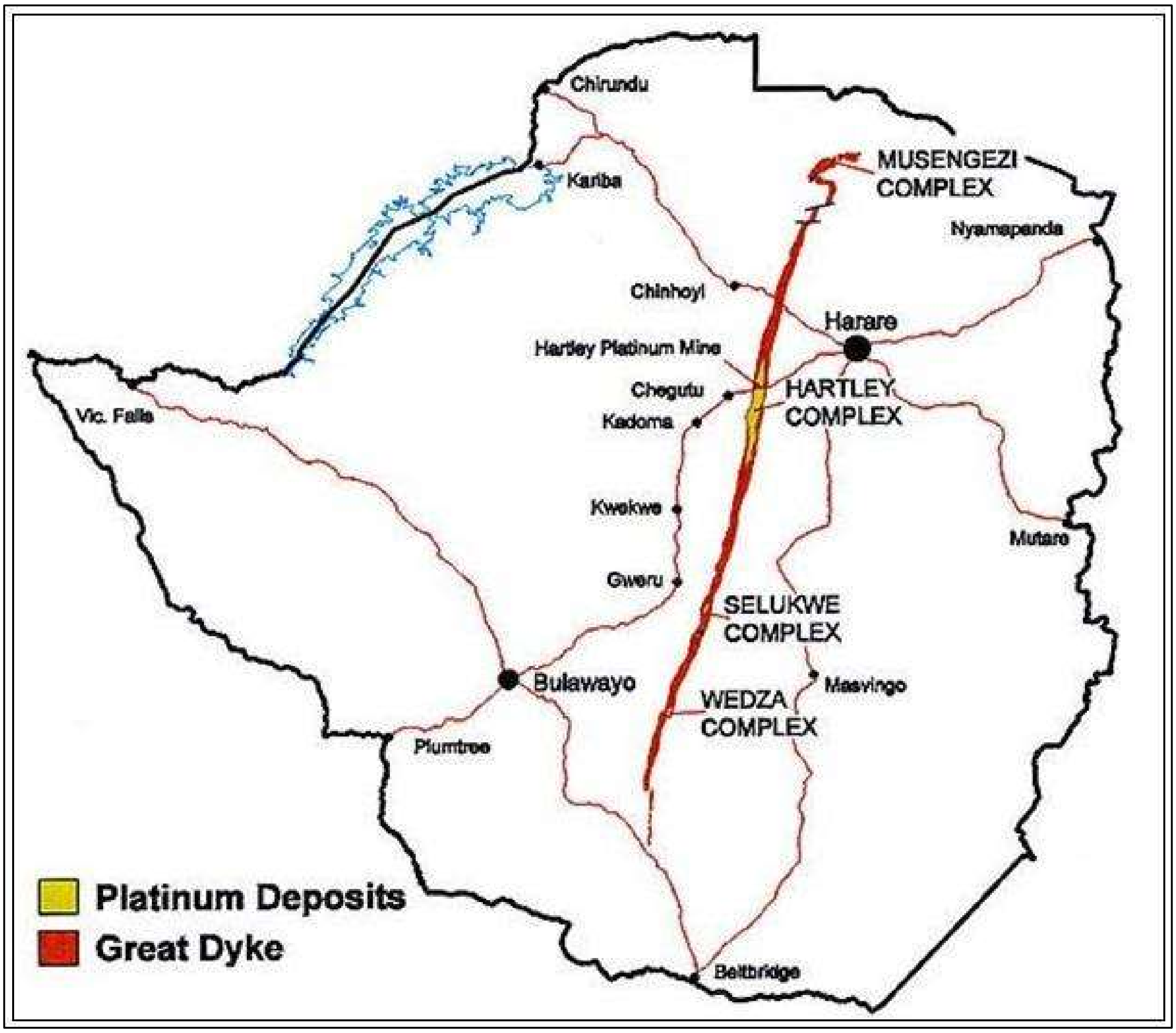

Figure 24 Platinum mining operations in Zimbabwe (Wilson, 1996)

The sites are underlain by gabbro and gabbronorite. Gabbro, the rock relevant to this study, is an intrusive, mafic, coarse-grained rock with allotriomorphic texture that contains low silica contents and is made up of pyroxene, hornblende, olivine, and Ca-plagioclase (Wilson, 1996).

4. Methodology

4.1. Soil profiling and sampling

The two sites were visited from 2018 to 2022 during which 65 samples (Table 3) were taken as part of the design phase geotechnical investigations and the construction of the tailings dams. Samples were divided into cohesive and non-cohesive categories based on relative fines content at the discretion of the engineering geologist in the field, and that were confirmed by the laboratory tests.

Table 3 Sample summary

No.	Site	Test	Sample ID	Date tested
Cohesive residual samples				
1	MTSF	Foundation indicator	SRK-110-1663	03/03/2021
2			SRK-110-1650	03/03/2021
3			SRK-110-1656	03/03/2021
4			SRK-110-1667	03/03/2021
5			SRK-110-1666	03/03/2021
6		MOD AASHTO	S481	24/07/2020
7			S482	24/07/2020
8			S483	24/07/2020
9			S484	24/07/2020
10			S485	24/07/2020
11			S503	25/07/2020
12		X-ray diffraction	MTSF C 01	03/04/2022
13			MTSF C 02	03/04/2022
14			MTSF C 03	03/04/2022
15			MTSF C 04	03/04/2022
16			MTSF C 05	03/04/2022
17	SMC	Foundation indicator	SRK-98-1522	25/08/2020
18			SRK-98-1529	25/08/2020
19			SRK-98-1531	25/08/2020
20			SRK-98-1532	25/08/2020
21		MOD AASHTO	Access road 1 east (ch2800-2960)	18/05/2022
22			Access road 1 east (ch2980-3160)	17/05/2022
23			Access road 1 east sample 2	23/05/2022
24			Access road 1 east sample 3	19/02/2022
25			Access road 1 west (ch280-360)	02/04/2022
26			Access road 1 east (ch280-480)	25/03/2022
27		X-ray dif	SMC C 01	15/03/2022

28			SMC C 02	15/03/2022
29			SMC C 03	20/03/2022
30			SMC C 04	20/03/2022
31			SMC C 05	20/03/2022
Non-cohesive residual samples				
32	MTSF	Foundation indicator	SRK-110-1649	03/03/2021
33			SRK-110-1651	03/03/2021
34			SRK-110-1652	03/03/2021
35			SRK-110-1653	03/03/2021
36			SRK-110-1654	03/03/2021
37			SRK-110-1655	03/03/2021
38			SRK-110-1664	03/03/2021
39		MOD AASHTO	SRK-110-1649	03/03/2021
40			SRK-110-1651	03/03/2021
41			SRK-110-1652	03/03/2021
42			SRK-110-1653	03/03/2021
43			SRK-110-1654	03/03/2021
44			SRK-110-1664	03/03/2021
45		X-ray diffraction	MTSF NC 01	26/05/2020
46			MTSF NC 02	26/05/2020
47			MTSF NC 03	26/05/2020
48			MTSF NC 04	26/05/2020
49			MTSF NC 05	26/05/2020
50	SMC	Foundation indicator	SRK-98-1519	25/08/2020
51			SRK-98-1528	25/08/2020
52			SRK-98-1530	25/08/2020
53			SRK-98-1534	25/08/2020
54			SRK-98-1535	25/08/2020
55		MOD AASHTO	Outfall channel berm (ch120-240) 1	04/07/2022
56			Outfall channel berm (ch120-240) 2	04/07/2022
57			Outfall channel berm (ch120-240) 3	20/06/2022
58			Outfall channel berm (ch240-360) 3	20/06/2022
59			Penstock line 1 (ch90-120) 1	03/06/2022
60			Penstock line 1 (ch90-120) 2	03/06/2022
61		X-ray diffraction	SMC NC 01	25/04/2022
62			SMC NC 02	25/04/2022
63			SMC NC 03	25/04/2022
64			SMC NC 04	25/04/2022
65			SMC NC 05	25/04/2022

Cohesive soils are soils that have cohesive properties due to the presence of fine particles that are primarily clay minerals. These soils are characterized by their ability to stick together and maintain their shape when wet, and when they become saturated with water they become very sticky and plastic making them difficult to work with during construction. Cohesive soils have a high cohesion meaning that they can resist shearing forces and exhibit cohesive strength when undisturbed. They are often associated with low permeability which can lead to water retention and slow drainage (Gautam, 2018).

Non-cohesive soils are soils that lack cohesive properties, and they are composed of larger particles such as sand, gravel, and sometimes silt. Unlike cohesive soils, non-cohesive soils do not stick together when wet and do not maintain their shape when subjected to shear forces. Non-cohesive soils have a lower proportion of fine particles and do not exhibit plasticity, and are therefore generally easier to work with during construction. Non-cohesive soils tend to be well-draining and are less likely to retain water, making them suitable for many construction applications where drainage is important (Keaton, 2018). Silt can be identified and subsequently distinguished from fine sand and clay through various field tests described by (Swart et al. 2023).

4.2. **X-Ray Powder Diffraction (XRD)**

The mineralogical make-up of the samples was determined at the X-Ray Analytical Facility, University of Pretoria. The samples from each locality were oven-dried, milled and prepped for testing. 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 mineralogy was determined by selecting the best–fitting pattern from the ICSD database to the measured diffraction pattern, using X'Pert High score plus software. The relative phase amounts (weight% of crystalline portion) were estimated using the Rietveld method. **Figure 25** shows the equipment and some of the pressed powders.

Figure 25 PANalytical X'Pert Pro powder diffractometer (left) and XRD pressed powder samples (right) (© Jason Tunnell)

4.3. Chemical index of alteration (CIA)

The Chemical Index of Alteration (CIA) is a geochemical metric used to assess the degree of weathering of rocks and sediments. A higher CIA value indicates a higher degree of chemical weathering. This is because weathering processes tend to leach out mobile cations like calcium (Ca), sodium (Na), and potassium (K), while leaving behind the relatively immobile aluminium (Al) (Nesbitt, et al., 1984) and (Goldberg, et al., 2010). It is calculated using the formula:

$$CIA = \left(\frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O}\right) \times 100 \quad (3)$$

Where:
- Al_2O_3 represents aluminium oxide
- CaO^* represents calcium oxide from silicate minerals (excluding carbonate and phosphate calcium)
- Na_2O represents sodium oxide
- K_2O represents potassium oxide

The steps taken to calculate the CIA are as follows:
- Determine the molecular weights of the relevant oxides
- Extract the required oxide compositions based on the percentages of each mineral in the different samples.
- Input data into eq (3) and calculate the CIA.

4.4. Foundation indicators

Samples taken from the MTSF, and SMC localities were submitted to the relevant laboratories for foundation indicator tests. The results included particle size distribution (PSD) using sieves for the coarse non-cohesive grain sizes and hydrometer testing for the fine cohesive fraction. It also analysed the moisture content and Atterberg limit according to SANS 3001. All the samples were plotted on a PSD curve and an A-line plasticity graph, and expansiveness was based on Van der Merwe's method (Van der Merwe, 1964) that relates the clay content and plasticity index to each other.

4.4.1. Particle Size Distribution (SANS 3001-GR1)

Particle size distribution (PSD) testing was conducted on the samples to determine the percentages of Gravel, sand, silt and clay as per the guidelines in SANS 3001. The PSD information is crucial for designing foundations, determining soil behaviour, and assessing the suitability of the soil for construction projects. The following steps outline the methodology of the PSD test:
- Sample Collection: Representative soil samples are collected from the sites where geotechnical investigations are conducted.
- Sample Preparation: The collected soil samples are prepared for testing that may involve drying, breaking up clumps, and removing organic material or debris.
- Sieve Analysis: Sieve a representative soil sample through a series of sieves with

progressively smaller openings separating the soil into different particle size fractions and then measuring the mass of soil retained on each sieve.

- Particle Size Calculation: Plot the particle size distribution on a logarithmic graph showing the percentage passing of soil particles through each sieve size, and include, if needed, the hydrometer analyses to be able to express the particle sizes in terms of gravel, sand, silt and clay fractions.
- Hydrometer Analysis (SANS 3001-GR3): For fine-grained soils the remaining soil particles from the sieving is dispersed in water, then the settling velocities of the particles is determined using a hydrometer, and finally the particle size distribution is calculated based on the sedimentation data.

4.4.2. Moisture Content (SANS 3001-GR20)

A soil's moisture content is an important parameter that indicates the fraction or percentage of water present in the soil pores, and can be presented in terms of volume or weight. The moisture content of a soil sample can be calculated using to Eq. 3 and based on the following standard method:

- Weighing the Sample: Weigh an empty, clean, and dry container or tin (often referred to as a moisture tin) and record its weight as W1.
- Adding the Soil: Place a portion of the soil sample into the moisture tin ensuring that the amount of soil is sufficient to provide a representative sample without it overflowing the tin.
- Recording the Combined Weight: Weigh the moisture tin with the soil and record its weight as W2.
- Oven-Drying: Place the moisture tin with the soil sample in an oven set to a standard temperature that is typically 105°C (221°F) causing the soil to heat and all moisture to be removed. the oven-dried soil reaches a constant weight meaning that there is no further reduction in weight, and this typically moisture removal typically takes several hours.
- Recording the Final Weight: Weigh the moisture tin with the dried soil sample and record its weight as W3.

$$\mathrm{M}C = \frac{W_2 - W_3}{W_3 - W_1} \times 100 \tag{4}$$

4.4.3. Atterberg Limits (SANS 3001-GR10)

The Atterberg limits include the liquid limit (LL), plastic limit (PL) and shrinkage limit (SL)that are used to classify fine-grained soils such as clay and silt. They are important for assessing the behaviour of fine-grained soils, including their potential for shrinkage, swelling, and moisture sensitivity. The Atterberg limits are typically determined through the following methods:

Liquid Limit (LL):

- Take a representative soil sample, ensuring that it is free from large particles and contaminants.
- Prepare a soil paste by adding water to the soil sample and thoroughly mixing it until it reaches a uniform consistency.
- Place a portion of the soil paste in a standard liquid limit device, such as a Casagrande

cup.
- Use a standard mechanical device to repeatedly drop a cup onto the soil paste until the two halves of the soil paste come into contact while recording the number of blows required to close the gap.
- Calculate the liquid limit using the number of blows and the calibration chart for the specific device used.

Plastic Limit (PL):
- Take a portion of the soil paste that was used for the liquid limit test.
- Roll the soil paste into a thread-like shape on a non-absorbent surface.
- Keep rolling the thread until it crumbles and can no longer be rolled without breaking.
- The moisture content of the soil paste at this point is the plastic limit.

Shrinkage Limit (SL):
- Take another portion of the soil paste that was used for the liquid and plastic limit tests.
- Form a small, flat and thin soil specimen.
- Place the specimen in an oven and dry it until there is no further reduction in size.
- Measure the moisture content of the soil specimen after drying, and this moisture content is the shrinkage limit.

Once the liquid limit, plastic limit and shrinkage limit are determined these values can be used to classify the soil based on its plasticity characteristics. Common classifications include the following:
- Non-plastic is when PL and LL are both very low.
- Low plasticity is when PL is low and LL is moderate.
- High plasticity is when PL and LL are both relatively high.

The results for each sample taken are plotted on an A-line graph showing soil consistency based on the Atterberg limits, and this method provides insights into how the soil's behaviour changes with moisture content to aid in classifying and assessing soil types.

4.4.4. Van der Merwe Method

The Van der Merwe chart, also known as the Van der Merwe shrink-swell chart, is a graphical tool used to assess the potential expansiveness of soils, particularly clayey soils (Van der Merwe, 1964). It helps in determining whether a soil is susceptible to significant volume changes (swelling and shrinking) with changes in moisture content. Once you have the LL and PI values, you can plot them on the Van der Merwe chart. The LL is plotted on the x-axis, and the PI is plotted on the y-axis. Each LL-PI combination results in a specific point on the chart. The position of the point on the Van der Merwe chart provides a quick visual assessment of the soil's expansiveness as per the below zones which indicate a potential percentage volume change:
- Low (<2%)
- Medium (2%)
- High (4%)
- Very high (8%).

4.4.5. *Grading modulus (SANS 3001-PR5)*

The grading modulus (*GM*) is the cumulative percentages retained on the 2 mm (P_2), 425 µm ($P_{0.425}$) and 75 µm ($P_{0.075}$) as shown in Eq. 4 (parameters simplified to be in mm and consistent throughout this article). A minimum value of GM = 0 indicates a very fine soil with all particles finer than 0.075 mm, and a maximum value of GM = 3 indicates that all the soil is coarse than 2 mm.

$$\mathrm{GM} = \frac{300 - (P_2 + P_{0.425} + P_{0.075})}{100} \tag{5}$$

4.4.6. *Specific gravity (SANS 5844-2)*

The specific gravity of the soil is dimensionless and represents the ratio of the density of the soil solids to the density of water. Different soils have different specific gravity values, and it is an important parameter for soil classification and engineering calculations, such as determining void ratios, porosity, and compaction characteristics.

A representative soil sample is collected and cleared of any organic material or foreign particles. The sample is then weighed and added to a glass jar with a known volume of water. The volumes of the water and soil is recorded. The soil is then removed and the displacement of the water is measured. Specific gravity of the soil is calculated according to Eq. 5.

$$\mathrm{SG} = \frac{M_1}{M_1 - V_W} \times \frac{V_W}{V_d} \tag{6}$$

Where:
SG = specific gravity of the soil (-/-)
M_1 = weight of the dry soil sample (kg)
M_w = weight of the container with water including the soil (kg)
V_w = volume of water (m^3)
V_d = volume of water displaced by the soil sample (m^3)

4.5. **MOD AASHTO compaction tests**

All samples were submitted for MOD AASHTO compaction testing that was conducted according to the methodology set out in SANS 3001 GR30 (SANS, 2013). The Modified Proctor Test is a standard laboratory test used to determine the maximum dry density and optimum moisture content of a soil or aggregate material for a given compaction effort. This test is commonly used in the construction of roads, foundations, and other civil engineering projects to assess the suitability of materials. The American Association of State Highway and Transportation Officials (AASHTO) provides guidelines for conducting this test as follows:

- Sample Preparation: Prepare the soil or aggregate sample by air-drying it, if necessary, to obtain the natural moisture content and removing any plants or roots.
- Determination of Initial Moisture Content: Conducted as per §4.3.2.
- Test Specimen Preparation: The sample is divided into several portions of known mass and volume to calculate dry density and additional water is added to each portion in

quantities ranging below and above anticipated OMC values

- Compaction: Each sample is placed in a compaction mould in layers and is subjected to a specified number of blows from a standard compaction hammer or mechanical compactor as outlined in §2.5.
- Dry Density and Optimum Moisture Content Calculation: The dry density for each compaction effort is calculated using the measured mass and mould volume. These are plotted on a curve of dry density versus moisture content and the point on the curve where the dry density is maximum is determined that represents the maximum dry density and the corresponding moisture content is the optimum moisture content.

5. Results

5.1. Soil profiles

The general soil profile sequence encountered at the MSTF site from top to bottom is as follows:

- Cohesive residual gabbro: slightly moist, orange brown to dark reddish brown, soft, fissured, sandy clay or gravelly clay with abundant coarse, medium and fine, subangular to subrounded gravel and cobbles.
- Non-cohesive residual gabbro: light-yellow grey frequently blotched orange, loose becoming dense with depth, relict textured and structured, clayey sand with coarse, medium and fine, subangular to subrounded gravel and cobbles of gabbro.

The general soil profile sequence encountered at the SMC site from top to bottom is as follows:

- Cohesive residual gabbro: Moist, soft, intact silty clay and resembled the colour of its overlying surficial material which was generally a dark red colluvium.
- Non-cohesive residual gabbro: Moist, dark yellowish grey speckled black, medium dense, intact, silty sand with occasional boulders and core stones of gabbro norite.

Figure 26 shows photographs of the material sampled for this investigation.

Figure 26 Photographs of sampled soil horizons (© Jason Tunnell)

5.2. **XRD analyses**

Table 4 and **Figure 27** show the relative abundance of all minerals found in the samples which show that predominant mineral found in both the MTSF and SMC non-cohesive samples is plagioclase at high average percentages of 47.57 % and 61.84 % respectively. This changes in the cohesive samples which are predominantly composed of clay minerals such as kaolinite and smectite, showing lower levels of plagioclase of 22.89% and 12.89%). The cohesive samples both contained between 29% and 47% kaolinite which was not present in the non-cohesive samples.

The plagioclase found in the non-cohesive samples most likely broke down into kaolinite whilst undergoing chemical weathering (decomposition). Other noticeable distinctions between the cohesive and non-cohesive samples are the decreased percentages of augite and enstatite in the cohesive samples and alternatively, the slightly higher amounts of smectite (10.88% and 17.94%) compared to their non-cohesive counterparts.

Plagioclase in the MTSF and SMC cohesive residual soils was 22.14% and 12.89% respectively, and in the non-cohesive residual soils it was 47.57% and 61.84% respectively. Kaolinite and smectite in the MTSF and SMC cohesive residual soils were 29.96% and 10.88%, and 40.16% and 17.94% respectively.

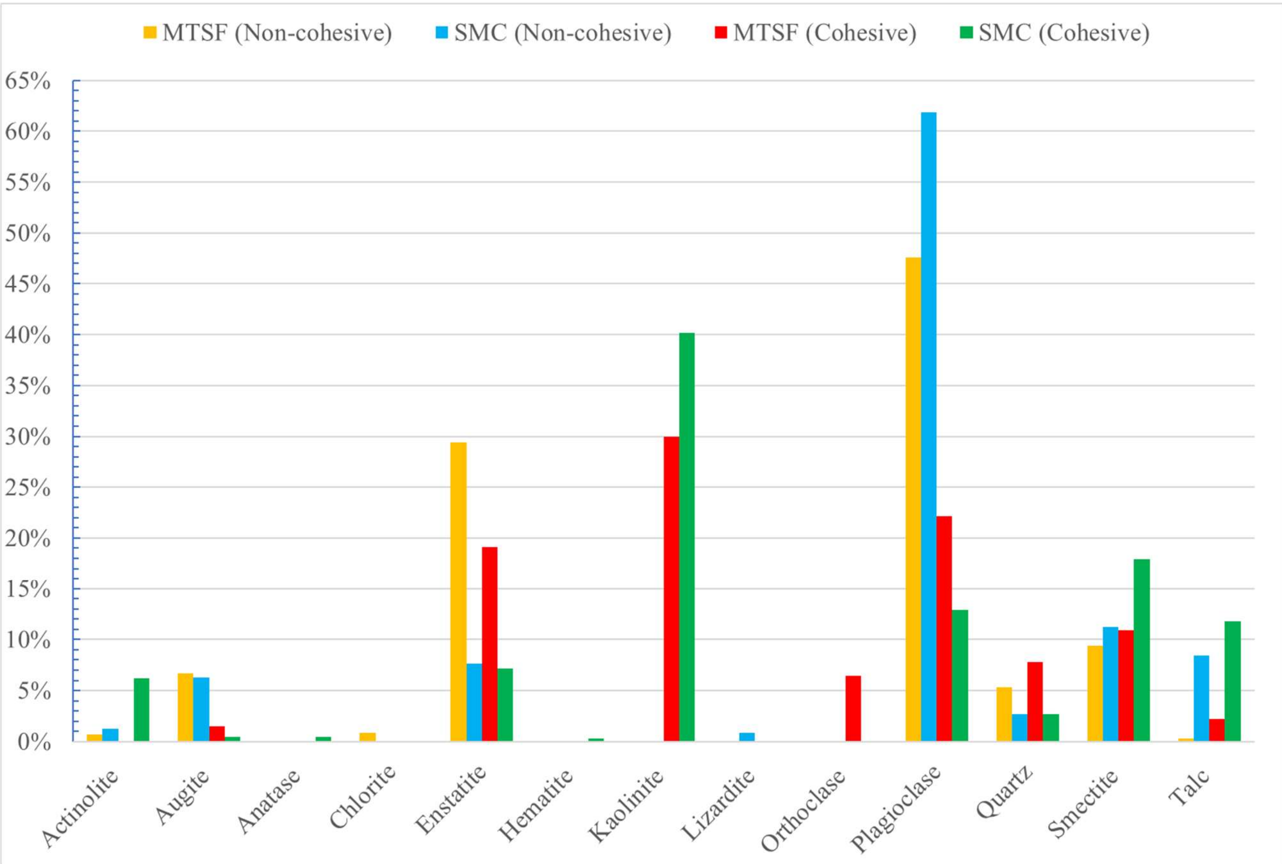

Figure 27 XRD results per mineral and site

Table 4 XRD results (relative abundance)

ID	Actinolite	Augite	Anatase	Chlorite	Enstatite	Hematite	Kaolinite	Lizardite	Orthoclase	Plagioclase	Quartz	Smectite	Talc	Total
Non-cohesive residual soil														
	-	7.04%	-	0.45%	28.72%	-	-	-	-	49.32%	4.73%	9.27%	0.47%	100.00%
	0.20%	6.21%	-	0.98%	28.56%	-	-	-	-	47.07%	5.23%	11.57%	0.18%	100.00%
MTSF	1.52%	8.28%	-	0.34%	29.88%	-	-	-	-	47.88%	5.62%	6.20%	0.28%	100.00%
	0.28%	6.50%	-	1.51%	27.86%	-	-	-	-	47.63%	5.74%	9.83%	0.65%	100.00%
	-	5.45%	-	1.06%	32.13%	-	-	-	-	45.97%	5.17%	10.19%	0.02%	99.99%
Average:	0.67%	6.70%	-	0.87%	29.43%	-	-	-	-	47.57%	5.30%	9.41%	0.32%	100.00%
	1.92%	8.73%	-	-	8.43%	-	-	0.56%	-	58.15%	2.48%	9.01%	10.73%	100.01%
	1.66%	7.25%	-	-	9.67%	-	-	0.66%	-	58.47%	1.19%	10.58%	10.52%	100.00%
SMC	0.74%	4.04%	-	-	8.61%	-	-	1.26%	-	64.67%	3.18%	10.77%	6.73%	100.00%
	0.88%	3.98%	-	-	7.34%	-	-	-	-	64.37%	3.59%	14.25%	5.58%	99.99%
	0.89%	7.56%	-	-	3.98%	0.07%	-	0.82%	-	63.53%	3.15%	11.35%	8.64%	99.99%
Average:	1.22%	6.31%	-	-	7.61%	0.07%	-	0.83%	-	61.84%	2.72%	11.19%	8.44%	100.00%
Cohesive residual soil														
	-	1.30%	-	-	20.58%	-	30.49%	-	8.38%	21.22%	7.79%	8.52%	1.73%	100.01%
	-	1.78%	-	-	19.84%	-	30.58%	-	5.11%	20.84%	8.78%	11.67%	1.40%	100.00%
MTSF	-	1.05%	-	-	19.74%	-	28.82%	-	6.47%	23.24%	7.19%	11.47%	2.01%	99.99%
	-	0.98%	-	-	17.94%	-	30.80%	-	7.03%	21.46%	7.00%	11.04%	3.75%	100.00%
	-	2.20%	-	-	17.68%	-	29.10%	-	5.26%	23.96%	8.05%	11.70%	2.05%	100.00%
Average:	-	1.46%	-	-	19.16%	-	29.96%	-	6.45%	22.14%	7.76%	10.88%	2.19%	100.00%
	5.69%	0.37%	0.26%	-	11.00%	0.31%	32.79%	-	-	15.28%	2.15%	15.06%	17.09%	100.00%
	7.24%	0.45%	0.35%	-	7.46%	0.23%	47.80%	-	-	11.16%	1.74%	16.58%	6.99%	100.00%
SMC	8.80%	0.58%	0.56%	-	8.84%	0.23%	41.46%	-	-	11.38%	1.66%	15.16%	11.33%	100.00%
	5.21%	0.61%	0.45%	-	4.09%	0.36%	41.43%	-	-	14.72%	2.80%	19.57%	10.75%	99.99%
	3.92%	0.47%	0.52%	-	4.35%	0.52%	37.30%	-	-	11.89%	5.07%	23.35%	12.59%	99.98%
Average:	6.17%	0.50%	0.43%	-	7.15%	0.33%	40.16%	-	-	12.89%	2.68%	17.94%	11.75%	99.99%

5.3. Chemical index of alteration

Using the molar mass and weight percentages of all the oxides present in the different samples, approximate CIA values were calculated following the methodology outlined in section 4.4.3. Only having X-ray Diffraction (XRD) data for the mineral composition of the soil samples, rather than the precise oxide compositions that would be provided by X-ray Fluorescence (XRF) data was a limitation. Consequently, the CIA values presented here are estimates based on typical oxide contents found in the identified minerals. These calculations therefore provide an approximate value for the degree of chemical weathering of the soils. From the results presented in Table 5 it is evident that the cohesive samples have undergone a higher degree of chemical weathering with CIA values of 81.98 and 89.76 for the MTSF and SMC samples respectively and CIA values of 63.91 and 63.42 for their non-cohesive counterparts.

Table 5 Chemical index of alteration

Mineral	Chemical formula	Molar mass (g/mol)	MTSF (Non-cohesive)	SMC (Non-cohesive)	MTSF (Cohesive)	SMC (Cohesive)
			Weight percentages			
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	780.45	1%	1%	-	6%
Augite	$(Ca,Na)(Mg,Fe,Al)(Al,Si)_2O_6CaMgSi_2$	216.57	7%	6%	1%	0%
Anatase	TiO_2	79.87	-	-	-	0%
Chlorite	$(Mg,Fe)_5Al_2Si_3O_{10}(OH)_8$	427.86	1%	-	-	-
Enstatite	$Mg_2Si_2O_6$	200.80	29%	8%	19%	7%
Hematite	Fe_2O_3	159.70	-	0%	-	0%
Kaolinite	$Al_2Si_2O_5(OH)_4$	194.18	-	-	30%	40%
Lizardite	$Mg_3Si_2O_5(OH)_4$	213.15	-	1%	-	-
Orthoclase	$KAlSi_3O_8$	278.35	-	-	6%	-
Plagioclase	$(Na,Ca)(Al,Si)_4 O_8$	262,24	48%	62%	22%	13%
Quartz	SiO_2	60.09	5%	3%	8%	3%
Smectite	$(Ca,Na)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2{\cdot}nH_2O$	340.36	9%	11%	11%	18%
Talc	$Mg_3Si_4O_{10}(OH)_2$	347.31	0%	8%	2%	12%
Chemical index of alteration (CIA):			**63.91**	**63,42**	**81,98**	**89,76**

5.4. Foundation indicators

The Atterberg limits and grading analysis are presented in Table 6 and the particle size distribution curves in **Figure 28**. The Unified Soil Classification System (USCS) is used to classify soils in terms of the amount of clay (C), silt (M), sand (S), gravel (G), and organic (O) materials, as well as whether plasticity is low (l) or high (H), and whether the soil is poorly graded (P) or well-graded (W). This is indicated in with two capital letters of which the first is dominant (ASTM, 2020).

Cohesive residual soil samples taken from the MTSF site classifies as clay of high plasticity in the USCS (CH) with one sample classifying as clayey sand (SC). An average clay content of 37% was returned for the MTSF cohesive samples with the higher clay percentage returned for these samples being supported by a low grading modulus (GM<1). The average plasticity index (PI) of material is 38.2 (ranging between 33 and 43). The particle size distribution (**Figure 28**) for this material correlates to the results and is indictive of a soil with a high clay content.

The SMC cohesive samples generally classify as clays of high plasticity (CH) because the samples have a high average clay content of 52% which correlates to the low average GM of 0.37 and an average plasticity index of 32.

Non-cohesive samples taken from the MTSF site returned a high average gravel and sand percentage of 49% and 47% respectively, and these results are supported by the high GM of 2. The samples generally had a very low clay percentage (1%) and this is supported by the low plasticity index of 11% as shown in **Figure 28**. In terms of USCS the samples ranged from well graded silty sand (SW-SM) to poorly graded clayey gravel (GP-GC).

The non-cohesive samples taken from the SMC site classify as a mixture of clayey sand (SC) and silty sand (SM). The samples had a lower gravel content than the MTSF samples and this is supported by the lower GM of 1.26. The samples did however return a high sand fraction of 74% and a low plasticity index of 10 (ranging from slightly plastic to 11).

The calculated GM values are in line with what is expected and confirm the categorization of the samples into cohesive and non-cohesive soils with the cohesive soils having GM values ranging from 0.14–0.89, and the non-cohesive soils having GM values ranging from 0.82–2.41.

It is evident from the graphical representation of the particle size distribution (PSD) for the samples taken that the samples identified as cohesive have more fines (clay and silt) than their non-cohesive counter parts. In general, both the cohesive and non-cohesive samples taken from the SMC site contained more fines than the MTSF samples. The MTSF non-cohesive samples contained considerably more gravel sized particles than any of the other samples taken from the two sites. The higher clay fractions shown in the particle size distribution graphs for the cohesive samples are concurrent with the XRD results which showed higher clay mineral contents for the cohesive samples.

Table 6 Foundation Indicator results

Site	USCS	Grading analysis				Atterberg limits				Moisture content (%)	GM	SG
		Gravel %	Sand %	Silt %	Clay %	Liquid Limit	Linear Shrinkage	Plastic Limit	Plasticity Index			
Cohesive residual soil												
MTSF	SC	7	50	16	27	55.0	24.5	22.0	33.0	23.1	0.77	2.77
	CH	3	39	14	44	69.0	29.0	31.0	38.0	38.5	0.46	2.71
	CH	9	44	19	28	62.0	27.0	27.0	35.0	25.1	0.74	2.77
	CH	1	42	14	43	71.0	29.5	28.0	43.0	8.8	0.46	2.76
	CH	1	42	13	44	69.0	30.5	27.0	42.0	42.2	0.52	2.74
Average(n=5)		**4**	**43**	**15**	**37**	**65.2**	**28.1**	**27.0**	**38.2**	**27.5**	**0.59**	**2.75**
SMC	CH	3	23	19	55	73.0	25.5	36.0	37.0	-	0.30	2.76
	CH	1	12	24	63	61.0	22.0	28.0	33.0	-	0.14	2.61
	CH	0	19	27	54	60.0	14.0	30.0	30.0	-	0.15	2.73
	CH	20	25	18	37	54.0	13.5	26.0	28.0	-	0.89	2.69
Average(n=4)		**6**	**20**	**22**	**52**	**62.0**	**18.8**	**30.0**	**32.0**	**-**	**0.37**	**2.70**
Non cohesive residual soil												
MTSF	SW-SM	18	77	4	1	-	0.5	-	SP	10.0	1.82	2.96
	SW-SM	56	41	2	1	-	0.5	-	SP	10.8	2.34	2.89
	GP-GC	63	34	2	1	32.0	6.5	19.0	13.0	12.4	2.41	2.81
	GP-GC	61	35	3	1	27.0	4.5	18.0	9.0	11.0	2.31	2.87
	SW-SC	58	38	3	1	29.0	5.0	19.0	10.0	8.0	2.31	2.83
	SW	55	43	1	1	-	0.5	-	SP	5.7	2.34	2.91
	SC	29	63	6	2	29.0	6.5	17.0	12.0	21.2	1.73	2.83
Average(n=7)		**49**	**47**	**3**	**1**	**29.3**	**3.4**	**18.3**	**11.0**	**11.3**	**2**	**3**
SMC	SC	8	73	15	4	32.0	6.0	21.0	11.0	-	1.24	2.67
	SC-SM	10	77	11	2	28.0	3.0	23.0	5.0	-	1.31	2.74
	SC	0	68	22	10	33.0	7.0	19.0	14.0	-	0.82	2.76
	SM	4	79	13	4	-	0.5	-	SP	-	1.23	2.84
	SW-SM	19	73	7	1	-	0.5	-	SP	-	1.72	2.87
Average(n=5)		**8**	**74**	**14**	**4**	**31.0**	**3.4**	**21.0**	**10.0**	**-**	**1.26**	**2.78**

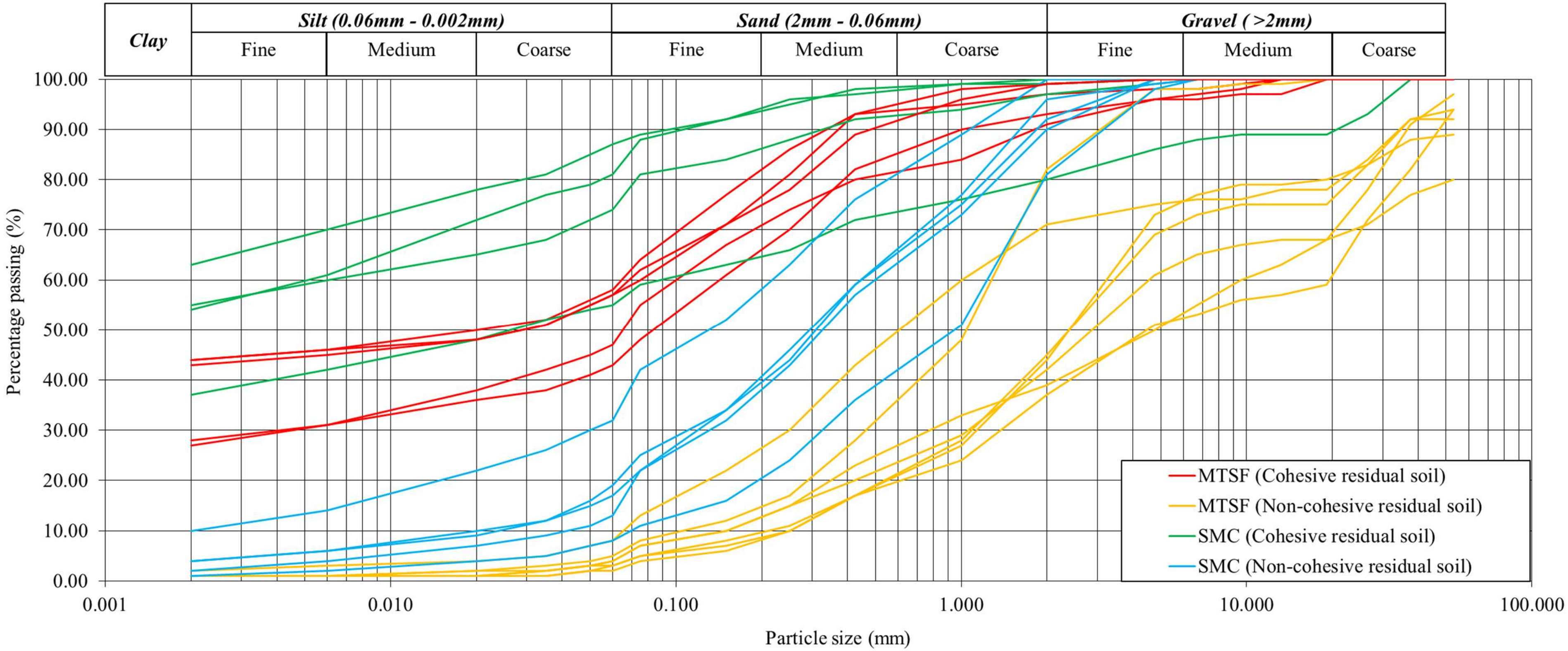

Figure 28 Particle Size Distribution graph of all samples

5.5. Atterberg Limits

The Atterberg Limits for the fine-grained fractions of the samples were plotted on a plasticity graph (A-line), using the relationship between the Plasticity Index (PI) and liquid limit (LL) and are depicted in **Figure 29**. The relationship is determined for the <425 µm soil fraction as the LL and PI are determined for that fraction, and this relationship is used to assess whether the fines component of the soil is dominated by silt or clay based on the Unified Soil Classification. All the non-cohesive samples are shown to have a low plasticity, and all the cohesive samples had a high to very high plasticity. Most of the cohesive samples plotted above the A-line indicating that the fines component of the samples is predominantly clay with exception to one cohesive sample from the SMC site.

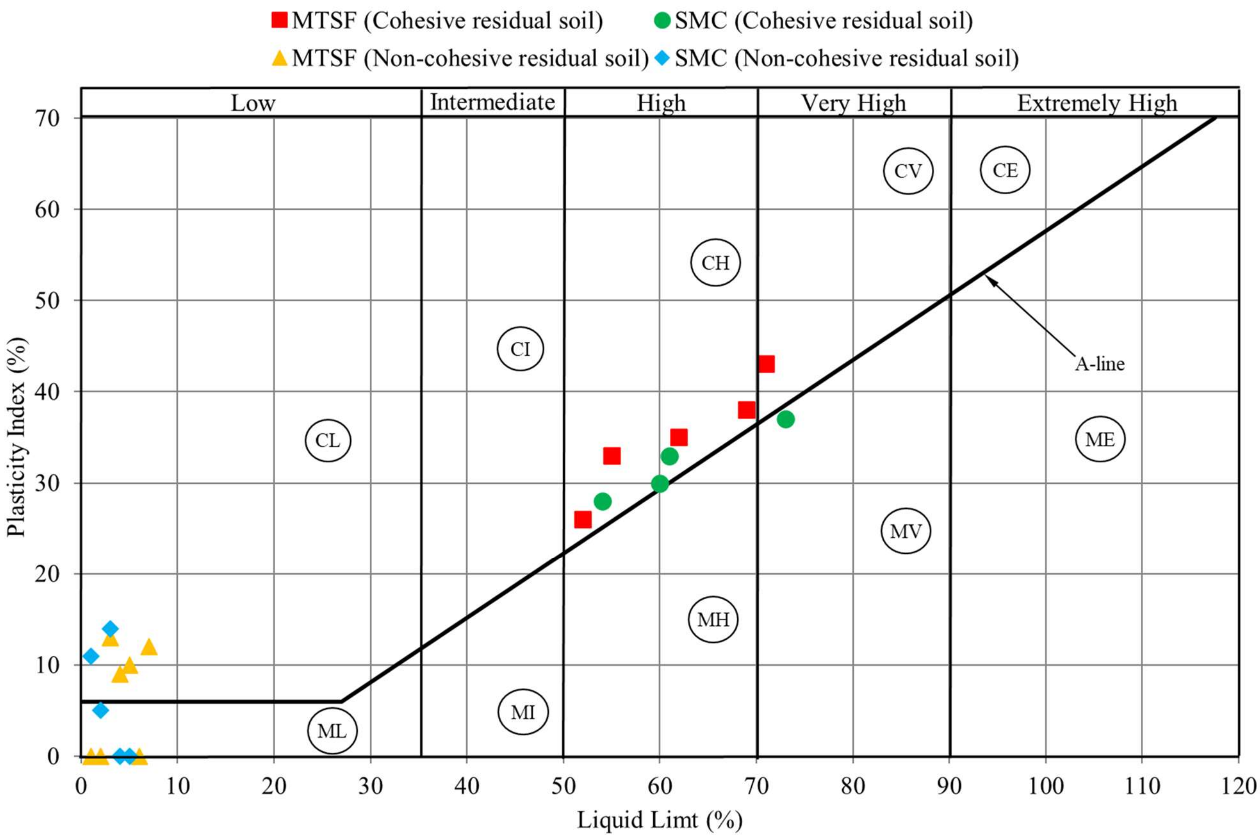

Figure 29 Samples indicated on the Atterberg Limits graph

5.6. Potential expansiveness

The results of the foundation indicator tests were plotted on the Van der Merwe (**Figure 30**) chart to assess the potential expansiveness of the soil samples. This chart depicts the samples as a function of the adjusted PI of the whole sample (PI_{ws}) calculated by the PI and by the fraction of the soil that passes the 0.425 mm sieve ($P_{0.425}$) (Eq. 6) against the clay percentage of each sample (Van der Merwe, 1964).

$$PI_{WS} = \text{PI} \times \left(\frac{P_{0.425}}{100}\right) \tag{7}$$

According to the Van der Merwe potential expansiveness graph it is evident that all the non-cohesive material tested is generally characterised by a low potential expansiveness (< 2%). With the exception of one MTSF cohesive sample plotting in the low range (<2%), all the cohesive samples tested plotted in the high to very high range (4-8%). This is indicative of high activity which indicates possible instability.

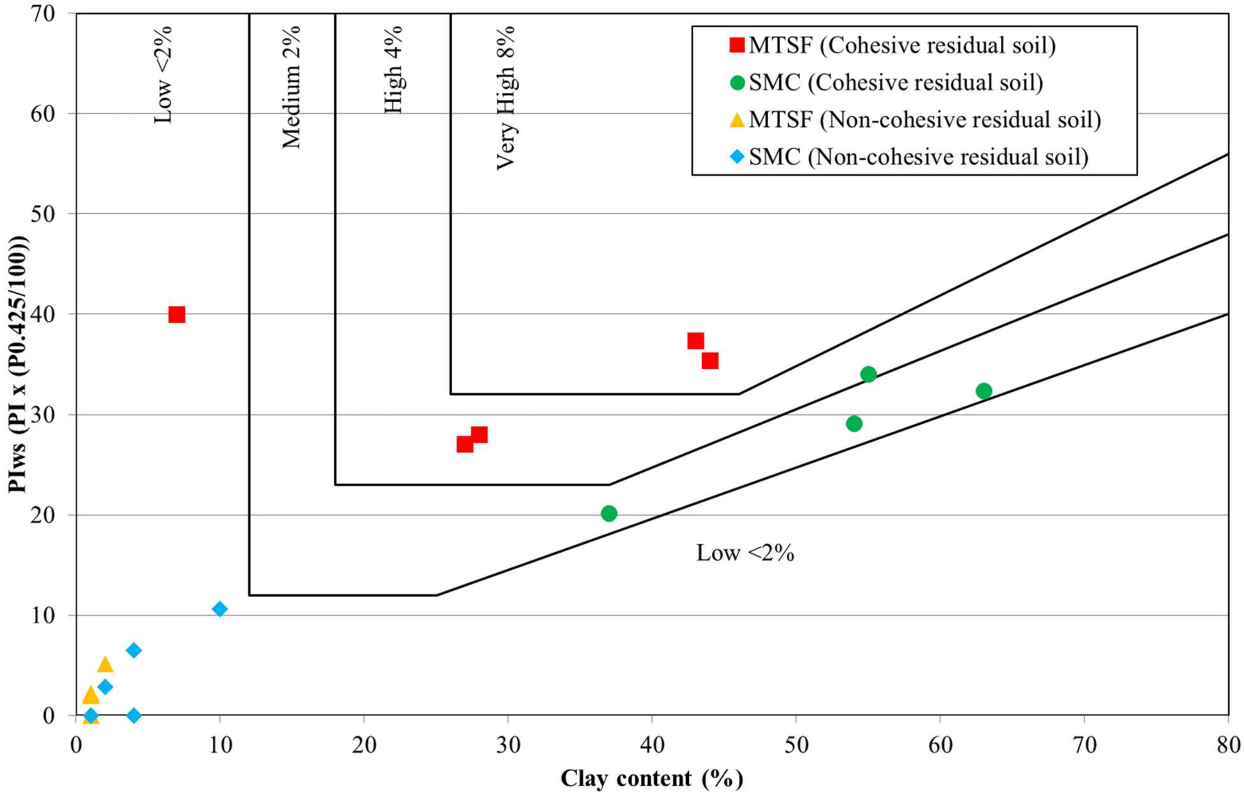

Figure 30 Van der Merwe potential expansiveness graph (Van der Merwe, 1964)

5.7. MOD AASHTO compaction testing

The maximum dry density (MDD) and the optimum moisture content (OMC) relationship were determined for 23 samples. A summary of the moisture and density relationship of the samples is included in Table 7. Eq. 3 shows the relationship between a soil's dry density and its specific gravity assuming that the specific gravity of the sample remains constant at a given moisture content.

Where:

ρ_d	=	Dry density (kg/m3)
ρ_w	=	Density of water (1000 kg/m3)
w	=	Water content (%)
SG	=	Specific gravity (unitless)

The cohesive samples returned a lower maximum dry density (MDD) and a higher optimal moisture content (OMC) in general compared to the non-cohesive samples. The cohesive residual samples taken from the MTSF site returned an average MDD of 1 907 kg/m^3 at an average OMC of 14.5 % while the SMC cohesive residual samples returned an average MDD of 1 667 kg/m^3 at an average OMC of 17.6 %. The non-cohesive samples taken from the MTSF and SMC sites both returned high average MDD results of 2 066 kg/m^3 and 2 068 kg/m^3 respectively. The OMC was also found to be lower than that of the cohesive samples at 10.4 % and 10.8 %.

Table 7 MOD AASHTO results

Site	MDD (Kg/m³)	OMC (%)	SG	Site	MDD (Kg/m³)	OMC (%)	SG
Cohesive residual				**Non-cohesive residual**			
MTSF	1827	15.3	2.77	**MTSF**	2099	9.1	2.96
	1943	14.7	2.71		2136	10.4	2.89
	1938	13.1	2.77		2055	10.4	2.81
	1921	14.3	2.76		2108	9.5	2.87
	1957	13.8	2.74		2088	10.9	2.83
	1857	15.7	2.72		1930	13.0	2.83
Average(n=6):	**1907**	**14.5**	**2.74**	**Average(n=6):**	**2069**	**10.6**	**2.86**
SMC	1611	15.6	2.76	**SMC**	2096	10.3	2.67
	1620	20.0	2.61		2085	10.5	2.74
	1625	14.5	2.73		2079	10.9	2.76
	1649	18.4	2.69		2097	10.3	2.84
	1708	19.7	-		2037	11.7	2.87
	1789	17.1	-		2016	11.3	2.00
Average(n=6):	**1667**	**17.6**	**2.70**	**Average(n=6):**	**2068**	**10.8**	**2.65**

For quality control purposes, the moisture-density relationship of the samples was compared to the 0%, 5% and 10% air voids curves shown in **Figure 31**) for a specific gravity (SG) deemed applicable to the material types. The 0% air voids curve represents the maximum possible density that the soil can be compacted to for a given water content. This degree of compaction is however unattainable in practice and serves as a quality control check to judge the correctness of the laboratory data as reported compaction results should plot completely to the left of the 0% air voids curve. Additionally, if reported compaction results plot left of the 10% air void line, it can be assumed that the result does not necessarily represent the maximum density of that sample.

From **Figure 31**, it is evident that majority of the samples plot between the 0% and 5% air void lines with exception to some of the SMC cohesive samples. The position of the air void lines was calculated using an average specific gravity of 2.74 from all the MOD samples taken. It is evident from the results that in general the non-cohesive samples tend to return a higher MDD at a lower OMC than the cohesive samples.

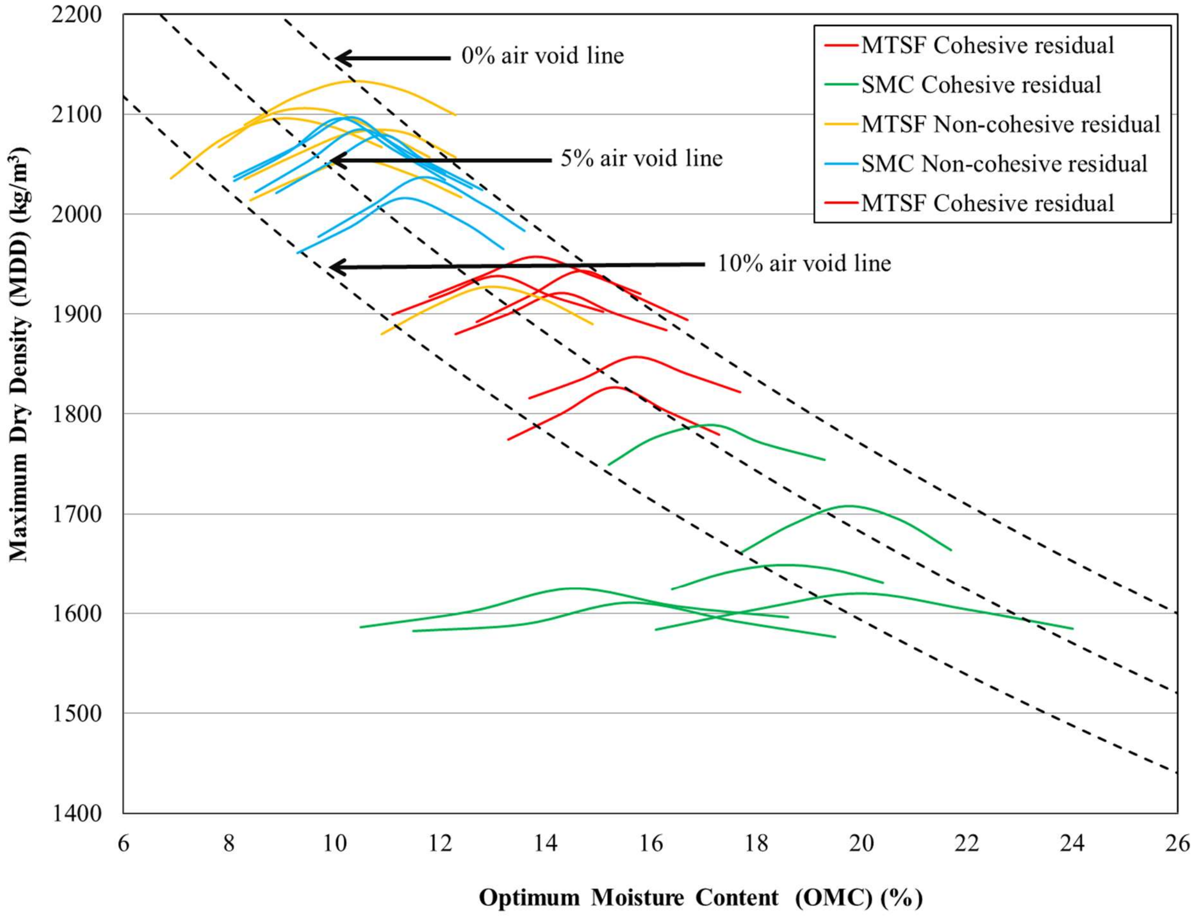

Figure 31 MOD AASHTO curves

6. Discussion

Based on the literature a variety of governing elements must be considered when determining a soil's compaction characteristics. Factors on compaction such as compactive effort and compaction method (machinery used) are defined by the project specifications, and it can be altered based on better understanding of the soils used for construction. Increased applied compactive efforts cause an increase in compaction, and the compaction method will affect the ease and speed of compaction,

It is important to use the correct machinery based on the properties of the geological media being compacted. If the machinery is too light then proper compaction will not be achieved, and if the machinery is too heavy the soil's physical properties can be altered due to breaking of mineral grains. These external factors are not relevant for this investigation as it was mitigated by applying the same compaction effort (MOD AASHTOO) to all samples.

The variable results are therefore the outcome of internal factors such as particle size and moisture content. It is evident that samples that exhibited smaller particle sizes and greater moisture contents produced lower maximum dry densities and therefore lower levels of compaction at the same compaction effort.

All the samples tested from the two sites presented had similar mineralogy comprising predominately of plagioclase in the non-cohesive samples and kaolinite in the cohesive samples, and the major difference identified between the sample sets was the presence of higher amounts of clay minerals (kaolinite, smectite) and talc in the cohesive samples. The relative abundance of other minerals such as augite and enstatite were found to be lower in the cohesive samples whilst the remaining mineral constituents did not vary much between the different sample sets.

Calculating the Chemical Index of Alteration showed that the cohesive samples from the two sites where in a more advanced stage of weathering in comparison to the non-cohesive samples. This is further highlighted by the greater abundance of secondary minerals in the cohesive samples such as smectite and kaolinite. **Figure 32** presents a graphical illustration of the average mineral abundance between the non-cohesive and cohesive samples found at the two project sites.

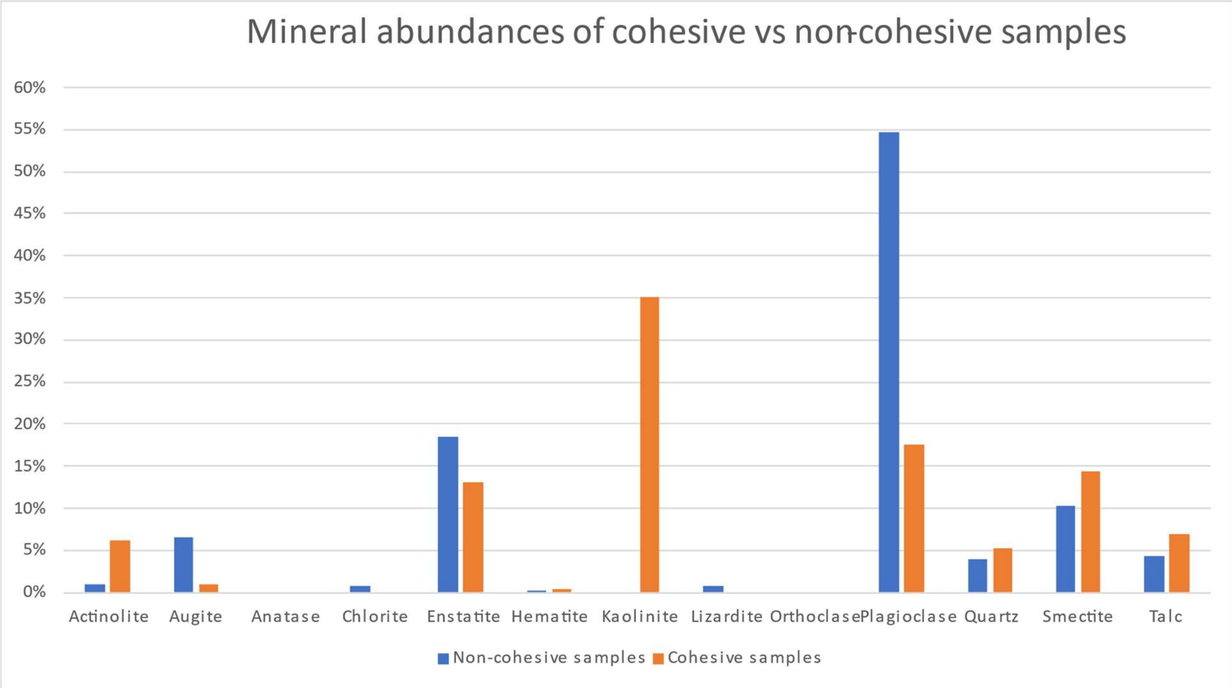

Figure 32 Mineral abundances of cohesive vs non-cohesive samples

The grading of the residual soils is dependent on the parent rock mineralogical composition, and then on the chemical weathering (decomposition) and/or physical (mechanical) weathering disintegration processes due to weathering of the rocks. Chemical weathering decompose rock to change mineralogy and structure, and physical weathering disintegrates rock into finer fragments of the same minerals. These can coexist, but the prior dominates in humid environments, and the latter in arid environments.

The cohesive soil was found to be overlying the non-cohesive soil on both site's. The soils at the surface are in a more advanced stage of weathering and exhibit greater cohesion because they have been more exposed to climatic conditions such as oxygen and water. This prolonged exposure accelerates chemical weathering processes, leading to the breakdown of the parent material and the formation of finer particles, including silt and clay-sized secondary minerals. As a result, these surface soils have lost much of their original structure and have become more cohesive. The underlying soils have been less exposed to these weathering agents, retaining their non-cohesive nature due to the lower degree of weathering.
The grading of the MTSF samples is mostly coarser than the SMC samples. Soils that had a coarser grain size and plotted higher on the PSD graphs, generally produced a higher maximum dry density than the soils with finer gradings. **Figure 33** provides a graphical representation of the varying gradings of material found across the 4 sites.

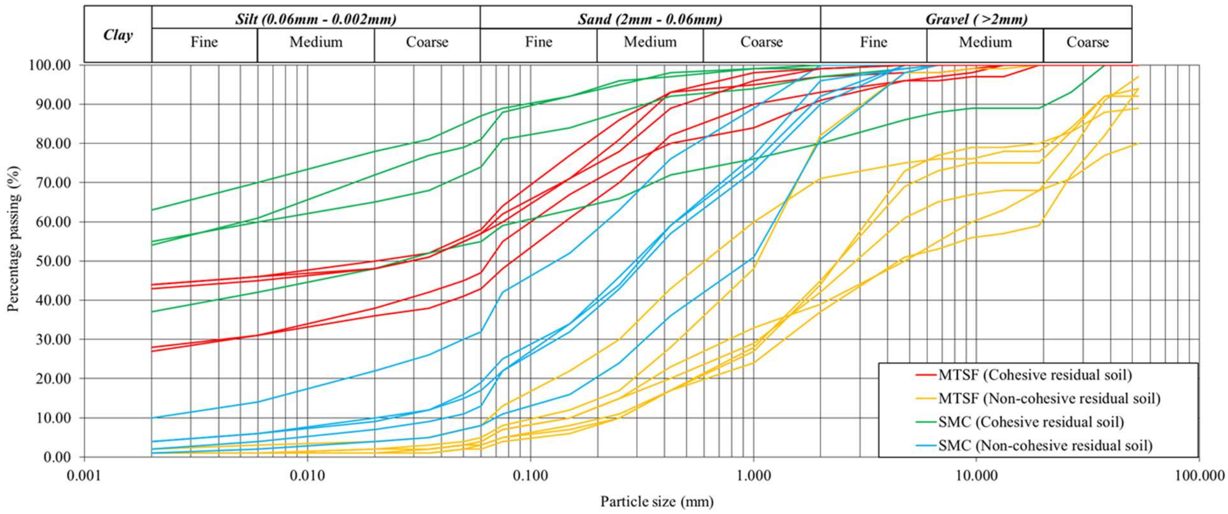

Figure 33 PSD of four sites

All the cohesive samples tested returned higher Atterberg limits than the non-cohesive samples due to the increased relative abundances of fine silt and clay minerals. The cohesive samples taken from the SMC site in Zimbabwe had the highest clay content, and due to that higher Atterberg limits. This correlates to the climatic conditions for the site that has increased temperature and rainfall and therefore more chemical weathering resulting in the formation of secondary minerals that are clayey in nature such as kaolinite and smectite.

Alcott showed the best correlation between compaction characteristics and the soil grading was found to exist for the clay fraction of a soil (Alcott, 1970). **Figure 34** shows the maximum dry density (MDD) obtained at the optimal moisture content (OMC) correlated with the clay and gravel contents of the samples. When comparing these compaction characteristics to the average gravel percentages a low correlation was found (0.2685– 0.3722 or about 27–37%), and the average clay percentages produced a high correlation (0.9134–0.9829 or about 91 –98%).

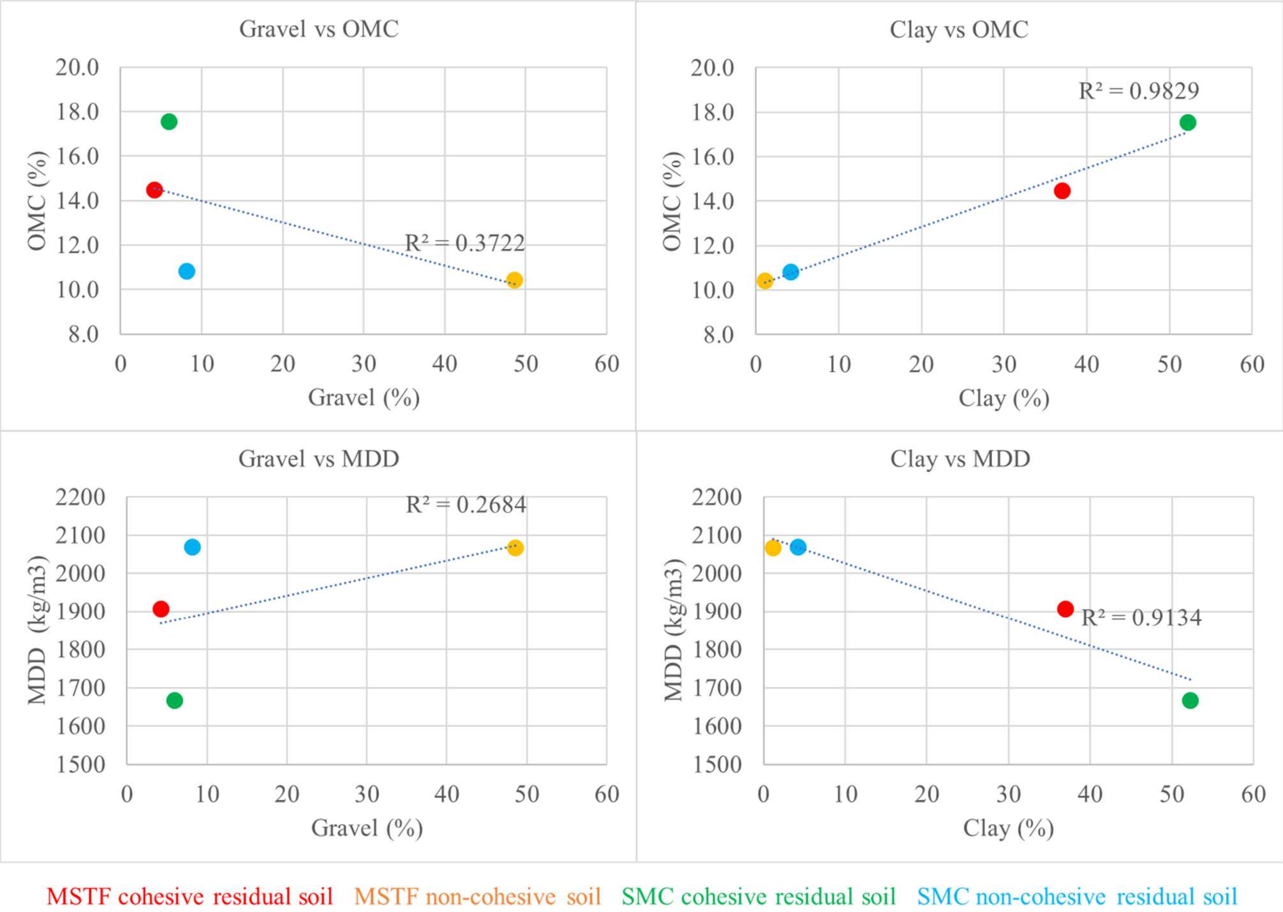

Figure 34 Gravel and clay percentages compared to compaction characteristics including optimal moisture content and maxim

Soils with a higher clay content have a higher affinity to retain water and therefore a higher OMC. As a clayey soil approaches OMC, compaction becomes difficult due to the higher pore pressures which counter the effects of compaction. This is evident in the results presented as samples containing more clay minerals plotted higher on the A-line and VDM graphs (**Figure 28** and **Figure 29**).

The cohesive samples returned lower levels of compaction than their non-cohesive counterparts. The smaller particle sizes in these samples mean that a greater surface area is available for the water particles to adhere to, causing higher pore pressures and subsequently a lower maximum dry density. Additional to the already lower maximum dry density exhibited by clay particles increased activity and expansiveness will result in an overall decrease in compaction over time. A summary of all the results is presented in **Table 8**.

Table 8 Summary of all results

Sample set	MTSF (Cohesive soil)	MTSF (Non-cohesive soil)	SMC (Cohesive soil)	SMC (Non-cohesive soil)
±Chemical index of alteration (CIA):	63.91	63,42	81,98	89,76
Grading analysis %)	Gravel: 4 Sand: 43 Silt: 15 Clay: 37	Gravel: 49 Sand: 47 Silt: 3 Clay: 1	Gravel: 6 Sand: 20 Silt: 22 Clay: 52	Gravel: 8 Sand: 74 Silt: 14 Clay: 4
A-line result	high to very high activity	Low activity	high to very high activity	Low activity
VDM result	medium to high expansiveness	low expansiveness	medium to high expansiveness	low expansiveness
MDD (Kg/m³)	1907	2066	1667	2068
OMC (%)	14.5	10.4	17.6	10.8

Effective TSF foundations require soils with high maximum dry density, optimal moisture content and low plasticity in order to reduce or eliminate shearing and settlement, increasing stability. The results show that cohesive soils, which have undergone significant weathering and contain high silt and clay content, exhibit lower maximum dry density, higher plasticity, making them unsuitable for TSF foundations. These properties pose risks for stability and drainage. Non-cohesive soils retain more of their original structure, are less weathered, and consist of coarser particles. They exhibit higher maximum dry density and more favourable moisture contents for compaction, making them more suitable for TSF foundations due to their better stability and drainage properties.

7. Conclusions

Through literature and laboratory testing conducted for this study, mineralogy has been identified as a major controlling factor in a soils ability to be compacted. The mineralogy of soil determines its physical and chemical properties and they both directly and indirectly affect a soils compaction characteristics, such as water content and particle size distribution. The compaction of the underlying strata of a tailings storage facility will greatly affect its stability by mitigating settlement, shearing and ultimately result in a stable, safer foundation.

7.1. **Main findings**

This study aimed to investigate residual gabbro soil through compiling appropriate mineralogical, mechanical, and geotechnical data to determine its effect on compaction during the construction of the foundations of tailings storage facilities. Residual gabbro soils were split into non-cohesive and cohesive sample sets for the Great Dyke in Zimbabwe and the Bushveld Igneous Complex in South Africa. Both regions are known for their platinum-rich ore bodies but pose very different climatic conditions which in turn provided insight into different stages of chemical weathering.

The collected samples were tested for compaction characteristics and mineralogy. From literature and the results presented, it is evident that mineralogy plays an important role in determining the compaction characteristics of soil. The major findings of interest in this study are as follows:

- Residual gabbro soils that are exposed to the elements such as high rainfall and temperatures tend to be more cohesive by nature due to greater stages of chemical weathering and results in the formation of more clayey and silty secondary minerals.
- The presence of more cohesive material such as clay in a soil, tends to increase the optimal moisture content due to clay’s ability to physically and chemically “hold” water molecules more tightly than sands or silts.

There is a strong correlation between a soils clay content and its compaction characteristics. From the results presented, a soils clay content is directly proportional to its optimal moisture content and inversely proportional to its maximum dry density. 2:1 layered silicate clays, such as smectite, encountered at the SMC site in Zimbabwe, exhibit significant activity and expansiveness. These clays have a unique structure that allows them to absorb large amounts of water and host free exchangeable cations. This high absorptive capacity leads to greater swelling and shrinkage, which greatly impacts their engineering properties. The expansive nature of smectite clays counteracts the effects of compaction, reducing stability and making them less suitable for use in construction requiring high structural integrity, such as in TSF foundations. This finding highlights the importance of identifying and characterizing clays in geotechnical assessments to ensure appropriate measures are taken to mitigate their expansive behaviour.

7.2. **Limitations and assumptions**

Restrictions and limitations on the transportation of soil samples out of Zimbabwe resulted in multiple accredited laboratories having to be utilized for this study. As noted in §5.6, some of the SMC cohesive samples plotted outside of the computed air void control lines bringing into question some of the results obtained. The author is however of the opinion that sufficient testing was conducted and enough research from previous studies was utilized to justify the interpreted conclusions presented.

7.3. **Way forward**

To assess the stability of foundations for tailings storage facilities and better understand the role mineralogy plays, further research into how mechanical compaction affects mineralogical fabric and texture should be conducted. Soil is a dynamic and ever-changing system, and the physical breakdown of minerals due to compaction can alter a soil's chemical and physical properties and therefore its stability. This specifically relates to its mineralogy that can change during wetting and oxidation, and it's pores and structures that can be reduced or destroyed during compaction.

Ongoing research should utilize controlled mixes of soils in a laboratory setting by mixing soils of equal mineralogy that is the key driver of a soil's compaction capability. Varying amounts of dominant clay minerals such as kaolinite and smectite should be added to a standard sample in differing percentages to identify their effect on compaction and to correlate the results to the findings of this study. A better understanding of the mineralogical composition of the underlying geological units will assist during the design and operation of tailings dams across the world, ultimately aiding the management of these super structures as per the requirements set out in the new GISTM standards.

This is now understood, and research can build towards enhancing the knowledge of foundation design for tailings dams around the world to improve stability and ultimately decrease or prevent failures in the future.

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I wish to express my appreciation to the following organisations and persons who made this project report possible:

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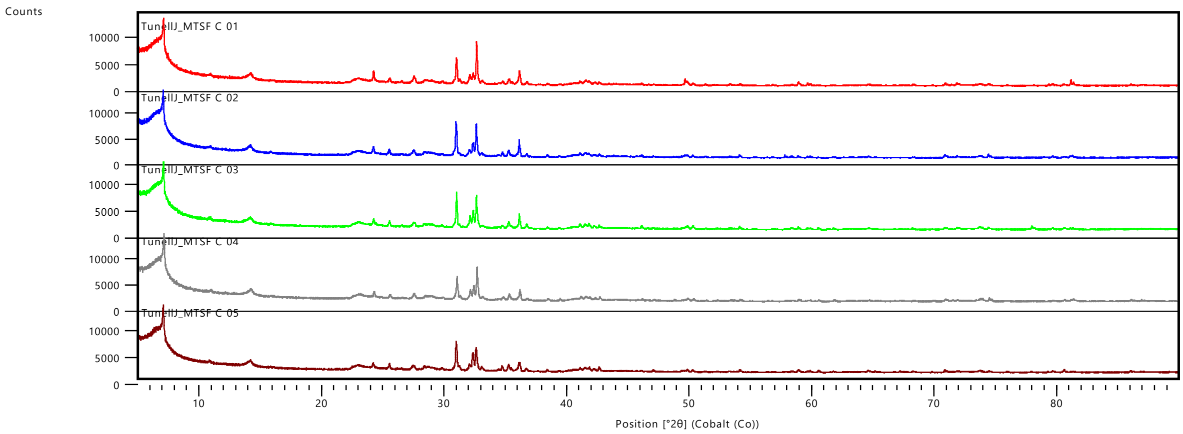
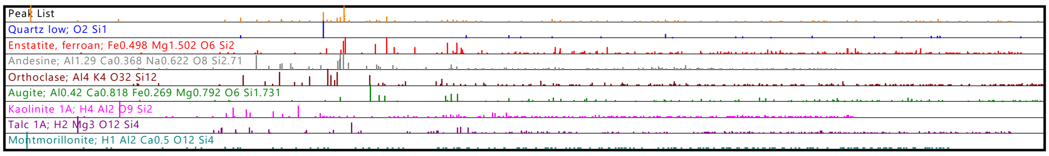
Laboratory Results:

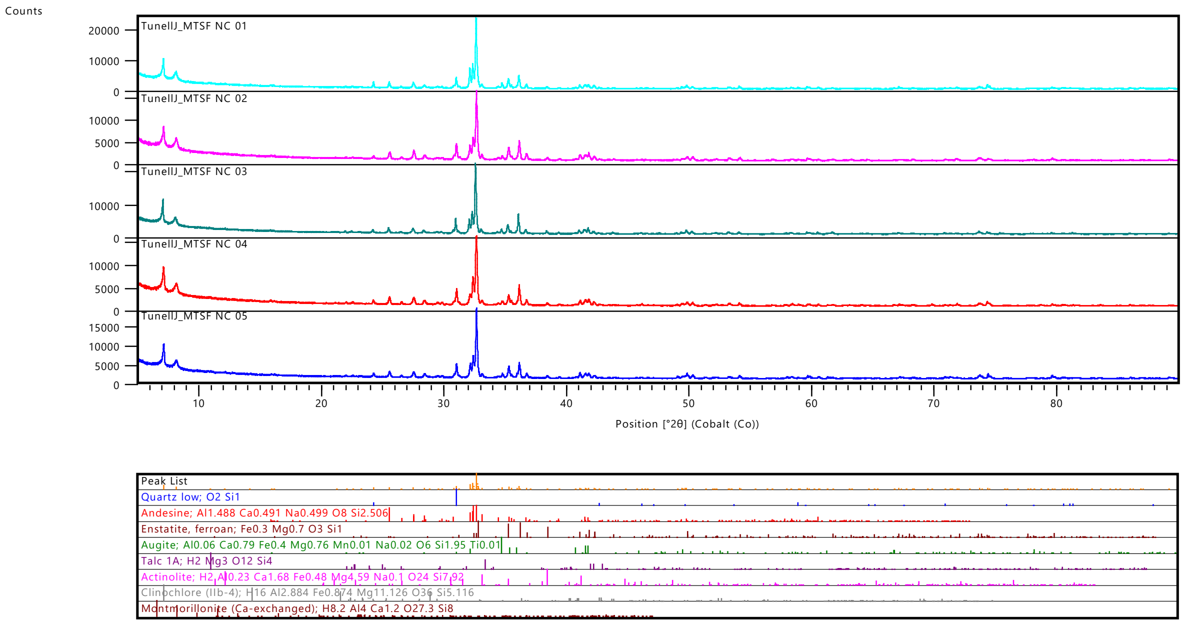
The samples were prepared according to the standardized Panalytical backloading system, which provides a nearly random distribution of the particles.

The samples were analyzed 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 mineralogy was determined by selecting the best–fitting pattern from the ICSD database to the measured diffraction pattern, using X'Pert Highscore plus software.

The relative phase amounts (weight% of crystalline portion) **were estimated** using the Rietveld method. The quantitative results are presented in an Excel sheet.



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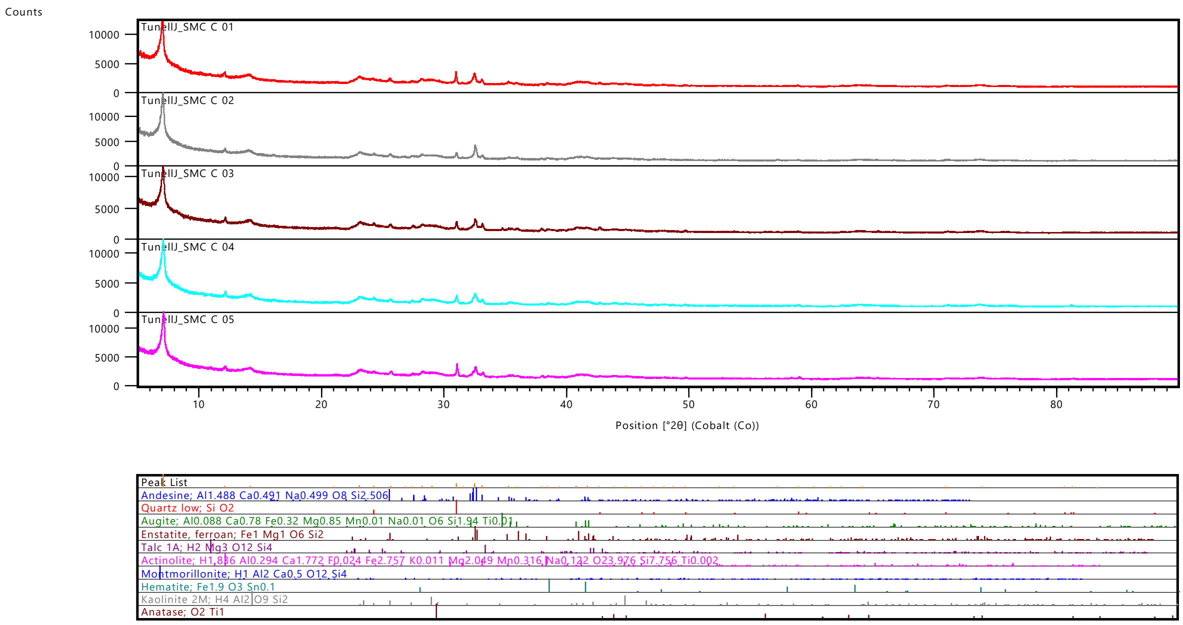
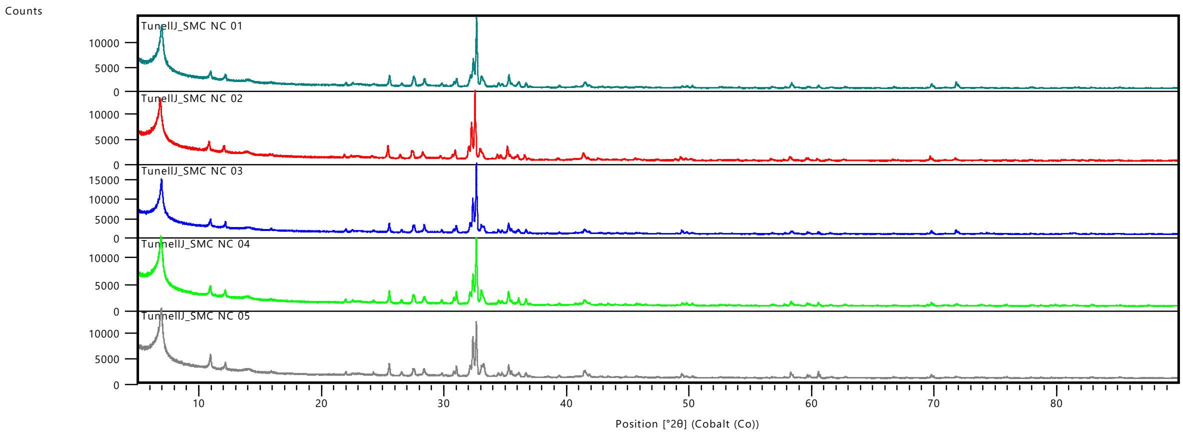
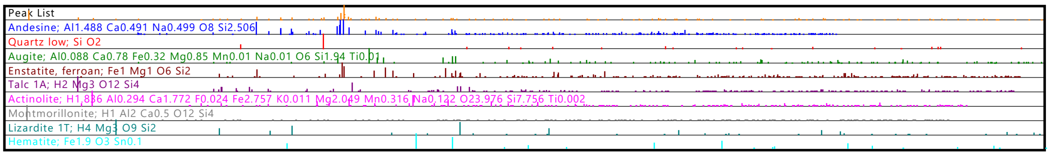
TunelIJ_MTSF NC 01
TunelIJ_MTSF NC 02
TunelIJ_MTSF NC 03
TunelIJ_MTSF NC 04
TunelIJ_MTSF NC 05
Position [°2θ] (Cobalt (Co))
Peak List
Quartz low; O2 Si1
Andesine; Al1.488 Ca0.491 Na0.499 O8 Si2.506
Enstatite, ferroan; Fe0.3 Mg0.7 O3 Si1
Augite; Al0.06 Ca0.79 Fe0.4 Mg0.76 Mn0.01 Na0.02 O6 Si1.95 Ti0.01
Talc 1A; H2 Mg3 O12 Si4
Actinolite; H2 Al0.23 Ca1.68 Fe0.48 Mg4.59 Na0.1 O24 Si7.92
Clinochlore (IIb-4); H16 Al2.884 Fe0.874 Mg11.126 O36 Si5.116
Montmorillonite (Ca-exchanged); H8.2 Al4 Ca1.2 O27.3 Si8


Counts
TunelIJ_SMC C 01
TunelIJ_SMC C 02
TunelIJ_SMC C 03
TunelIJ_SMC C 04
TunelIJ_SMC C 05
Position [°2θ] (Cobalt (Co))
Peak List
Andesine; Al1.488 Ca0.491 Na0.499 O8 Si2.506
Quartz low; Si O2
Augite; Al0.088 Ca0.78 Fe0.32 Mg0.85 Mn0.01 Na0.01 O6 Si1.94 Ti0.01
Enstatite, ferroan; Fe1 Mg1 O6 Si2
Talc 1A; H2 Mg3 O12 Si4
Actinolite; H1.836 Al0.294 Ca1.772 F0.024 Fe2.757 K0.011 Mg2.049 Mn0.316 Na0.132 O23.976 Si7.756 Ti0.002
Montmorillonite; H1 Al2 Ca0.5 O12 Si4
Hematite; Fe1.9 O3 Sn0.1
Kaolinite 2M; H4 Al2 O9 Si2
Anatase; O2 Ti1





	Quartz	Enstatite	Plagioclase	Orthoclase	Augite	Kaolinite	Talc	Smectite		
MTSF C 01	7.79	20.58	21.22	8.38	1.3	30.49	1.73	8.52		
MTSF C 02	8.78	19.84	20.84	5.11	1.78	30.58	1.4	11.67		
MTSF C 03	7.19	19.74	23.24	6.47	1.05	28.82	2.01	11.47		
MTSF C 04	7	17.94	21.46	7.03	0.98	30.8	3.75	11.04		
MTSF C 05	8.05	17.68	23.96	5.26	2.2	29.1	2.05	11.7		
	Quartz	**Plagioclase**	**Enstatite**	**Augite**	**Talc**	**Actinolite**	**Chlorite**	**Smectite**		
MTSF NC 01	4.73	49.32	28.72	7.04	0.47	0	0.45	9.27		
MTSF NC 02	5.23	47.07	28.56	6.21	0.18	0.2	0.98	11.57		
MTSF NC 03	5.62	47.88	29.88	8.28	0.28	1.52	0.34	6.2		
MTSF NC 04	5.74	47.63	27.86	6.5	0.65	0.28	1.51	9.83		
MTSF NC 05	5.17	45.97	32.13	5.45	0.02	0	1.06	10.19		
	Plagioclase	**Quartz**	**Augite**	**Enstatite**	**Talc**	**Actinolite**	**Hematite**	**Kaolinite**	**Anatase**	**Smectite**
SMC C 01	15.28	2.15	0.37	11	17.09	5.69	0.31	32.79	0.26	15.06
SMC C 02	11.16	1.74	0.45	7.46	6.99	7.24	0.23	47.8	0.35	16.58

SMC C 03	11.38	1.66	0.58	8.84	11.33	8.8	0.23	41.46	0.56	15.16
SMC C 04	14.72	2.8	0.61	4.09	10.75	5.21	0.36	41.43	0.45	19.57
SMC C 05	11.89	5.07	0.47	4.35	12.59	3.92	0.52	37.3	0.52	23.35
	Plagioclase	**Quartz**	**Augite**	**Enstatite**	**Talc**	**Actinolite**	**Lizardite**	**Hematite**	**Smectite**	
SMC NC 01	58.15	2.48	8.73	8.43	10.73	1.92	0.56	0	9.01	
SMC NC 02	58.47	1.19	7.25	9.67	10.52	1.66	0.66		10.58	
SMC NC 03	64.67	3.18	4.04	8.61	6.73	0.74	1.26	0	10.77	
SMC NC 04	64.37	3.59	3.98	7.34	5.58	0.88	0	0	14.25	
SMC NC 05	63.53	3.15	7.56	3.98	8.64	0.89	0.82	0.07	11.35	

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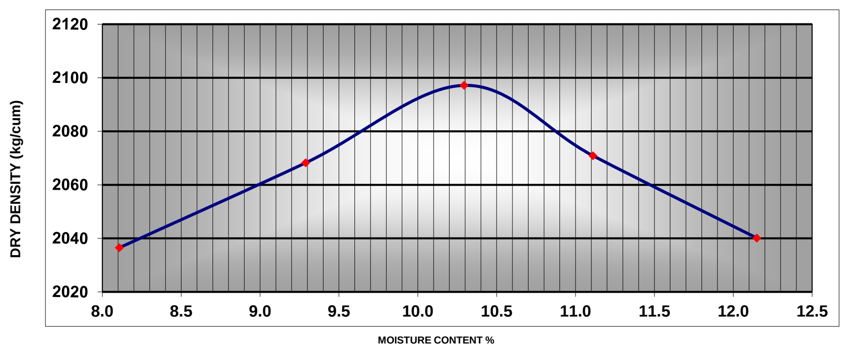
Contractor:	**MASFOS CONSTRUCTION**	**Test Ref.No :**	**Outfall Channell Berm**
Project:	**TAILINGS STORAGE FACILITIES**	**Sampled by:**	**S MANYIKA**
MOISTURE DENSITY RELATION		**Date of Sampled:**	**17.06.2022**
SANS 3001 : GR30 - 2015		**Date of Test:**	**20.06.2022**

Compaction Effort	**Modified AASHTO**				
Sample No.		**Location**	**Outfall Channell Berm**	**Chainage**	**CH: 0+240-0+360**
Material	**insitu**			**Layer No.**	**Layer 3**
		Mould Wt. g	**4907**	**Mould vol cm^3**	**2316**

Determination No.	**1**	**2**	**3**	**4**	**5**		
Wt. of wet soil + Mold g	**10006**	**10142**	**10264**	**10236**	**10206**		
Wt. of wet soil g	**5099**	**5235**	**5357**	**5329**	**5299**		
Wet density kg/m^3	**2202**	**2260**	**2313**	**2301**	**2288**		
Dry density (γ) kg/m^3	**2037**	**2068**	**2097**	**2071**	**2040**		

Moisture Content % (D1)	**8**	**9**	**10**	**11**	**12**		
Container No.	**A**	**B**	**C**	**D**	**E**		
Wt. of container g	**104**	**105**	**105**	**104**	**107**		
Wt. of wet soil + Container g	**704**	**705**	**705**	**704**	**707**		
Wt. of dry soil + Container g	**659.0**	**654.0**	**649.0**	**644.0**	**642.0**		
Wt. of dry soil g	**555.0**	**549.0**	**544.0**	**540.0**	**535.0**		
Moisture content % (D) g	**8.1**	**9.3**	**10.3**	**11.1**	**12.1**		
Hygro (D-D1)	**0.1**	**0.3**	**0.3**	**0.1**	**0.1**		



M.D.D (kg/m^3)	**2097**	**O.M.C %**	**10.3**

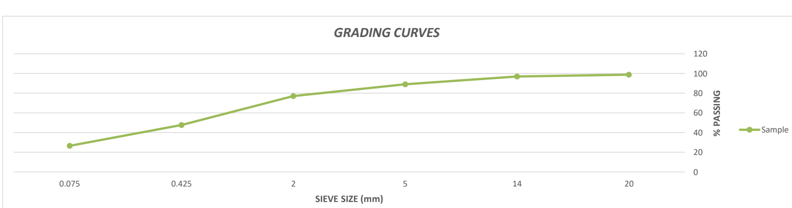
REMARKS

Tested by	**S. MANYIKA**		
Checked by	**P. MANGUDYA**		
Date	**20.06.22**		

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	**Ref No.**	
Contractor :	MASFOS	**Source**	CH 0+240-0+360
Sample :	Outfall Channell Berm	**Date**	20.06.2022

SIEVE SIZE	% Passing LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			
20			98.8
14			97
5			89.1
2			77
0.425			47.6
0.075			26.5



TESTED BY	**S. MANYIKA**	**DATE: 20-06-22**
CHECKED BY	**P. MANGUDYA**	**DATE: 20-06-22**

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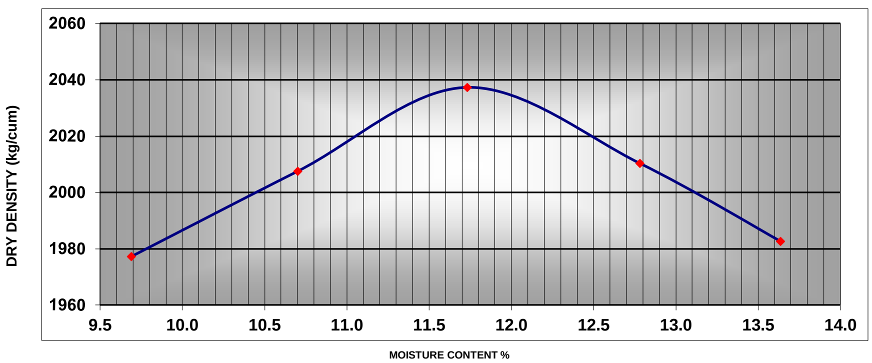
Contractor:	MASFOS CONSTRUCTION	Test Ref.No :	Penstock Line 1
Project:	TAILINGS STORAGE FACILITIES	Sampled by:	P MANGUDYA
MOISTURE DENSITY RELATION SANS 3001 : GR30 - 2015		Date of Sampled:	31.05.2022
		Date of Test:	03.06.2022

Compaction Effort	Modified AASHTO				
Sample No.		Location	Penstock line 1	Chainage	CH:0+090-0+120
Material	insitu			Layer No.	insitu
		Mould Wt. g	4907	Mould vol cm^3	2316

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	9930	10054	10179	10158	10125		
Wt. of wet soil g	5023	5147	5272	5251	5218		
Wet density kg/m^3	2169	2222	2276	2267	2253		
Dry density (γ) kg/m^3	1977	2008	2037	2010	1983		

Moisture Content % (D1)	7	8	9	10	11		
Container No.	A	B	C	D	E		
Wt. of container g	134	134	134	130	130		
Wt. of wet soil + Container g	734	734	734	730	730		
Wt. of dry soil + Container g	681.0	676.0	671.0	662.0	658.0		
Wt. of dry soil g	547.0	542.0	537.0	532.0	528.0		
Moisture content % (D) g	9.7	10.7	11.7	12.8	13.6		
Hygro (D-D1)	2.7	2.7	2.7	2.8	2.6		



M.D.D (kg/m^3)	2037	O.M.C %	11.7

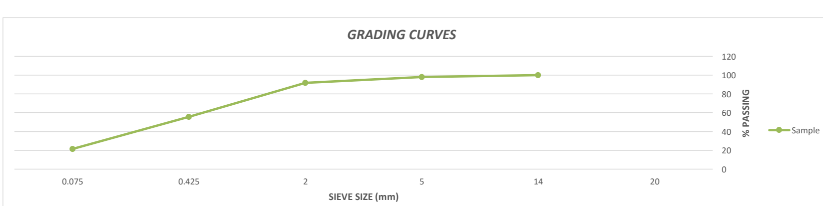
REMARKS

Tested by	S. MANYIKA		
Checked by	P. MANGUDYA		
Date	03.06.2022		

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	Ref No.	
Contractor :	MASFOS	Source	CH:0+090-0+120
Sample :	Penstock line 1	Date	03.06.2022

	% Passing		
SIEVE SIZE	LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			
20			
14			100
5			98
2			91.8
0.425			55.6
0.075			21.5



TESTED BY	S. MANYIKA	DATE: 03-06-22
CHECKED BY	P. MANGUDYA	DATE: 03-06-22

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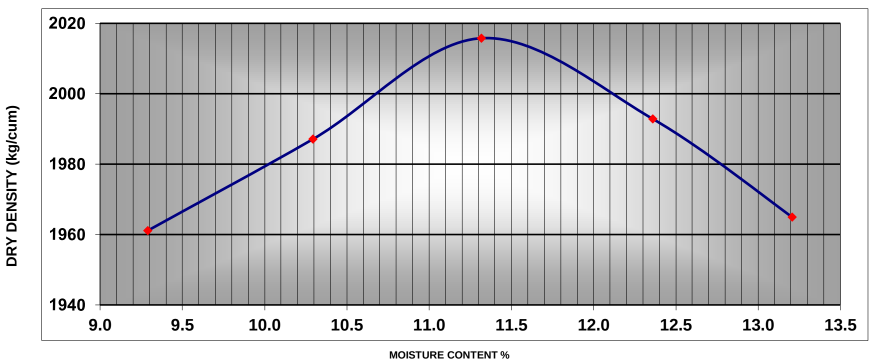
Contractor:	MASFOS CONSTRUCTION	Test Ref.No :	Penstock Line 1
Project:	TAILINGS STORAGE FACILITIES	Sampled by:	P MANGUDYA
MOISTURE DENSITY RELATION		Date of Sampled:	31.05.2022
SANS 3001 : GR30 - 2015		Date of Test:	03.06.2022

Compaction Effort	Modified AASHTO				
Sample No.		Location	Penstock line 1	Chainage	CH:0+090-0+120
Material	insitu			Layer No.	insitu
		Mould Wt. g	4907	Mould vol cm^3	2316

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	9871	9983	10104	10093	10059		
Wt. of wet soil g	4964	5076	5197	5186	5152		
Wet density kg/m^3	2143	2192	2244	2239	2225		
Dry density (γ) kg/m^3	1961	1987	2016	1993	1965		

Moisture Content % (D1)	7	8	9	10	11		
Container No.	A	B	C	D	E		
Wt. of container g	130	134	134	130	134		
Wt. of wet soil + Container g	730	734	734	730	734		
Wt. of dry soil + Container g	679.0	678.0	673.0	664.0	664.0		
Wt. of dry soil g	549.0	544.0	539.0	534.0	530.0		
Moisture content % (D) g	9.3	10.3	11.3	12.4	13.2		
Hygro (D-D1)	2.3	2.3	2.3	2.4	2.2		



M.D.D (kg/m^3)	2016	O.M.C %	11.3

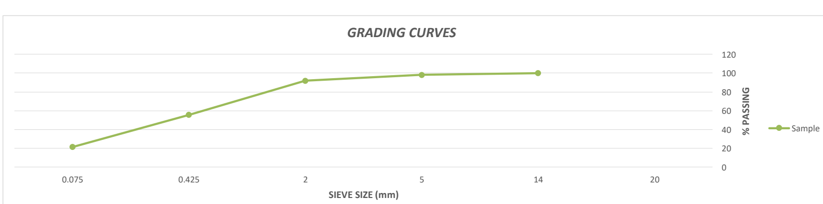
REMARKS

Tested by	S. MANYIKA
Checked by	P. MANGUDYA
Date	03.06.2022

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	Ref No.	
Contractor :	MASFOS	Source	CH:0+090-0+120
Sample :	Penstock line 1	Date	03.06.2022

	% Passing		
SIEVE SIZE	LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			
20			
14			100
5			98
2			91.8
0.425			55.6
0.075			21.5



TESTED BY	S. MANYIKA	DATE: 03-06-22
CHECKED BY	P. MANGUDYA	DATE: 03-06-22

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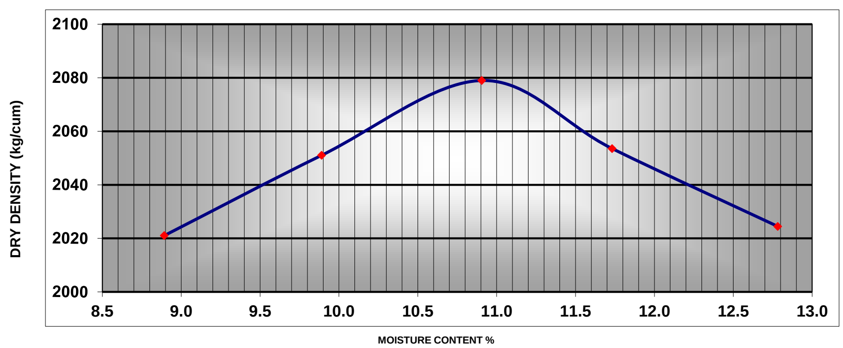
Contractor:	MASFOS CONSTRUCTION	Test Ref.No :	Outfall Channell Berm
Project:	TAILINGS STORAGE FACILITIES	Sampled by:	S MANYIKA
		Date of Sampled:	17.06.2022
		Date of Test:	20.06.2022

MOISTURE DENSITY RELATION
SANS 3001 : GR30 - 2015

Compaction Effort	Modified AASHTO				
Sample No.		Location	Outfall Channell Berm	Chainage	CH: 0+240-0+360
Material	insitu			Layer No.	Layer 3
		Mould Wt. g	4907	Mould vol cm^3	2316

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	10004	10127	10247	10221	10195		
Wt. of wet soil g	5097	5220	5340	5314	5288		
Wet density kg/m^3	2201	2254	2306	2294	2283		
Dry density (γ) kg/m^3	2021	2051	2079	2054	2024		

Moisture Content % (D1)	8	9	10	11	12		
Container No.	A	B	C	D	E		
Wt. of container g	104	105	105	104	107		
Wt. of wet soil + Container g	704	705	705	704	707		
Wt. of dry soil + Container g	655.0	651.0	646.0	641.0	639.0		
Wt. of dry soil g	551.0	546.0	541.0	537.0	532.0		
Moisture content % (D) g	8.9	9.9	10.9	11.7	12.8		
Hygro (D-D1)	0.9	0.9	0.9	0.7	0.8		



M.D.D (kg/m^3)	2079	O.M.C %	10.9

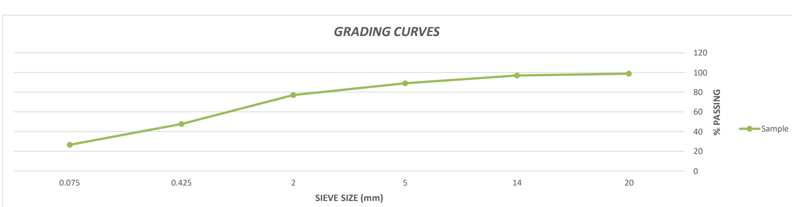
REMARKS

Tested by	S. MANYIKA
Checked by	P. MANGUDYA
Date	20.06.22

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	Ref No.	
Contractor :	MASFOS	Source	CH 0+240-0+360
Sample :	Outfall Channell Berm	Date	20.06.2022

	% Passing		
SIEVE SIZE	LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			
20			98.8
14			97
5			89.1
2			77
0.425			47.6
0.075			26.5



TESTED BY	S. MANYIKA	DATE: 20-06-22
CHECKED BY	P. MANGUDYA	DATE: 20-06-22

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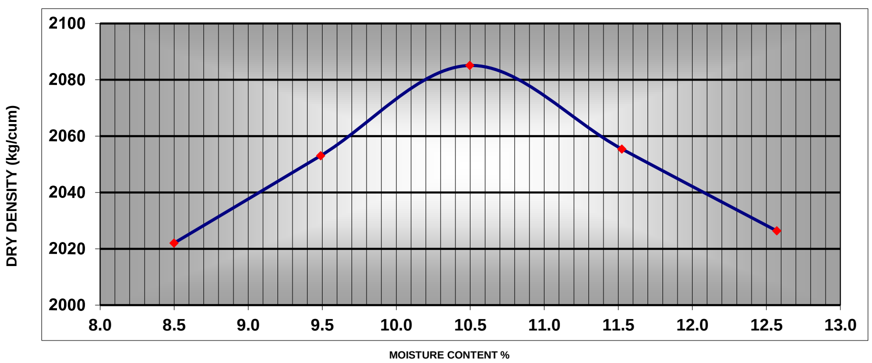
Contractor:	MASFOS CONSTRUCTION	Test Ref.No :	Outfall Channell Berm
Project:	TAILINGS STORAGE FACILITIES	Sampled by:	S MANYIKA
MOISTURE DENSITY RELATION SANS 3001 : GR30 - 2015		Date of Sampled:	29.06.2022
		Date of Test:	04.07.2022

Compaction Effort	Modified AASHTO					
Sample No.		Location	Outfall Channell Berm		Chainage	CH: 0+120-0+240
Material	insitu				Layer No.	Layer 5
			Mould Wt. g	4907	Mould vol cm^3	2316

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	9988	10113	10243	10216	10190		
Wt. of wet soil g	5081	5206	5336	5309	5283		
Wet density kg/m^3	2194	2248	2304	2292	2281		
Dry density (γ) kg/m^3	2022	2053	2085	2055	2026		

Moisture Content % (D1)	7	8	9	10	11		
Container No.	A	B	C	D	E		
Wt. of container g	104	105	104	105	107		
Wt. of wet soil + Container g	704	705	704	705	707		
Wt. of dry soil + Container g	657.0	653.0	647.0	643.0	640.0		
Wt. of dry soil g	553.0	548.0	543.0	538.0	533.0		
Moisture content % (D) g	8.5	9.5	10.5	11.5	12.6		
Hygro (D-D1)	1.5	1.5	1.5	1.5	1.6		



M.D.D (kg/m^3)	2085	O.M.C %	10.5

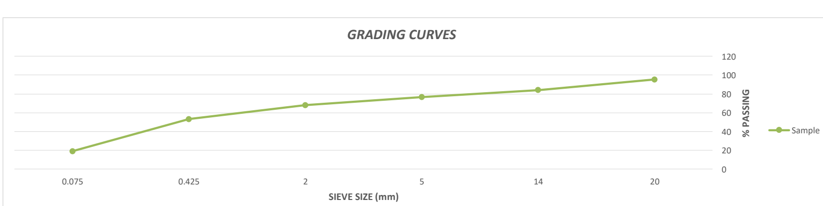
REMARKS

Tested by	S. MANYIKA
Checked by	P. MANGUDYA
Date	20.06.22

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	Ref No.	
Contractor :	MASFOS	Source	CH 0+120-0+240
Sample :	Outfall Channell Berm	Date	20.06.2022

SIEVE SIZE	% Passing LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			
20			95.3
14			84.2
5			76.7
2			68.1
0.425			53.2
0.075			19



TESTED BY	S. MANYIKA	DATE: 01-07-22
CHECKED BY	P. MANGUDYA	DATE: 04-07-22

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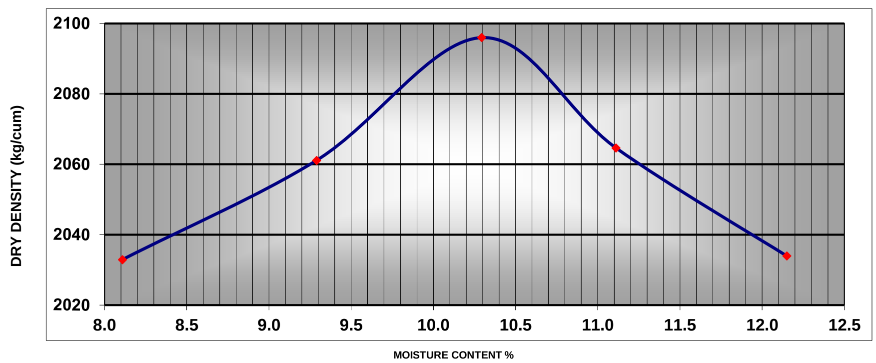
Contractor:	MASFOS CONSTRUCTION					Test Ref.No :	Outfall Channell Berm
Project:	TAILINGS STORAGE FACILITIES					Sampled by:	S MANYIKA
MOISTURE DENSITY RELATION SANS 3001 : GR30 - 2015						Date of Sampled:	29.06.2022
						Date of Test:	04.07.2022
Compaction Effort	Modified AASHTO						
Sample No.		Location	Outfall Channell Berm			Chainage	CH: 0+120-0+240
Material	insitu					Layer No.	Layer 5
			Mould Wt. g	4907		Mould vol cm^3	2316

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	9997	10124	10261	10220	10190		
Wt. of wet soil g	5090	5217	5354	5313	5283		
Wet density kg/m^3	2198	2253	2312	2294	2281		
Dry density (γ) kg/m^3	2033	2061	2096	2065	2034		
Moisture Content % (D1)	7	8	9	10	11		
Container No.	A	B	C	D	E		
Wt. of container g	104	105	105	104	107		
Wt. of wet soil + Container g	704	705	705	704	707		
Wt. of dry soil + Container g	659.0	654.0	649.0	644.0	642.0		
Wt. of dry soil g	555.0	549.0	544.0	540.0	535.0		
Moisture content % (D) g	8.1	9.3	10.3	11.1	12.1		
Hygro (D-D1)	1.1	1.3	1.3	1.1	1.1		



M.D.D (kg/m^3)	2096	O.M.C %	10.3

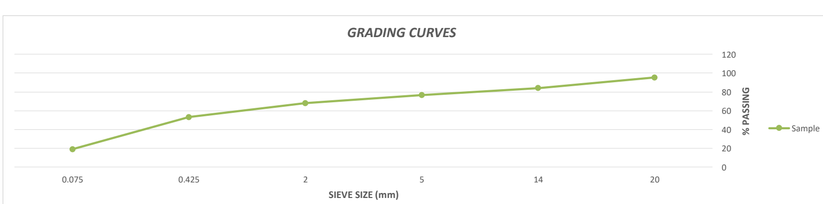
REMARKS

Tested by	S. MANYIKA		
Checked by	P. MANGUDYA		
Date	20.06.22		

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	Ref No.	
Contractor :	MASFOS	Source	CH 0+120-0+240
Sample :	Outfall Channell Berm	Date	20.06.2022

SIEVE SIZE	% Passing LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			
20			95.3
14			84.2
5			76.7
2			68.1
0.425			53.2
0.075			19



TESTED BY	S. MANYIKA	DATE: 01-07-22
CHECKED BY	P. MANGUDYA	DATE: 04-07-22

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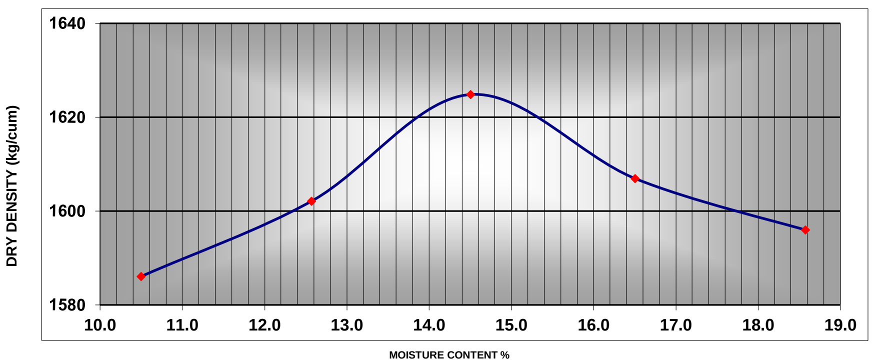
Contractor:	MASFOS CONSTRUCTION	Test Ref.No :	Access Road 1 East
Project:	TAILINGS STORAGE FACILITIES	Sampled by:	P MANGUDYA
MOISTURE DENSITY RELATION SANS 3001 : GR30 - 2015		Date of Sampled:	18.05.2022
		Date of Test:	23.05.2022

Compaction Effort	Modified AASHTO				
Sample No.		Location	Acces Road 1 East	Chainage	CH:0+2800-0+2960
Material	Subgrade			Layer No.	Subgrade
		Mould Wt. g	4907	Mould vol cm^3	2316

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	8966	9084	9216	9243	9290		
Wt. of wet soil g	4059	4177	4309	4336	4383		
Wet density kg/m^3	1753	1804	1861	1872	1892		
Dry density (γ) kg/m^3	1586	1602	1625	1607	1596		

Moisture Content % (D1)	5	7	9	11	13		
Container No.	A	B	C	D	E		
Wt. of container g	130	137	130	137	130		
Wt. of wet soil + Container g	730	737	730	737	730		
Wt. of dry soil + Container g	673.0	670.0	654.0	652.0	636.0		
Wt. of dry soil g	543.0	533.0	524.0	515.0	506.0		
Moisture content % (D) g	10.5	12.6	14.5	16.5	18.6		
Hygro (D-D1)	5.5	5.6	5.5	5.5	5.6		



M.D.D (kg/m^3)	1625	O.M.C %	14.5

REMARKS

Tested by	S. MANYIKA
Checked by	P. MANGUDYA
Date	24.05.2022

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	Ref No.	
Contractor :	MASFOS	Source	CH:0+2800-0+2960
Sample :	Access Road 1 East	Date	23.05.2022

	% Passing		
SIEVE SIZE	LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			
20			100
14			99.6
5			99.3
2			99
0.425			97.1
0.075			80.5

TESTED BY	S. MANYIKA	DATE: 23-05-22
CHECKED BY	P. MANGUDYA	DATE: 24-05-22

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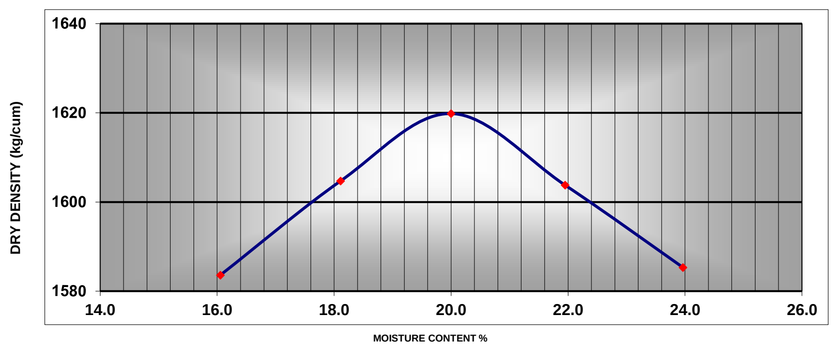
Contractor:	MASFOS CONSTRUCTION	Test Ref.No :	Access Road 1 East
Project:	TAILINGS STORAGE FACILITIES	Sampled by:	T. NYAZIKA
MOISTURE DENSITY RELATION SANS 3001 : GR30 - 2015		Date of Sampled:	14.05.2022
		Date of Test:	17.05.2022

Compaction Effort	Modified AASHTO				
Sample No.		Location	Acces Road 1 East	Chainage	CH:0+2980-0+3160
Material	Subgrade			Layer No.	Subgrade
		Mould Wt. g	4824	Mould vol cm^3	2331

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	9108	9242	9355	9383	9405		
Wt. of wet soil g	4284	4418	4531	4559	4581		
Wet density kg/m^3	1838	1895	1944	1956	1965		
Dry density (γ) kg/m^3	1584	1605	1620	1604	1585		

Moisture Content % (D1)	7	9	11	13	15		
Container No.	A	B	C	D	E		
Wt. of container g	70	75	70	70	70		
Wt. of wet soil + Container g	670	675	670	670	670		
Wt. of dry soil + Container g	587.0	583.0	570.0	562.0	554.0		
Wt. of dry soil g	517.0	508.0	500.0	492.0	484.0		
Moisture content % (D) g	16.1	18.1	20.0	22.0	24.0		
Hygro (D-D1)	9.1	9.1	9.0	9.0	9.0		



M.D.D (kg/m^3)	1620		O.M.C %	20.0

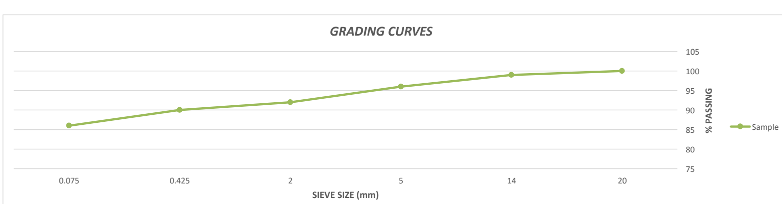
REMARKS

Tested by	S. MANYIKA		
Checked by	P. MANGUDYA		
Date	17.05.2022		

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	Ref No.	
Contractor :	MASFOS	Source	CH:0+2980-0+3160
Sample :	Access Road 1 East	Date	17.05.2022

	% Passing		
SIEVE SIZE	LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			100
26.5			100
20			100
14			99
5			96
2			92
0.425			90
0.075			86



TESTED BY	S. MANYIKA	DATE: 17-05-22
CHECKED BY	P. MANGUDYA	DATE: 17-05-22

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Stand No 11071 ,
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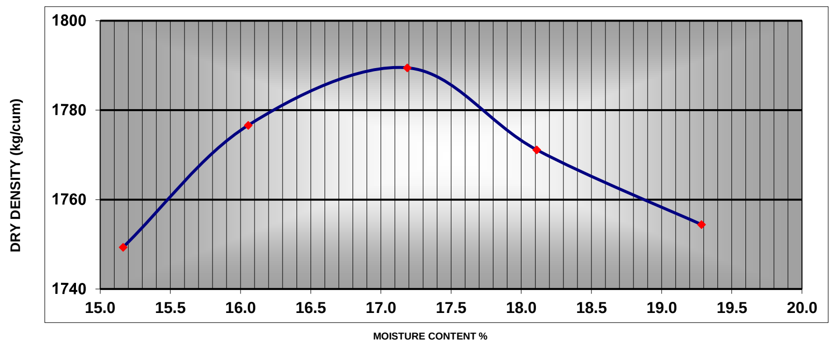
Harare

+263 772 801 110/ +263 778 475 396

Contractor:	MASFOS CONSTRUCTION	Test Ref.No :	Access Rd 1 West 2
Project:	TAILINGS STORAGE FACILITIES	Sampled by:	T NYAZIKA
MOISTURE DENSITY RELATION		Date of Sampled:	24.03.2022
SANS 3001 : GR30 - 2015		Date of Test:	25.03.2022

Compaction Effort	Modified AASHTO				
Sample No.		Location	Acces Road 1 west	Chainage	CH280-CH480
Material	Subgrade			Layer No.	Subgrade
		Mould Wt. g	4850	Mould vol cm^3	2329

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	9542	9652	9734	9722	9724		
Wt. of wet soil g	4692	4802	4884	4872	4874		
Wet density kg/m^3	2015	2062	2097	2092	2093		
Dry density (γ) kg/m^3	1749	1777	1789	1771	1754		
Moisture Content % (D1)	11	12	13	14	15		
Container No.	A	B	C	D	E		
Wt. of container g	75	75	75	75	75		
Wt. of wet soil + Container g	675	675	675	675	675		
Wt. of dry soil + Container g	596.0	592.0	587.0	583.0	578.0		
Wt. of dry soil g	521.0	517.0	512.0	508.0	503.0		
Moisture content % (D) g	15.2	16.1	17.2	18.1	19.3		
Hygro (D-D1)	4.2	4.1	4.2	4.1	4.3		



M.D.D (kg/m^3)	1789	O.M.C %	17.1

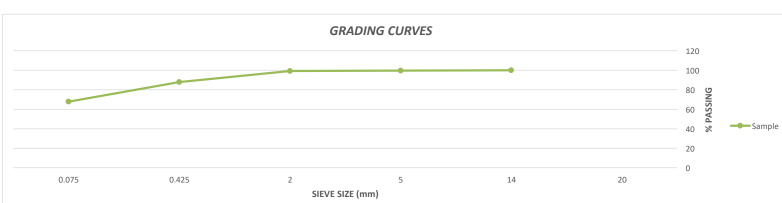
REMARKS

Tested by	S. MANYIKA	
Checked by	P. MANGUDYA	
Date	28.03.2022	

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	Ref No.	
Contractor :	MASFOS	Source	CH280-CH480
Sample :	Access Road 1 West Sample 3	Date :	25.03.2022

SIEVE SIZE	% Passing LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			
20			
14			100
5			99.6
2			99.2
0.425			87.9
0.075			67.8



TESTED BY	S. MANYIKA	DATE: 25-03-22
CHECKED BY	P. MANGUDYA	DATE: 28-03-22

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Harare

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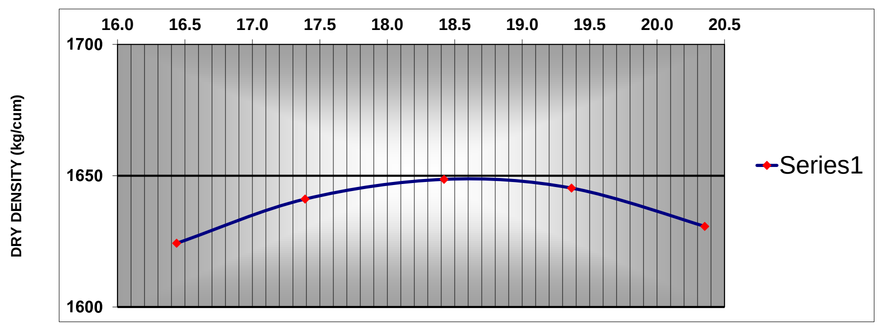
Contractor:	Masimba/Fossil Joint Venture	Test Ref.No :	Access Rd 1 East 3
Project:	TAILINGS STORAGE FACILITIES	Sampled by:	B Majukwa
MOISTURE DENSITY RELATION SANS 3001 : GR30 - 2015		Date of Sampled:	17.02.2022
		Date of Test:	19.02.2022

Compaction Effort	Modified AASHTO				
Sample No.	TSF0009	Location	Access Road 1 East Sample 3	Chainage	TBA
Material	Brown Gravelly Clay {Insitu}			Layer No.	Subgrade
		Mould Wt. g	4916	Mould vol cm^3	2327

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	9317	9399	9459	9486	9483		
Wt. of wet soil g	4401	4483	4543	4570	4567		
Wet density kg/m^3	1891	1927	1952	1964	1963		
Dry density (γ) kg/m^3	1624	1641	1649	1645	1631		

Moisture Content % (D1)	10	11	12	13	14		
Container No.	A	B	C	D	E		
Wt. of container g	75	75	70	72	75		
Wt. of wet soil + Container g	755	750	745	750	755		
Wt. of dry soil + Container g	659.0	650.0	640.0	640.0	640.0		
Wt. of dry soil g	584.0	575.0	570.0	568.0	565.0		
Moisture content % (D) g	16.4	17.4	18.4	19.4	20.4		
Hygro (D-D1)	6.4	6.4	6.4	6.4	6.4		



MOISTURE CONTENT %

M.D.D (kg/m^3)	1649	O.M.C %	18.4

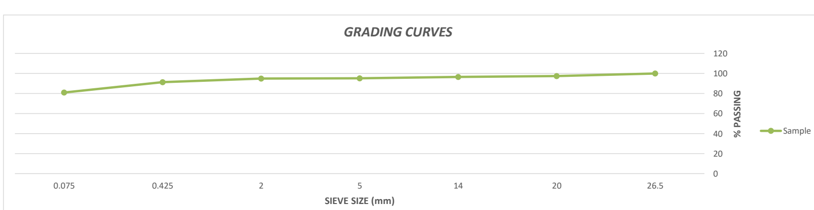
REMARKS

Tested by	D Nyazema
Checked by	O Mutunduru
Date	21.02.2022

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	**Ref No.**	TSF0009
Contractor :	MASFOS	**Source**	
Sample :	Access Road 1 East Sample 3	**Date :**	19.02.2022

	% Passing		
SIEVE SIZE	LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			100
20			97.5
14			96.6
5			95.2
2			94.9
0.425			91.4
0.075			81



TESTED BY	D. NYAZEMA	DATE : 19-02-22
CHECKED BY	W. MUTUNDURU	DATE : 19-02-22

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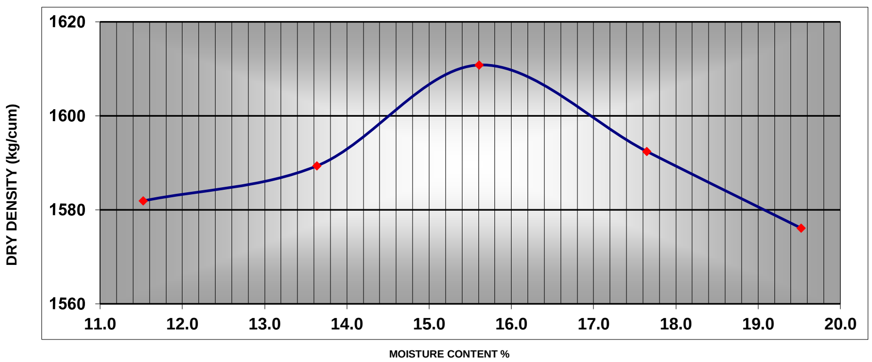
Contractor:	MASFOS CONSTRUCTION	Test Ref.No :	Access Road 1 East
Project:	TAILINGS STORAGE FACILITIES	Sampled by:	P MANGUDYA
MOISTURE DENSITY RELATION SANS 3001 : GR30 - 2015		Date of Sampled:	18.05.2022
		Date of Test:	23.05.2022

Compaction Effort	Modified AASHTO				
Sample No.		Location	Acces Road 1 East	Chainage	CH:0+2800-0+2960
Material	Subgrade			Layer No.	Subgrade
		Mould Wt. g	4907	Mould vol cm^3	2316

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	8993	9090	9220	9246	9270		
Wt. of wet soil g	4086	4183	4313	4339	4363		
Wet density kg/m^3	1764	1806	1862	1873	1884		
Dry density (γ) kg/m^3	1582	1589	1611	1592	1576		

Moisture Content % (D1)	5	7	9	11	13		
Container No.	A	B	C	D	E		
Wt. of container g	130	137	137	130	130		
Wt. of wet soil + Container g	730	737	737	730	730		
Wt. of dry soil + Container g	668.0	665.0	656.0	640.0	632.0		
Wt. of dry soil g	538.0	528.0	519.0	510.0	502.0		
Moisture content % (D) g	11.5	13.6	15.6	17.6	19.5		
Hygro (D-D1)	6.5	6.6	6.6	6.6	6.5		



M.D.D (kg/m^3)	1611	O.M.C %	15.6

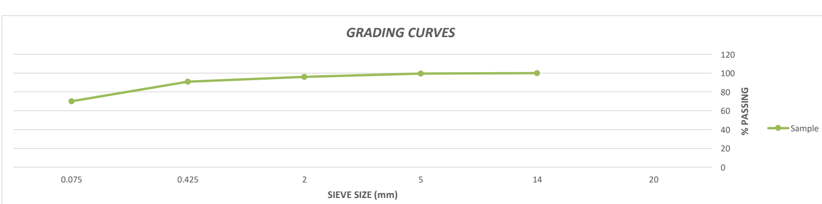
REMARKS

Tested by	S. MANYIKA		
Checked by	P. MANGUDYA		
Date	24.05.2022		

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF		Ref No.	
Contractor :	MASFOS	3333	Source	CH:0+2800-0+2960
Sample :	Access Road 1 East		Date	23.05.2022

SIEVE SIZE	% Passing LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			
20			
14			100
5			99.6
2			96
0.425			91
0.075			70.1



TESTED BY	S. MANYIKA	DATE: 23-05-22
CHECKED BY	P. MANGUDYA	DATE: 24-05-22

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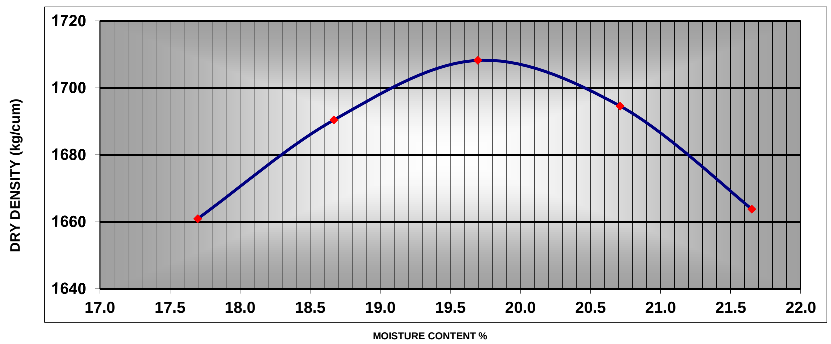
Contractor:	MASFOS CONSTRUCTION	Test Ref.No :	Access Road 1 West
Project:	TAILINGS STORAGE FACILITIES	Sampled by:	D NYAZEMA
MOISTURE DENSITY RELATION		Date of Sampled:	31.03.2022
SANS 3001 : GR30 - 2015		Date of Test:	02.04.2022

Compaction Effort	Modified AASHTO						
Sample No.		Location	Acces Road 1 West			Chainage	CH:0+280-0+360
Material	Subgrade					Layer No.	Subgrade
			Mould Wt. g	4825		Mould vol cm^3	2327

Determination No.	1	2	3	4	5		
Wt. of wet soil + Mold g	9374	9493	9583	9585	9535		
Wt. of wet soil g	4549	4668	4758	4760	4710		
Wet density kg/m^3	1955	2006	2045	2046	2024		
Dry density (γ) kg/m^3	1661	1690	1708	1695	1664		

Moisture Content % (D1)	10	11	12	13	14		
Container No.	A	B	C	D	E		
Wt. of container g	78	72	72	78	75		
Wt. of wet soil + Container g	630	625	625	620	620		
Wt. of dry soil + Container g	547.0	538.0	534.0	527.0	523.0		
Wt. of dry soil g	469.0	466.0	462.0	449.0	448.0		
Moisture content % (D) g	17.7	18.7	19.7	20.7	21.7		
Hygro (D-D1)	7.7	7.7	7.7	7.7	7.7		



M.D.D (kg/m^3)	1708	O.M.C %	19.7

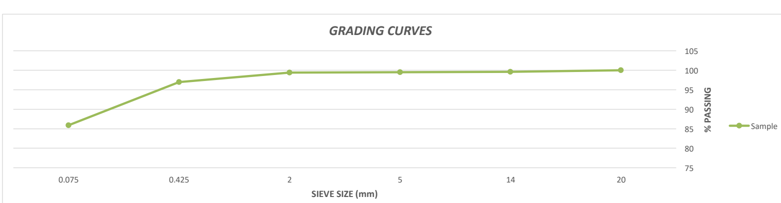
REMARKS

Tested by	S. MANYIKA		
Checked by	P. MANGUDYA		
Date	04.04.2022		

SIEVE ANALYSIS/ GRADING SANS3001-AG1 AND SANS3001-GR10

Project :	SMC - TSF	Ref No.	
Contractor :	MASFOS	Source	CH:0+280-0+360
Sample :	Access Road 1 West	Date	04.04.2022

	% Passing		
SIEVE SIZE	LOWER LIMIT	UPPER LIMIT	SAMPLE
37.5			
26.5			
20			100
14			99.6
5			99.5
2			99.4
0.425			97
0.075			85.9



TESTED BY	S. MANYIKA	DATE: 02-04-22
CHECKED BY	P. MANGUDYA	DATE: 04-04-22

Specialised Testing Laboratory (Pty) Ltd
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Unit 1, 13 Bloubokkie Street, Koedoespoort 0186
Roelof | 072 674 6343 | roelof@stlab.co.za
Gerrie | 082 309 4448 | gerrie@stlab.co.za
www.stlab.co.za

Quality | Excellence | On Time

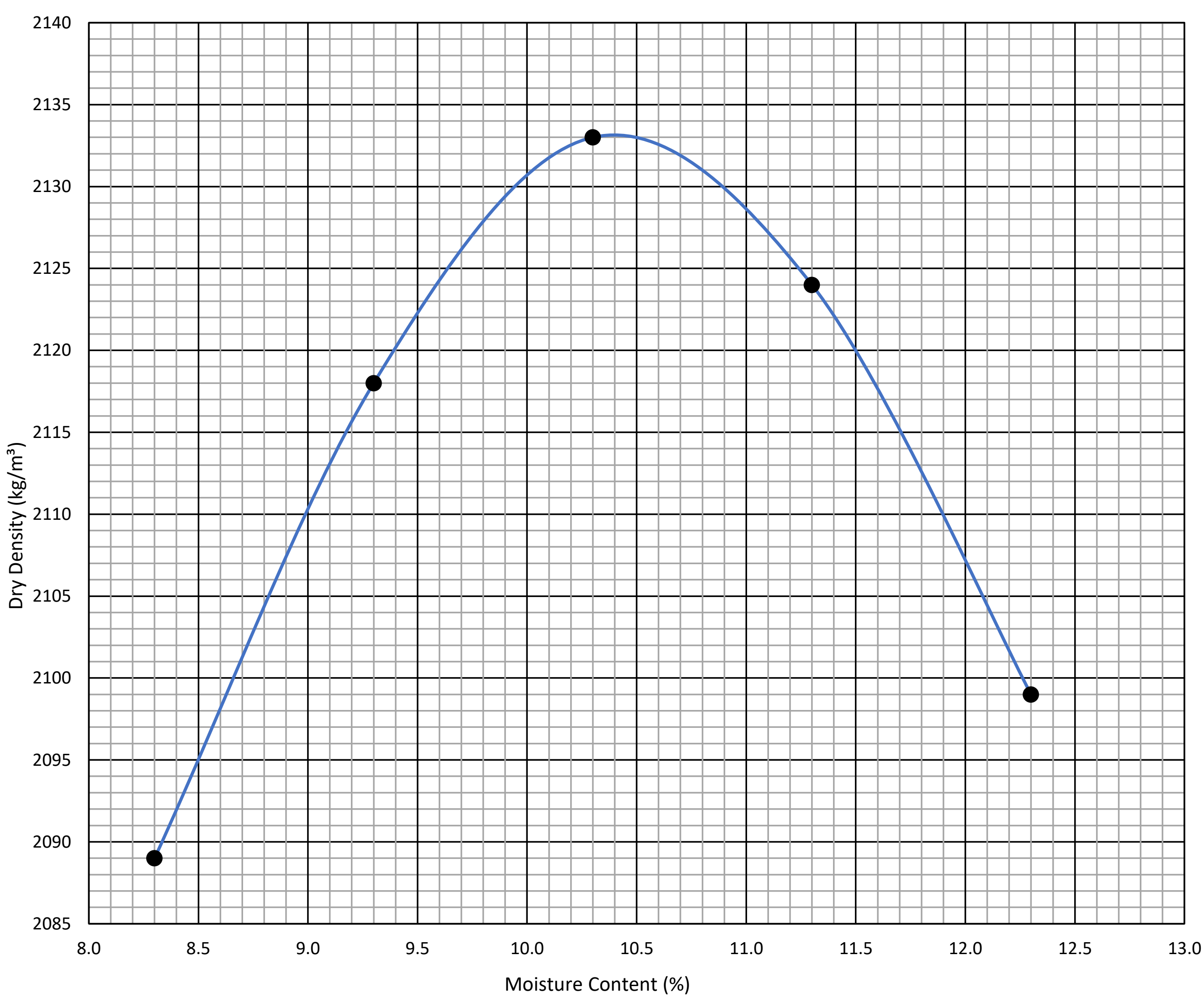
Client Name:	SRK Consulting	**Job Number:**	SRK-110
Project Name:	560333: Mareesburg TSF Phase 4	**Lab Number:**	SRK-110-1651
Sample:	TPA04	**Method:**	SANS 3001 GR30
Depth: (m)	0.9 - 1.2	**Date:**	03-Mar-21

MDD & OMC DETERMINATION (Mod. AASHTO)

Sheet Reference: R-STL-013 Rev01

Maximum Dry Density: **2136** kg/m³ Optimum Moisture Content: **10.4** %

Moisture Content (%)	8.3	9.3	10.3	11.3	12.3			
Dry Density (kg/m³)	2089	2118	2133	2124	2099			



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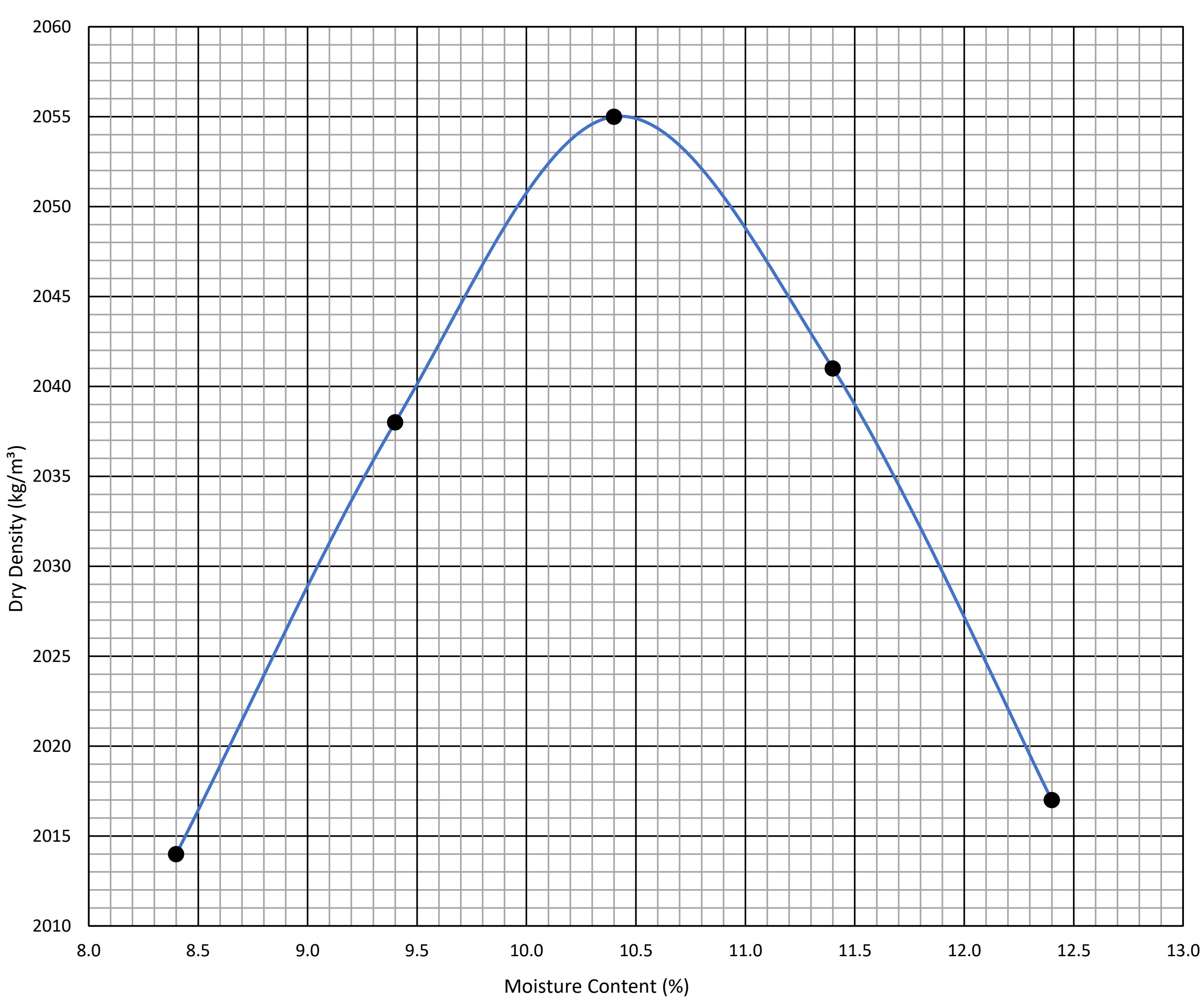
Client Name:	SRK Consulting	**Job Number:**	SRK-110
Project Name:	560333: Mareesburg TSF Phase 4	**Lab Number:**	SRK-110-1652
Sample:	TPA06	**Method:**	SANS 3001 GR30
Depth: (m)	1.2 - 1.6	**Date:**	03-Mar-21

MDD & OMC DETERMINATION (Mod. AASHTO)

Sheet Reference: R-STL-013 Rev01

Maximum Dry Density: **2055** kg/m³ Optimum Moisture Content: **10.4** %

Moisture Content (%)	8.4	9.4	10.4	11.4	12.4			
Dry Density (kg/m³)	2014	2038	2055	2041	2017			



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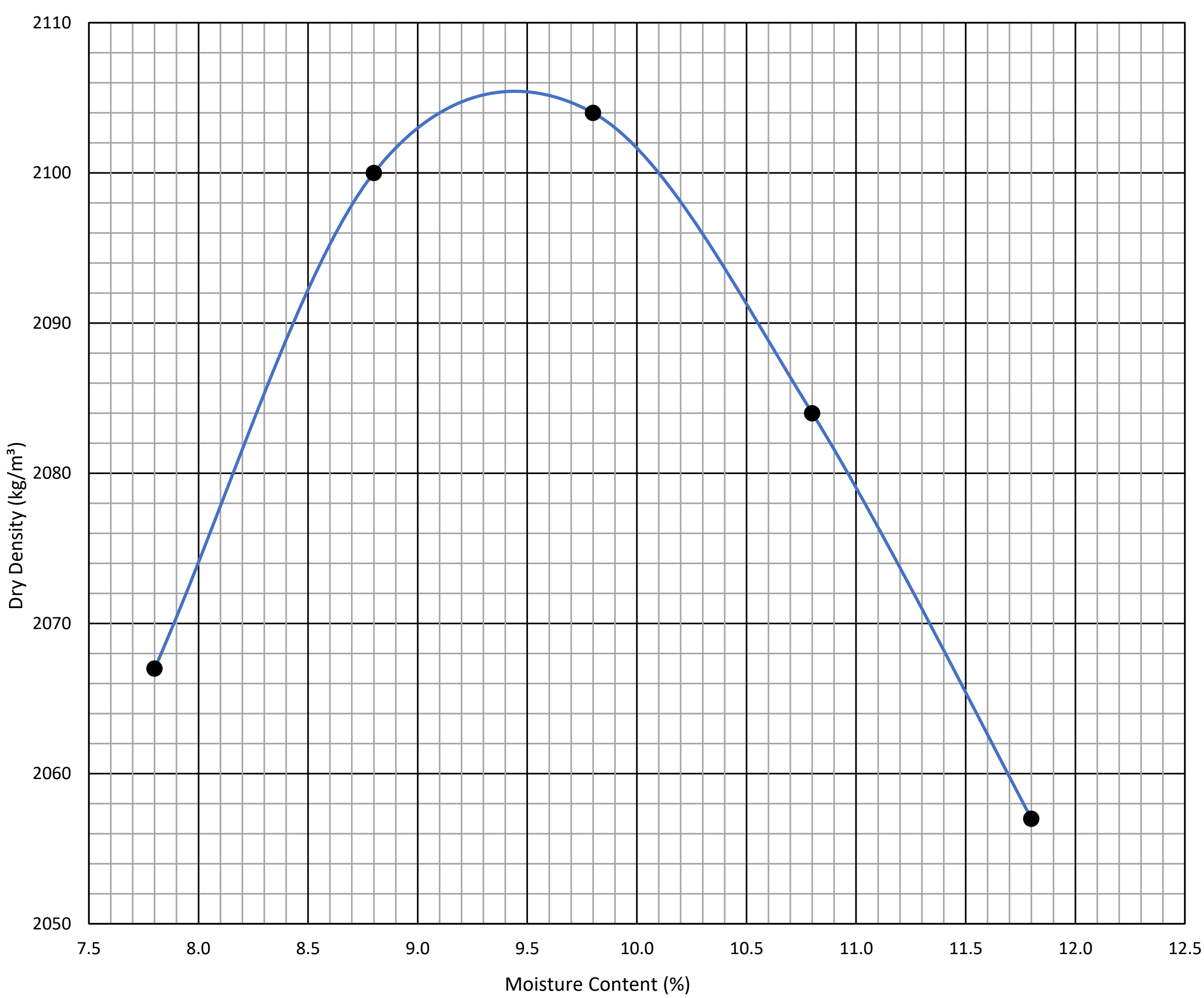
Client Name:	SRK Consulting	**Job Number:**	SRK-110
Project Name:	560333: Mareesburg TSF Phase 4	**Lab Number:**	SRK-110-1653
Sample:	TPA07	**Method:**	SANS 3001 GR30
Depth: (m)	1.0 - 1.5	**Date:**	03-Mar-21

MDD & OMC DETERMINATION (Mod. AASHTO)

Sheet Reference:
R-STL-013 Rev01

Maximum Dry Density: **2108** kg/m³   Optimum Moisture Content: **9.5** %

Moisture Content (%)	7.8	8.8	9.8	10.8	11.8			
Dry Density (kg/m³)	2067	2100	2104	2084	2057			



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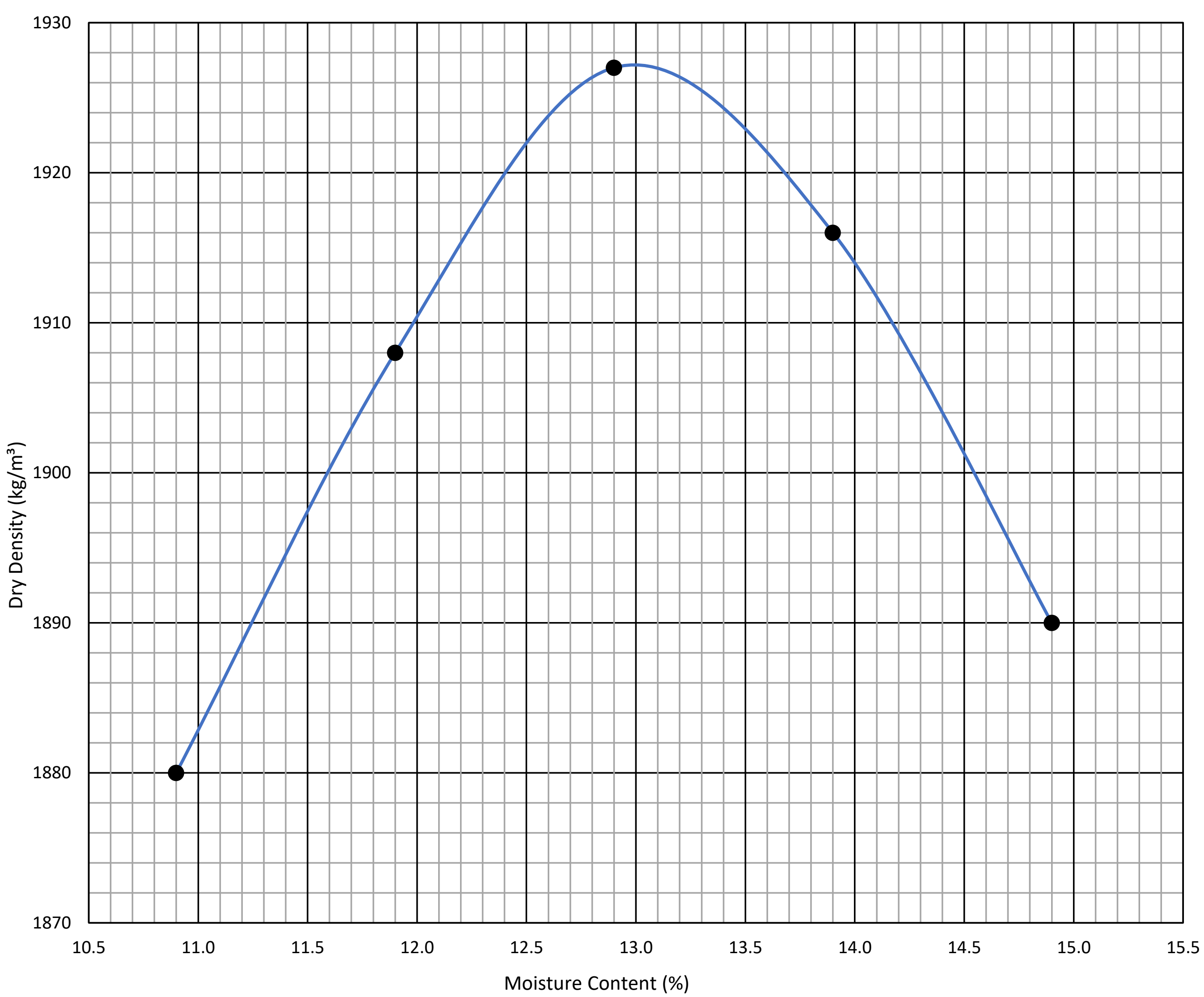
Client Name:	SRK Consulting	**Job Number:**	SRK-110
Project Name:	560333: Mareesburg TSF Phase 4	**Lab Number:**	SRK-110-1664
Sample:	TPB04	**Method:**	SANS 3001 GR30
Depth: (m)	2.7 - 3.0	**Date:**	03-Mar-21

MDD & OMC DETERMINATION (Mod. AASHTO)

Sheet Reference:
R-STL-013 Rev01

Maximum Dry Density: **1930** kg/m³   Optimum Moisture Content: **13.0** %

Moisture Content (%)	10.9	11.9	12.9	13.9	14.9			
Dry Density (kg/m³)	1880	1908	1927	1916	1890			



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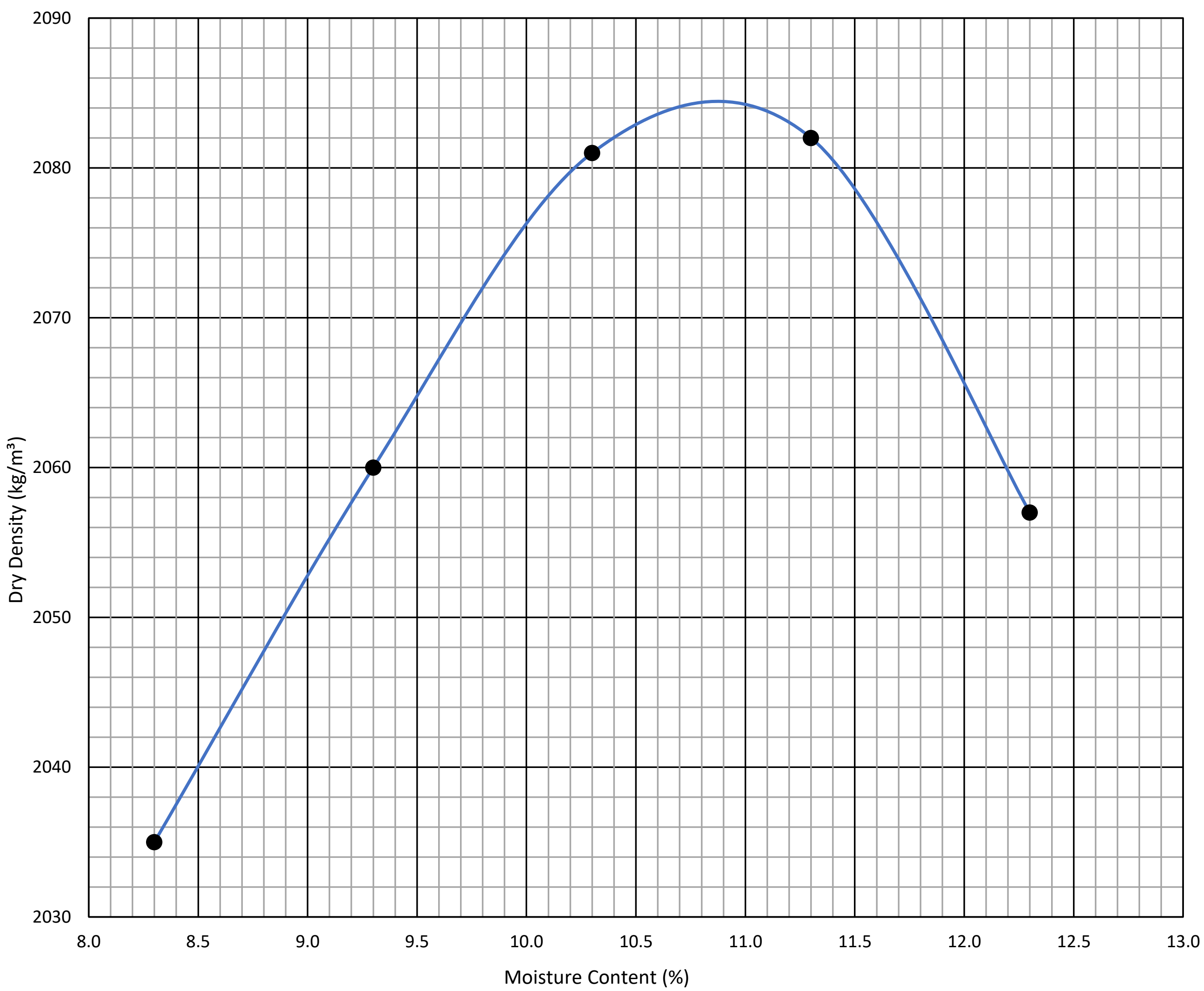
Client Name:	SRK Consulting	**Job Number:**	SRK-110
Project Name:	560333: Mareesburg TSF Phase 4	**Lab Number:**	SRK-110-1654
Sample:	TPA09	**Method:**	SANS 3001 GR30
Depth: (m)	1.8 - 2.2	**Date:**	03-Mar-21

MDD & OMC DETERMINATION (Mod. AASHTO)

Sheet Reference: R-STL-013 Rev01

Maximum Dry Density: **2088** kg/m³ Optimum Moisture Content: **10.9** %

Moisture Content (%)	8.3	9.3	10.3	11.3	12.3			
Dry Density (kg/m³)	2035	2060	2081	2082	2057			



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Gerrie | 082 309 4448 | gerrie@stlab.co.za
www.stlab.co.za

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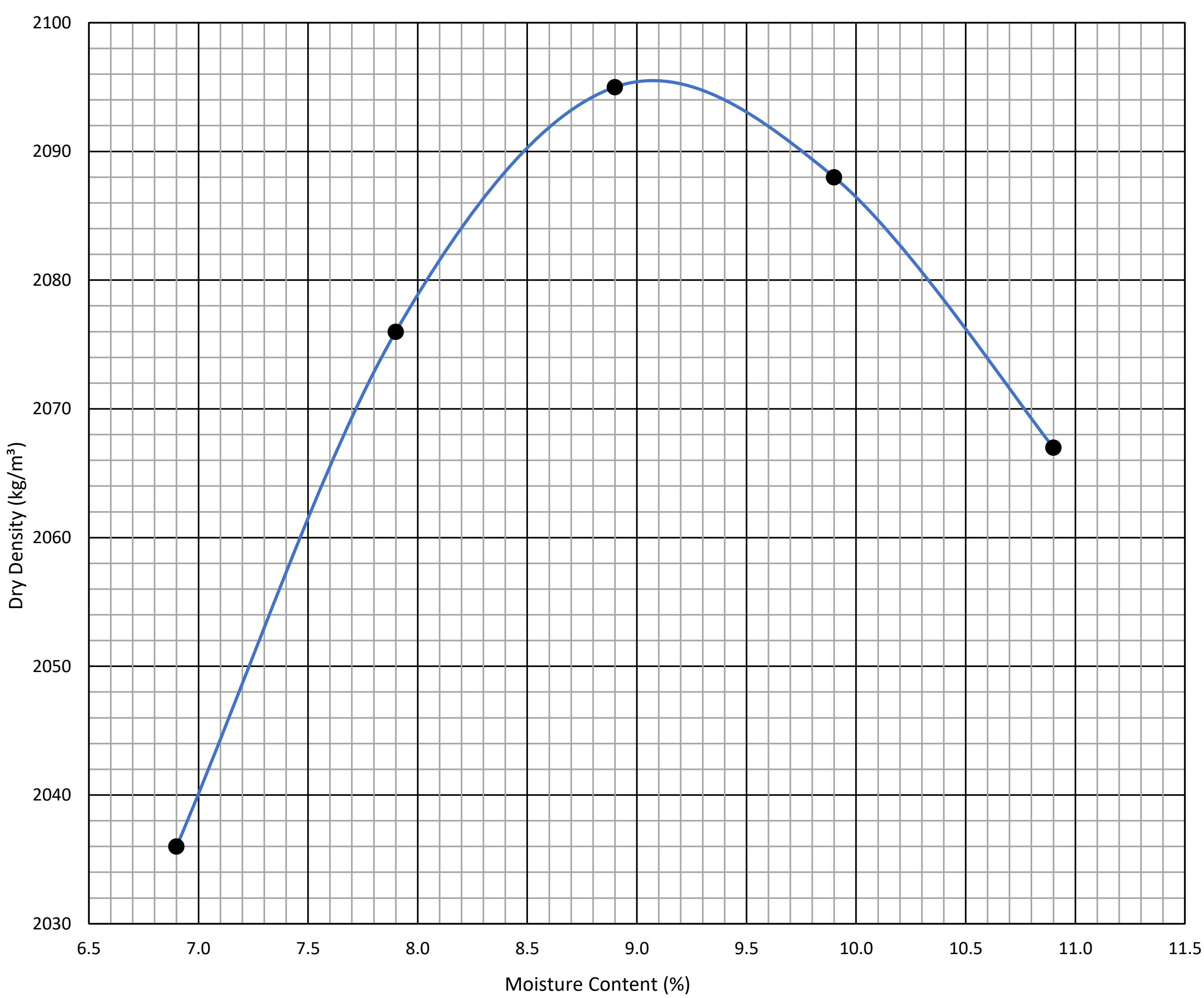
Client Name:	SRK Consulting	**Job Number:**	SRK-110
Project Name:	560333: Mareesburg TSF Phase 4	**Lab Number:**	SRK-110-1649
Sample:	TPA01	**Method:**	SANS 3001 GR30
Depth: (m)	1.0 - 1.4	**Date:**	03-Mar-21

MDD & OMC DETERMINATION (Mod. AASHTO)

Sheet Reference: R-STL-013 Rev01

Maximum Dry Density: **2099** kg/m³ Optimum Moisture Content: **9.1** %

Moisture Content (%)	6.9	7.9	8.9	9.9	10.9			
Dry Density (kg/m³)	2036	2076	2095	2088	2067			



ROADLAB

Roadlab Mareesburg TSF
Phase II
Steelpoort
Tel: +27 74 702 5188 Fax:
Email: florence@roadlab.co.za
Web: www.roadlab.co.za

Job Request No.: L
SRK Consulting Enginners
Stefanutti Mareesburg
Sinnovile
Pretoria
Attention : Mr T Thantsa

Client Ref.No.: L

Date Reported : 2020/07/27

Project : MAREESBURG TSF PHASE II

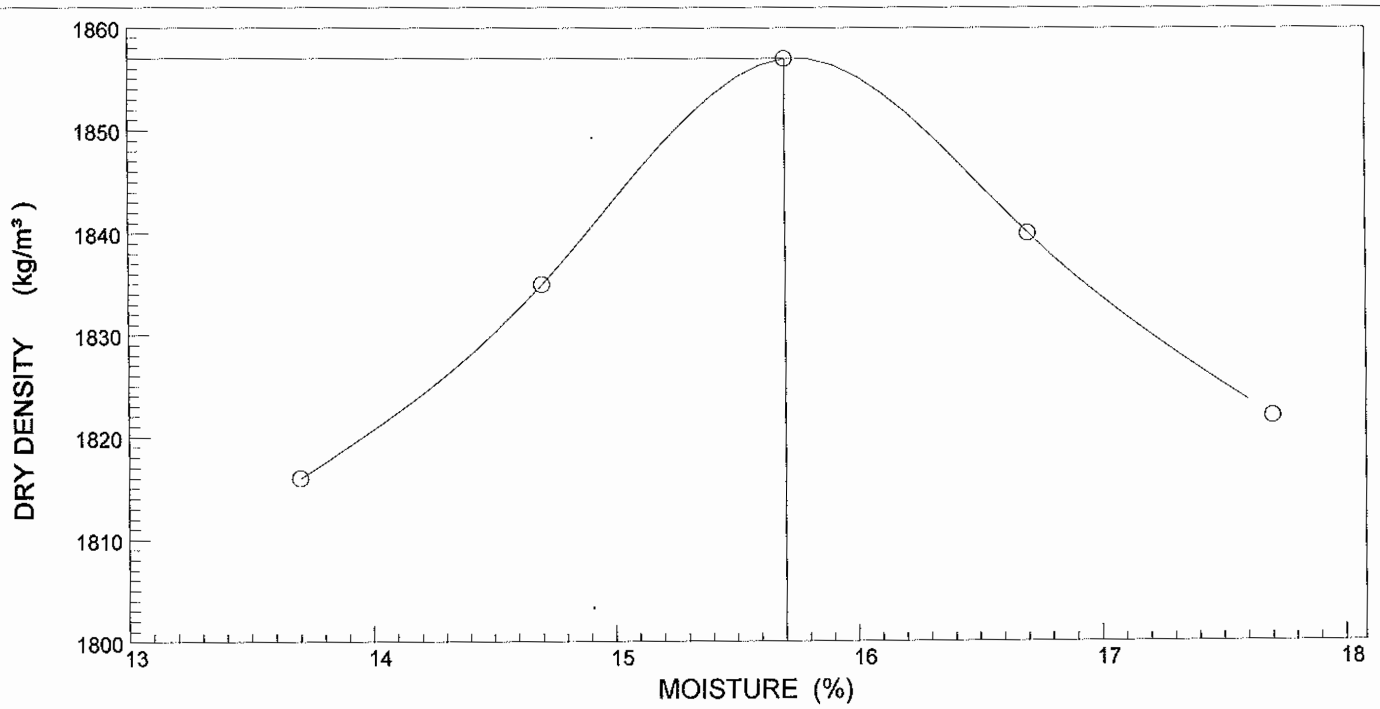
BORROW PIT 3 - MOD TEST RESULTS

SANS 3001-GR30/GR31/GR20

SAMPLE NO.	S503
CONTAINER FOR SAMPLING	Sampling Bag
SIZE / APPROX. MASS OF SAMPLE	50kg
MOISTURE CONDITION OF SAMPLE	Optimum Moist
LAYER TESTED / SAMPLED FROM	Borrow Pit 3
MATERIAL DESCRIPTION	
HOLE NO./ km / CHAINAGE	Excavated Material
ROAD NO.	Borrow Pit 3
DATE RECEIVED	2020/07/25
DATE SAMPLED	2020/07/25
CLIENT MARKING	L
COLOUR AND TYPE	Dark Reddish Weathered Stones

POINT NO.	1	2	3	4	5			
DRY DENSITY (kg/m³)	1816	1835	1857	1840	1822			
MOISTURE (%)	13,7	14,7	15,7	16,7	17,7			

MAXIMUM DRY DENSITY (kg/m³) : 1857	OPTIMUM MOISTURE CONTENT (%) : 15,7



Deviation from Test Method :
Remarks and Notes : Sampled @ 16:00 pm

Report compiled by : Mr A Hlanya

Prog.ver 10.7 (2019/11/07)

Florence Gungqa
Manager

ROADLAB	Laboratory Test Request	Ref: Origin Sequence Request number: L324

Contractor: Stefanutti Stocks Axsys JV

Contracts Number: CMMJV339JV PHASE 2

Work Section/Location or area– Borrow pit 3 – 24/07/2020

Type of Test – Mod, grading & PI

Chainages – Site borrow pit

Date – 24/07/2020

Time– 08:00, 12:00PM & 16:00PM

COMPRESSIVE STRENGHT ON CONCRETE CUBES

Date cast	Cube mark	Number of cubes	Age to be tested	Origin of Cubes	Slump measured	Required strength

Issued by Stefanutti	Received by Laboratory
Request sent by: Omega Mkhabele	Received by...
Date: 24/07/2020 Time: 15:00	Date.......................... Time.........................

Test no	chainage	Offset .m	Type of test							Other-Specify
		Densities	Road indicator	Grading	PI	Proctor	~~CBR~~ Mod	Hydrometer	Concrete cubes/moulds	
1	Borrow Pit 3			X	X		X			3 times a day
2										
3										

Remarks (by Lab)..

Returned by Laboratory	Received by Contractor
Form completed by........Florence........	Return form received by ....
Date 25/07/2020 Time....14h00....................	Date............................. Time................................

ROADLAB

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Web: www.roadlab.co.za

Date Reported : 2020/07/25

Client Ref.No.: L324

Job Request No.: L324
SRK Consulting Enginners
Stefanutti Mareesburg
Sinnovile
Pretoria
Attention : Mr T Thantsa

Project : MAREESBURG TSF PHASE II

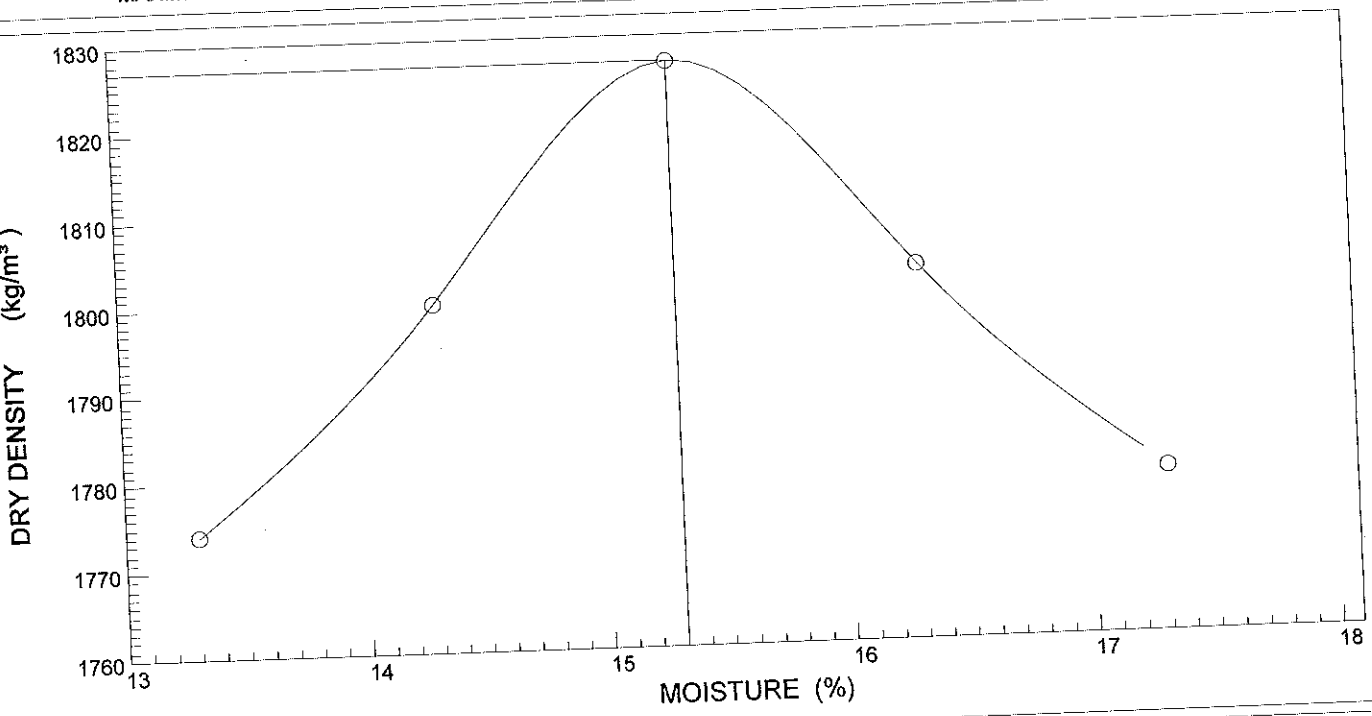
BORROW PIT 3 - MOD TEST RESULTS

SANS 3001-GR30/GR31/GR20

SAMPLE NO.	S481
CONTAINER FOR SAMPLING	Sampling Bag
SIZE / APPROX. MASS OF SAMPLE	50kg
MOISTURE CONDITION OF SAMPLE	Optimum Moist
LAYER TESTED / SAMPLED FROM	Borrow Pit 3
MATERIAL DESCRIPTION	
HOLE NO./ km / CHAINAGE	Excavated Material
ROAD NO.	Borrow Pit 3
DATE RECEIVED	2020/07/24
DATE SAMPLED	2020/07/24
CLIENT MARKING	L324
COLOUR AND TYPE	Light Reddish Quartzitic material

POINT NO.	1	2	3	4	5			
DRY DENSITY (kg/m³)	1774	1800	1827	1803	1779			
MOISTURE (%)	13,3	14,3	15,3	16,3	17,3			

MAXIMUM DRY DENSITY (kg/m³) : 1827 | OPTIMUM MOISTURE CONTENT (%) : 15,3



Deviation from Test Method :
Remarks and Notes : Sampled @ 12:00 pm

Florence Gungqa
Manager

Report compiled by : Miss XF Gungqa

Prog.ver 10.7 (2019/11/07)

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Pretoria
Attention : Mr T Thantsa

Client Ref.No.: L324

Date Reported : 2020/07/25

Project : MAREESBURG TSF PHASE II

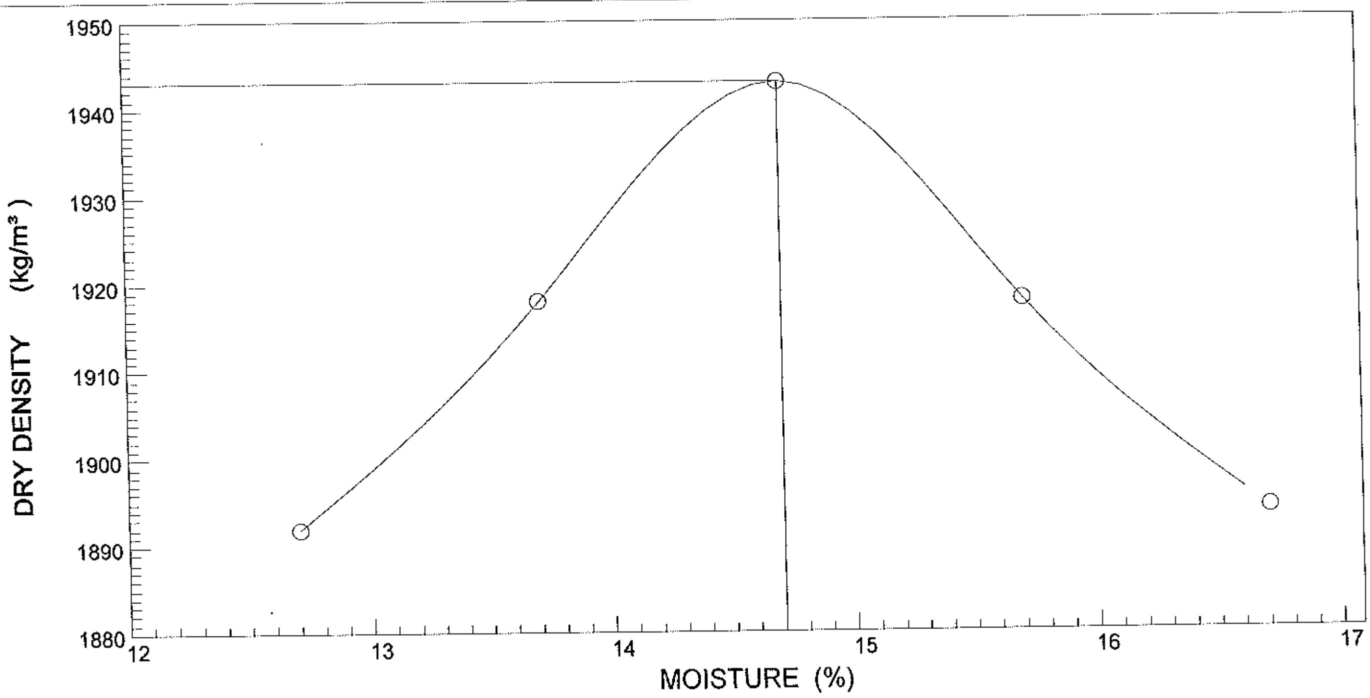
BORROW PIT 3 - MOD TEST RESULTS

SANS 3001-GR30/GR31/GR20

SAMPLE NO.	S482
CONTAINER FOR SAMPLING	Sampling Bag
SIZE / APPROX. MASS OF SAMPLE	50kg
MOISTURE CONDITION OF SAMPLE	Optimum Moist
LAYER TESTED / SAMPLED FROM	Borrow Pit 3
MATERIAL DESCRIPTION	
HOLE NO./ km / CHAINAGE	Excavated Material
ROAD NO.	Borrow Pit 3
DATE RECEIVED	2020/07/24
DATE SAMPLED	2020/07/24
CLIENT MARKING	L324
COLOUR AND TYPE	Light Reddish & Quartzitic Material

POINT NO.	1	2	3	4	5			
DRY DENSITY (kg/m³)	1892	1918	1943	1918	1894			
MOISTURE (%)	12,7	13,7	14,7	15,7	16,7			

MAXIMUM DRY DENSITY (kg/m³) : 1943	OPTIMUM MOISTURE CONTENT (%) : 14,7



Deviation from Test Method :
Remarks and Notes : Sampled @ 8:00 am

Florence Gungqa
Manager

Report compiled by : Miss XF Gungqa

Prog.ver 10.7 (2019/11/07)

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Project : MAREESBURG TSF PHASE II

BORROW PIT 3 - MOD TEST RESULTS

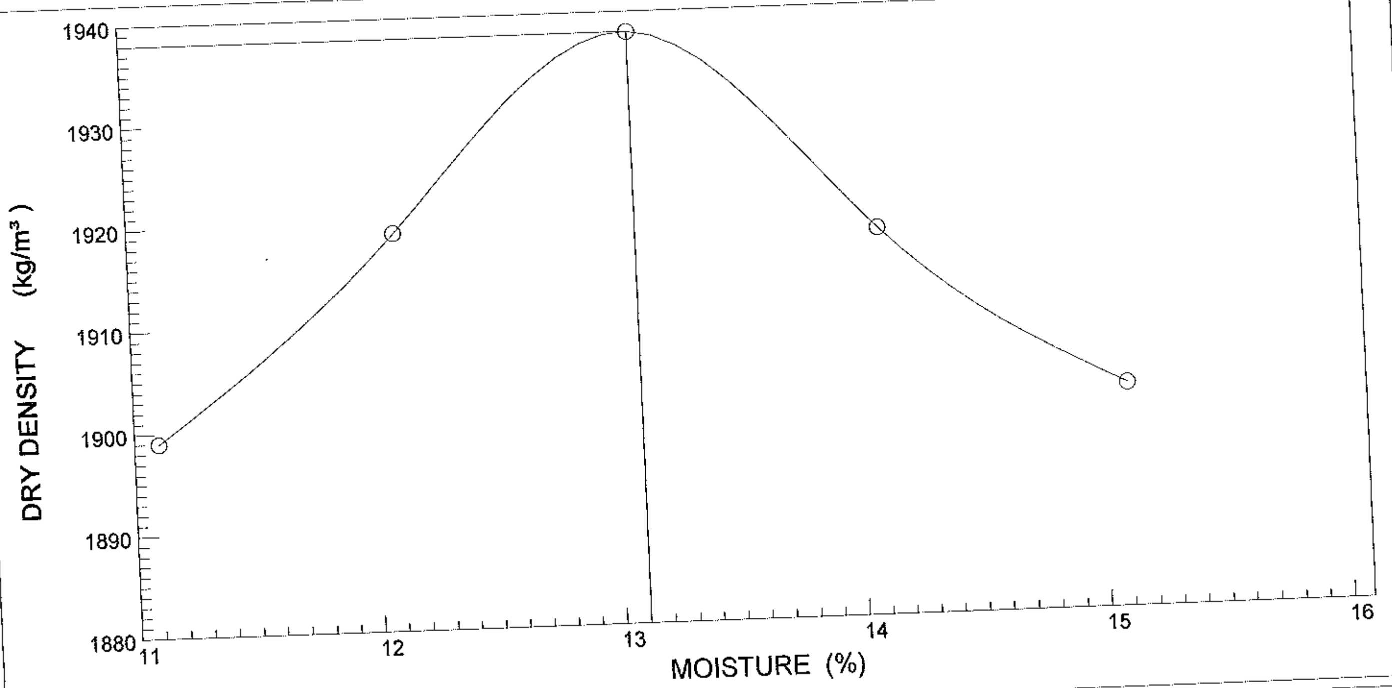
SANS 3001-GR30/GR31/GR20

SAMPLE NO.	S483
CONTAINER FOR SAMPLING	Sampling Bag
SIZE / APPROX. MASS OF SAMPLE	50kg
MOISTURE CONDITION OF SAMPLE	Optimum Moist
LAYER TESTED / SAMPLED FROM	Borrow Pit 3
MATERIAL DESCRIPTION	
HOLE NO./ km / CHAINAGE	Excavated Material
ROAD NO.	Borrow Pit 3
DATE RECEIVED	2020/07/24
DATE SAMPLED	2020/07/24
CLIENT MARKING	L324
COLOUR AND TYPE	Light Reddish & Quartzitic Material

POINT NO.	1	2	3	4	5			
DRY DENSITY (kg/m³)	1899	1919	1938	1918	1902			
MOISTURE (%)	11,1	12,1	13,1	14,1	15,1			

MAXIMUM DRY DENSITY (kg/m³) : 1938

OPTIMUM MOISTURE CONTENT (%) : 13,1



Deviation from Test Method :
Remarks and Notes : Sampled @ 8:00 am

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Manager

Report compiled by : Miss XF Gungqa

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Project : MAREESBURG TSF PHASE II

BORROW PIT 3 - MOD TEST RESULTS

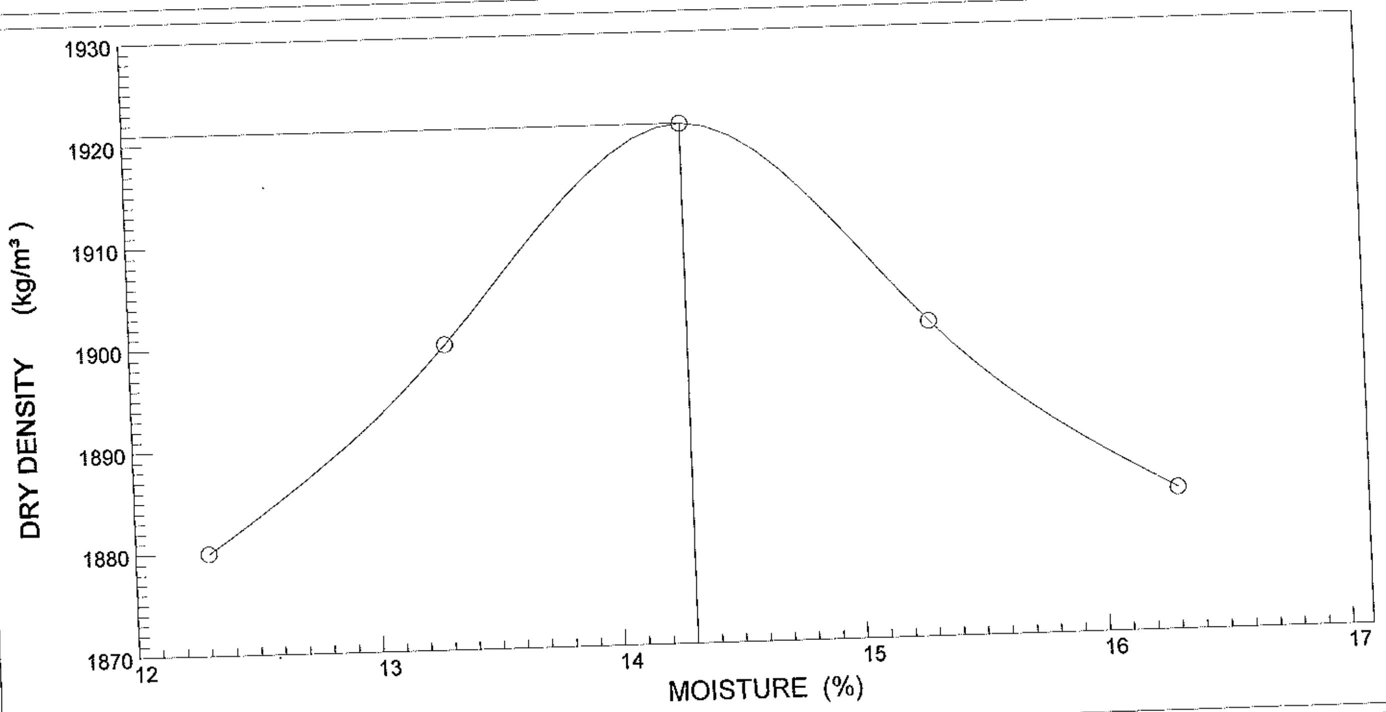
SANS 3001-GR30/GR31/GR20

SAMPLE NO.	S484
CONTAINER FOR SAMPLING	Sampling Bag
SIZE / APPROX. MASS OF SAMPLE	50kg
MOISTURE CONDITION OF SAMPLE	Optimum Moist
LAYER TESTED / SAMPLED FROM	Borrow Pit 3
MATERIAL DESCRIPTION	
HOLE NO./ km / CHAINAGE	Excavated Material
ROAD NO.	Borrow Pit 3
DATE RECEIVED	2020/07/24
DATE SAMPLED	2020/07/24
CLIENT MARKING	L324
COLOUR AND TYPE	Light Reddish & Quartzitic Material

POINT NO.	1	2	3	4	5			
DRY DENSITY (kg/m³)	1880	1900	1921	1901	1884			
MOISTURE (%)	12,3	13,3	14,3	15,3	16,3			

MAXIMUM DRY DENSITY (kg/m³) : 1921

OPTIMUM MOISTURE CONTENT (%) : 14,3



Deviation from Test Method :
Remarks and Notes : Sampled @ 12:00 pm

Florence Gungqa
Manager

Report compiled by : Mr A Hlanya

Prog.ver 10.7 (2019/11/07)

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SRK Consulting Enginners
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Attention : Mr T Thantsa

Client Ref.No.: L324

Date Reported : 2020/07/25

Project : MAREESBURG TSF PHASE II

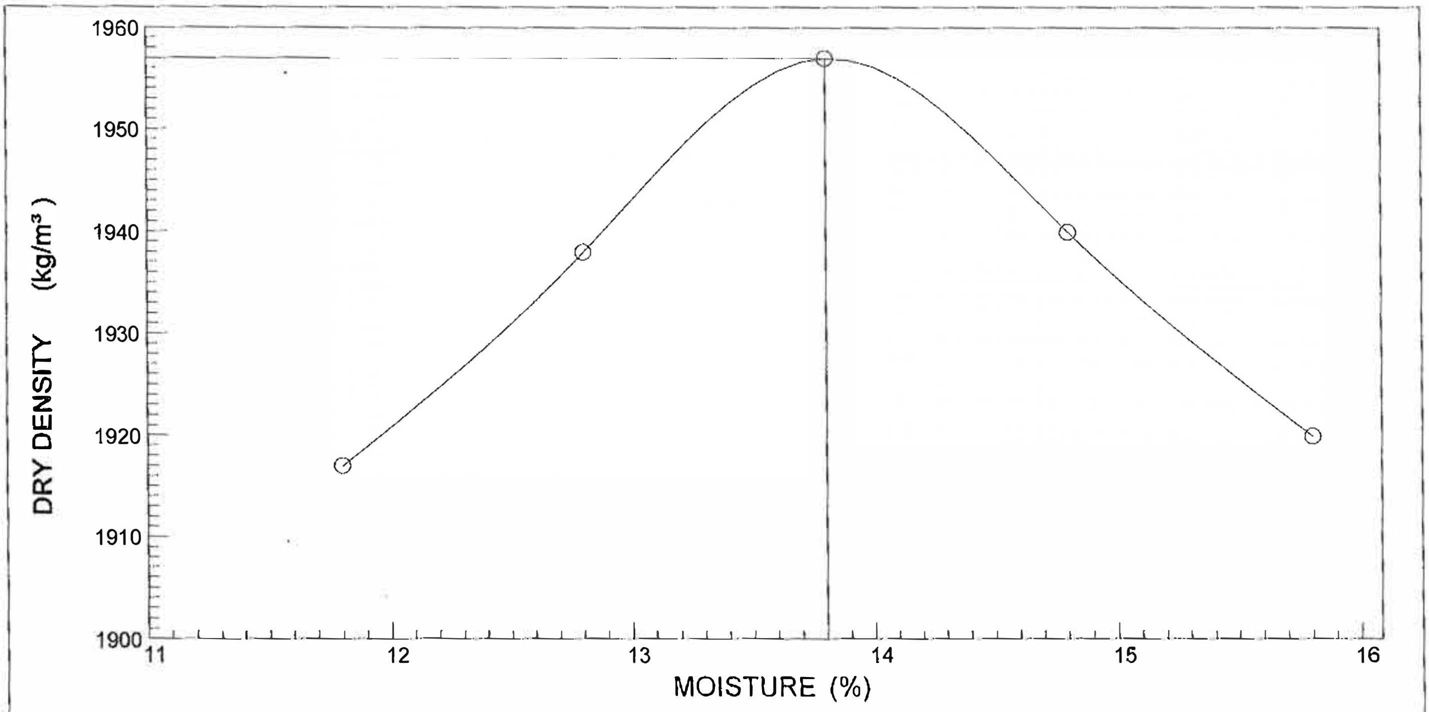
BORROW PIT 3 - MOD TEST RESULTS

SANS 3001-GR30/GR31/GR20

SAMPLE NO.	S485
CONTAINER FOR SAMPLING	Sampling Bag
SIZE / APPROX. MASS OF SAMPLE	50kg
MOISTURE CONDITION OF SAMPLE	Optimum Moist
LAYER TESTED / SAMPLED FROM	Borrow Pit 3
MATERIAL DESCRIPTION	
HOLE NO./ km / CHAINAGE	Excavated Material
ROAD NO.	Borrow Pit 3
DATE RECEIVED	2020/07/24
DATE SAMPLED	2020/07/24
CLIENT MARKING	L324
COLOUR AND TYPE	Light Reddish & Quartzitic Material

POINT NO.	1	2	3	4	5			
DRY DENSITY (kg/m^3)	1917	1938	1957	1940	1920			
MOISTURE (%)	11,8	12,8	13,8	14,8	15,8			

MAXIMUM DRY DENSITY (kg/m^3) : 1957 | OPTIMUM MOISTURE CONTENT (%) : 13,8



Deviation from Test Method :
Remarks and Notes : Sampled @ 12:00 pm

Report compiled by : Mr A Hlanya

Prog.ver 10.7 (2019/11/07)

Florence Guhgqa
Manager

Client Name: SRK Consulting
Project Name: 552477: SMC TSF Ext.
Job Number: SRK-98
Date: 2020-08-25
Method: SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR							Sheet Ref: R-STL-011-Rev02
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**			
Sample	TP01-20	TP03-20	TP08-20	Sample	TP01-20	TP03-20	TP08-20
Depth (m)	2.4 - 2.6	1.6 - 1.9	1.0 - 1.1	Depth (m)	2.4 - 2.6	1.6 - 1.9	1.0 - 1.1
Lab No	SRK-98-1518	SRK-98-1519	SRK-98-1522	Lab No	SRK-98-1518	SRK-98-1519	SRK-98-1522
53.0	**100**	**100**	**100**	Liquid Limit (%)	**-**	**32**	**73**
37.5	**100**	**100**	**100**	Plastic Limit (%)	**-**	**21**	**36**
26.5	**100**	**100**	**100**	Plasticity Index (%)	**SP**	**11**	**37**
19.0	**100**	**100**	**100**	Linear Shrinkage (%)	**0.5**	**6.0**	**25.5**
13.2	**98**	**100**	**100**	PI of whole sample	**-**	**6**	**34**
9.5	**98**	**100**	**100**				
6.7	**96**	**100**	**100**	% Gravel	**17**	**8**	**3**
4.75	**95**	**100**	**99**	% Sand	**72**	**73**	**23**
2.00	**83**	**92**	**97**	% Silt	**10**	**15**	**19**
1.00	**60**	**75**	**94**	% Clay	**1**	**4**	**55**
0.425	**44**	**59**	**92**	Activity	**0.0**	**2.8**	**0.7**
0.250	**33**	**44**	**88**				
0.150	**23**	**34**	**84**	% Soil Mortar	**83**	**92**	**97**
0.075	**14**	**25**	**81**				
0.060	**11**	**19**	**74**	Grading Modulus	**1.59**	**1.24**	**0.30**
0.050	**10**	**16**	**72**	Moisture Content (%)	**N / T**	**N / T**	**N / T**
0.035	**6**	**12**	**68**	Relative Density (SG)*	**2.759**	**2.67**	**2.764**
0.020	**4**	**10**	**65**				
0.006	**2**	**6**	**60**	Unified (ASTM D2487)	**SM**	**SC**	**CH**
0.002	**1**	**4**	**55**	AASHTO (M145-91)	**A - 1 - b**	**A - 2 - 6**	**A - 7 - 5**

Remarks: *: Determined
N / T: Not Tested

Specialised Testing Laboratory (Pty) Ltd
Asphalt | Aggregate | Bitumen | Geotechnical
Quality | Excellence | On Time
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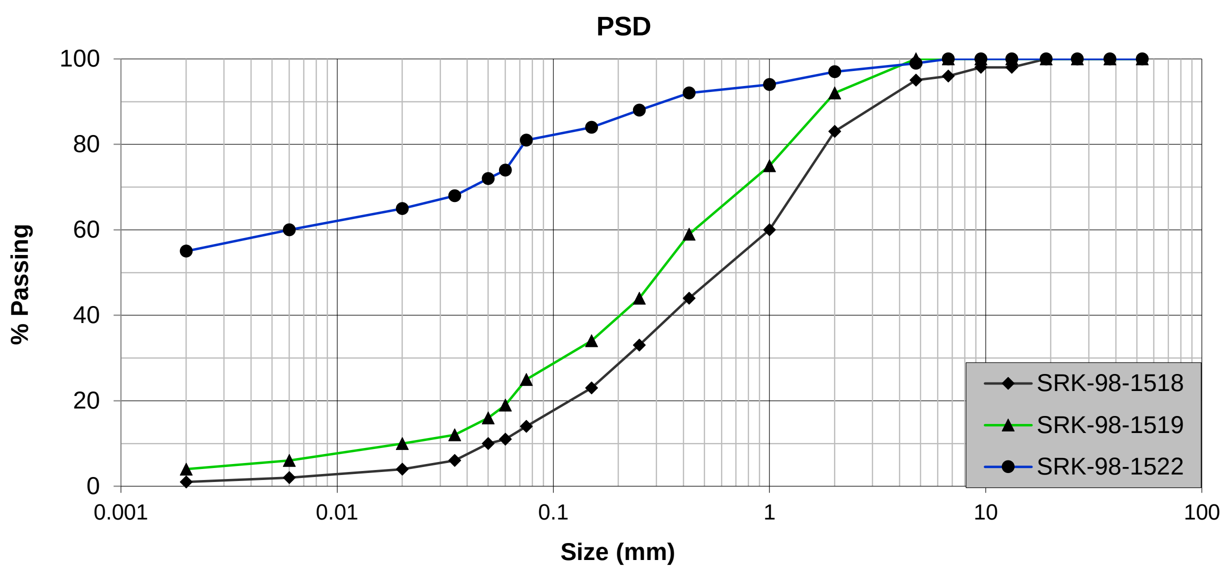
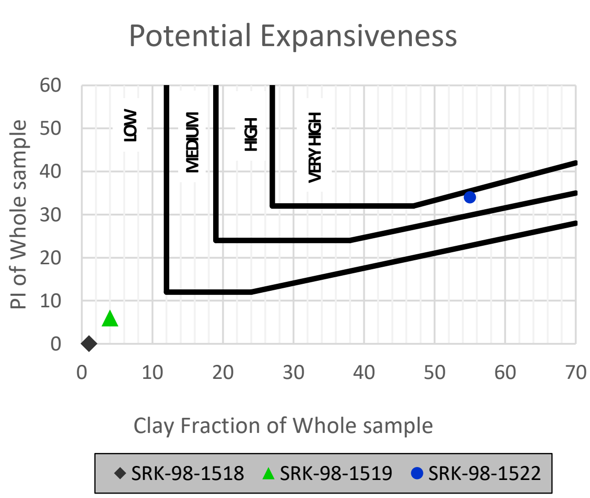
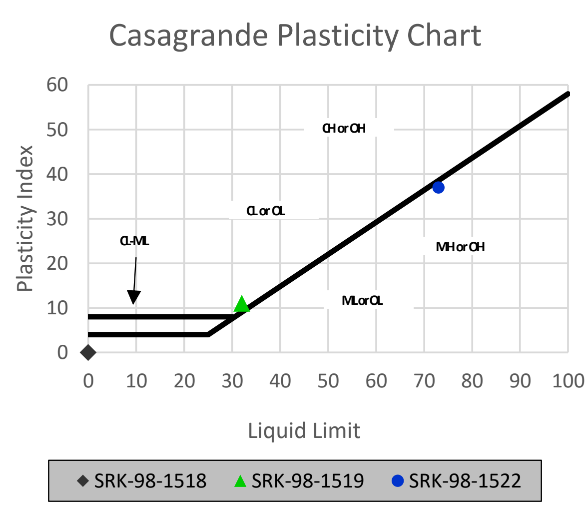
Gerrie | 082 309 4448 | gerrie@stlab.co.za
www.stlab.co.za

Client Name:	SRK Consulting
Project Name:	552477: SMC TSF Ext.
Job Number:	SRK-98
Date:	2020-08-25
Method:	SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR	**Sheet Ref: R-STL-011-Rev02**







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Project Name: 552477: SMC TSF Ext.
Job Number: SRK-98
Date: 2020-08-25
Method: SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR							Sheet Ref: R-STL-011-Rev02
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				Atterberg Limits & Classification			
Sample	TP08-20	TP15-20	TP19-20	Sample	TP08-20	TP15-20	TP19-20
Depth (m)	2.2 - 2.4	1.9 - 2.1	1.0 - 1.2	Depth (m)	2.2 - 2.4	1.9 - 2.1	1.0 - 1.2
Lab No	SRK-98-1523	SRK-98-1528	SRK-98-1529	Lab No	SRK-98-1523	SRK-98-1528	SRK-98-1529
53.0	**100**	**100**	**100**	Liquid Limit (%)	**30**	**28**	**61**
37.5	**100**	**100**	**100**	Plastic Limit (%)	**19**	**23**	**28**
26.5	**100**	**100**	**100**	Plasticity Index (%)	**11**	**5**	**33**
19.0	**100**	**100**	**100**	Linear Shrinkage (%)	**5.5**	**3.0**	**22.0**
13.2	**100**	**100**	**100**	PI of whole sample	**3**	**3**	**32**
9.5	**100**	**100**	**100**				
6.7	**99**	**100**	**100**	% Gravel	**25**	**10**	**1**
4.75	**97**	**100**	**100**	% Sand	**66**	**77**	**12**
2.00	**75**	**90**	**99**	% Silt	**6**	**11**	**24**
1.00	**47**	**73**	**99**	% Clay	**3**	**2**	**63**
0.425	**29**	**57**	**98**	Activity	**3.7**	**2.5**	**0.5**
0.250	**21**	**43**	**95**				
0.150	**16**	**32**	**92**	% Soil Mortar	**75**	**90**	**99**
0.075	**12**	**22**	**89**				
0.060	**9**	**13**	**87**	Grading Modulus	**1.84**	**1.31**	**0.14**
0.050	**8**	**11**	**85**	Moisture Content (%)	**N / T**	**N / T**	**N / T**
0.035	**7**	**9**	**81**	Relative Density (SG)*	**2.765**	**2.743**	**2.609**
0.020	**6**	**7**	**78**				
0.006	**4**	**4**	**70**	Unified (ASTM D2487)	**SW-SC**	**SC-SM**	**CH**
0.002	**3**	**2**	**63**	AASHTO (M145-91)	**A - 2 - 6**	**A - 2 - 4**	**A - 7 - 6**

Remarks: *: Determined
N / T: Not Tested

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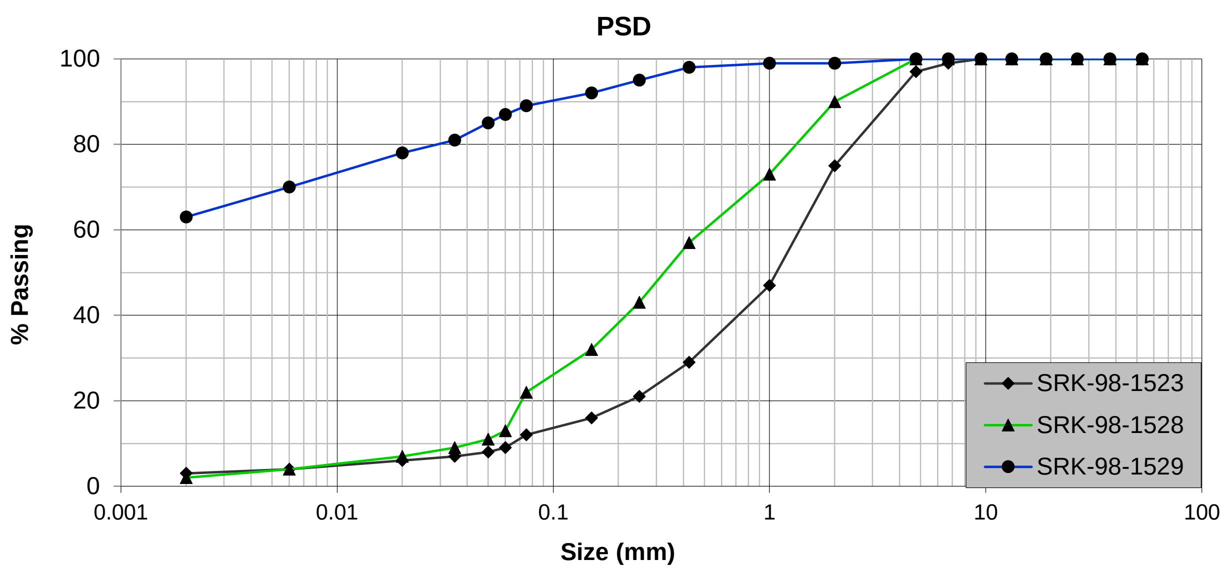
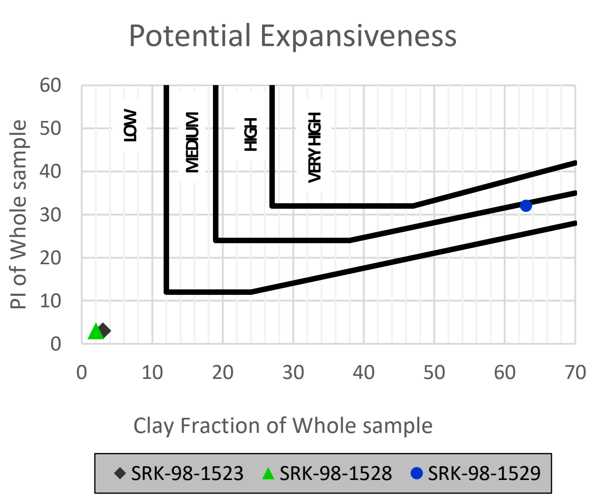
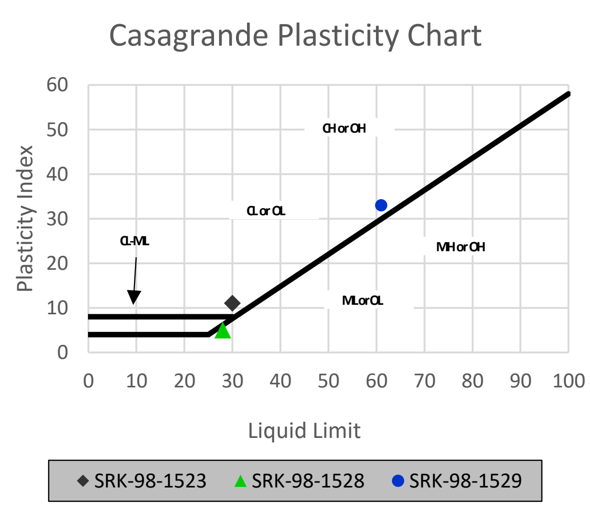
Client Name:	SRK Consulting
Project Name:	552477: SMC TSF Ext.
Job Number:	SRK-98
Date:	2020-08-25
Method:	SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR	Sheet Ref: R-STL-011-Rev02







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FOUNDATION INDICATOR						**Sheet Ref: R-STL-011-Rev02**	
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**			
Sample	TP19-20	TP25-20	TP26-20	Sample	TP19-20	TP25-20	TP26-20
Depth (m)	1.6 - 1.9	0.6 - 0.8	0.3 - 0.5	Depth (m)	1.6 - 1.9	0.6 - 0.8	0.3 - 0.5
Lab No	SRK-98-1530	SRK-98-1531	SRK-98-1532	Lab No	SRK-98-1530	SRK-98-1531	SRK-98-1532
53.0	**100**	**100**	**100**	Liquid Limit (%)	**33**	**60**	**54**
37.5	**100**	**100**	**100**	Plastic Limit (%)	**19**	**30**	**26**
26.5	**100**	**100**	**93**	Plasticity Index (%)	**14**	**30**	**28**
19.0	**100**	**100**	**89**	Linear Shrinkage (%)	**7.0**	**14.0**	**13.5**
13.2	**100**	**100**	**89**	PI of whole sample	**11**	**29**	**20**
9.5	**100**	**100**	**89**				
6.7	**100**	**100**	**88**	% Gravel	**0**	**0**	**20**
4.75	**100**	**100**	**86**	% Sand	**68**	**19**	**25**
2.00	**100**	**100**	**80**	% Silt	**22**	**27**	**18**
1.00	**89**	**99**	**76**	% Clay	**10**	**54**	**37**
0.425	**76**	**97**	**72**	Activity	**1.4**	**0.6**	**0.8**
0.250	**63**	**96**	**66**				
0.150	**52**	**92**	**63**	% Soil Mortar	**100**	**100**	**80**
0.075	**42**	**88**	**59**				
0.060	**32**	**81**	**55**	Grading Modulus	**0.82**	**0.15**	**0.89**
0.050	**30**	**79**	**54**	Moisture Content (%)	**N / T**	**N / T**	**N / T**
0.035	**26**	**77**	**52**	Relative Density (SG)*	**2.761**	**2.73**	**2.685**
0.020	**22**	**72**	**48**				
0.006	**14**	**61**	**42**	Unified (ASTM D2487)	**SC**	**CH**	**CH**
0.002	**10**	**54**	**37**	AASHTO (M145-91)	**A - 6**	**A - 7 - 5**	**A - 7 - 6**

Remarks: *: Determined
N / T: Not Tested

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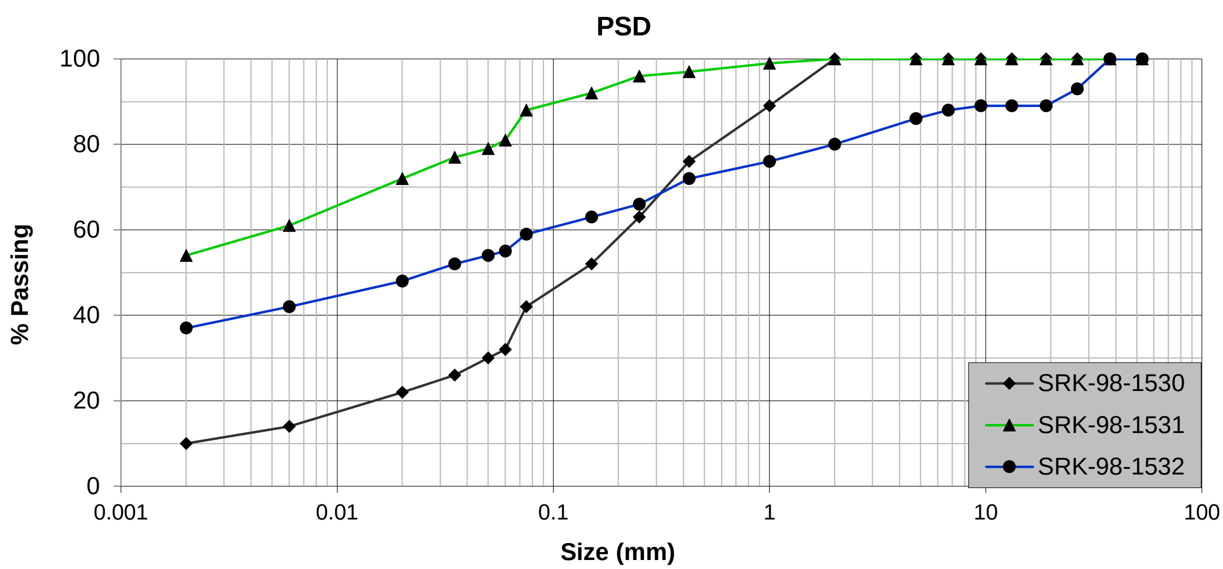
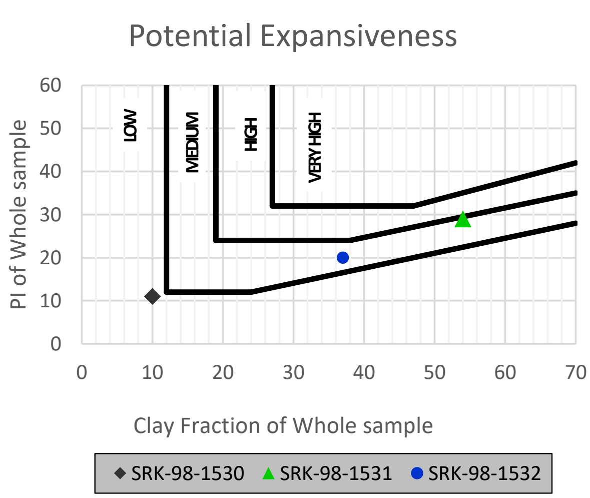
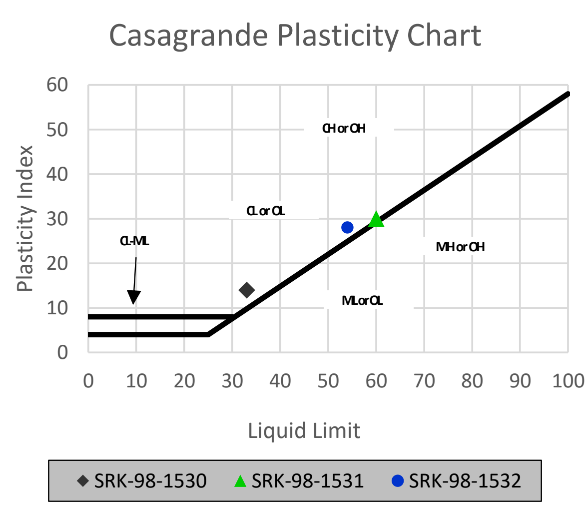
Job Number: SRK-98
Date: 2020-08-25
Method: SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR	Sheet Ref: R-STL-011-Rev02







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Project Name: 552477: SMC TSF Ext.
Job Number: SRK-98
Date: 2020-08-25
Method: SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR							**Sheet Ref: R-STL-011-Rev02**
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**			
Sample	TP26-20	TP25-20	TP27-20	Sample	TP26-20	TP25-20	TP27-20
Depth (m)	0.3 - 0.5	1.4 - 1.6	0.9 - 1.2	Depth (m)	0.3 - 0.5	1.4 - 1.6	0.9 - 1.2
Lab No	SRK-98-1533	SRK-98-1534	SRK-98-1535	Lab No	SRK-98-1533	SRK-98-1534	SRK-98-1535
53.0	**100**	**100**	**100**	Liquid Limit (%)	**50**	**-**	**-**
37.5	**100**	**100**	**100**	Plastic Limit (%)	**26**	**-**	**-**
26.5	**100**	**100**	**100**	Plasticity Index (%)	**24**	**SP**	**SP**
19.0	**100**	**100**	**100**	Linear Shrinkage (%)	**12.5**	**0.5**	**0.5**
13.2	**100**	**100**	**100**	PI of whole sample	**23**	**-**	**-**
9.5	**100**	**100**	**100**				
6.7	**100**	**100**	**100**	% Gravel	**1**	**4**	**19**
4.75	**100**	**99**	**98**	% Sand	**29**	**79**	**73**
2.00	**99**	**96**	**81**	% Silt	**30**	**13**	**7**
1.00	**98**	**77**	**51**	% Clay	**40**	**4**	**1**
0.425	**95**	**59**	**36**	Activity	**0.6**	**0.0**	**0.0**
0.250	**90**	**46**	**24**				
0.150	**87**	**34**	**16**	% Soil Mortar	**99**	**96**	**81**
0.075	**79**	**22**	**11**				
0.060	**70**	**17**	**8**	Grading Modulus	**0.27**	**1.23**	**1.72**
0.050	**68**	**15**	**7**	Moisture Content (%)	**N / T**	**N / T**	**N / T**
0.035	**64**	**12**	**5**	Relative Density (SG)*	**2.647**	**2.842**	**2.868**
0.020	**59**	**9**	**4**				
0.006	**47**	**6**	**2**	Unified (ASTM D2487)	**CH**	**SM**	**SW-SM**
0.002	**40**	**4**	**1**	AASHTO (M145-91)	**A - 7 - 6**	**A - 2 - 4**	**A - 1 - b**

Remarks: *: Determined
N / T: Not Tested

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Quality | Excellence | On Time

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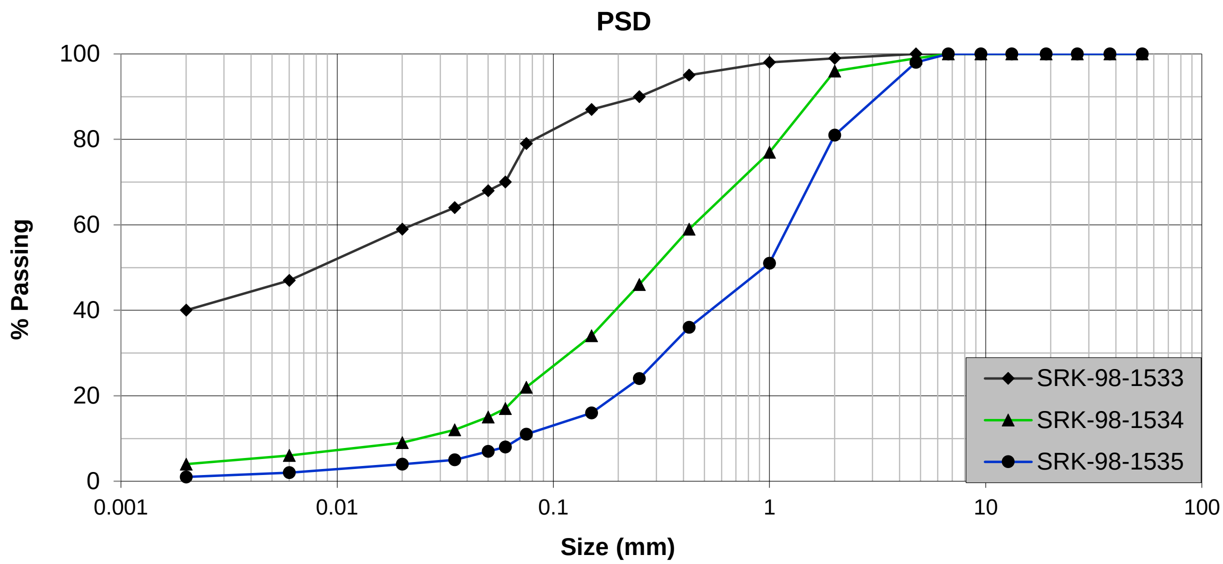
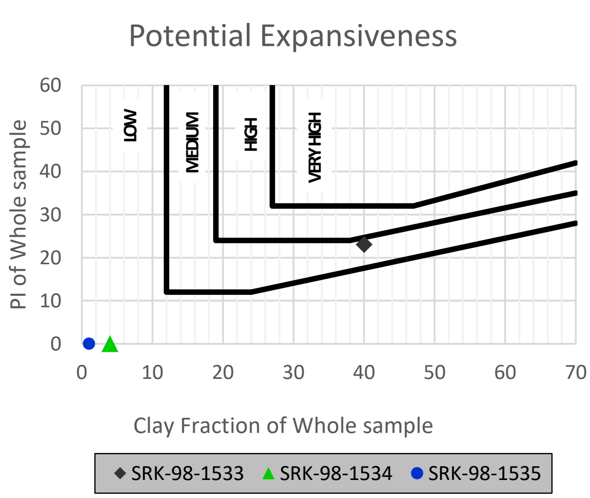
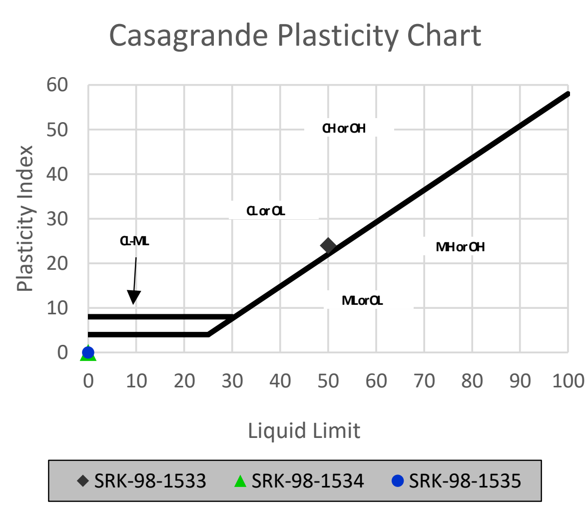
Client Name:	SRK Consulting
Project Name:	552477: SMC TSF Ext.
Job Number:	SRK-98
Date:	2020-08-25
Method:	SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR	Sheet Ref: R-STL-011-Rev02







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Job Number:	SRK-98
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Method:	SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR							**Sheet Ref: R-STL-011-Rev02**
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**			
Sample	North Portal	South Portal	Feed 1	Sample	North Portal	South Portal	Feed 1
Depth (m)	Stockpile	Stockpile	-	Depth (m)	Stockpile	Stockpile	-
Lab No	SRK-98-1552	SRK-98-1553	SRK-98-1554	Lab No	SRK-98-1552	SRK-98-1553	SRK-98-1554
53.0	**70**	**67**	**100**	Liquid Limit (%)	**25**	**20**	**-**
37.5	**62**	**54**	**100**	Plastic Limit (%)	**16**	**15**	**-**
26.5	**53**	**45**	**100**	Plasticity Index (%)	**9**	**5**	**NP**
19.0	**40**	**36**	**100**	Linear Shrinkage (%)	**5.0**	**3.0**	**0.0**
13.2	**34**	**31**	**100**	PI of whole sample	**1**	**0**	**-**
9.5	**30**	**27**	**100**				
6.7	**26**	**25**	**100**	% Gravel	**81**	**82**	**0**
4.75	**23**	**23**	**100**	% Sand	**14**	**16**	**41**
2.00	**19**	**18**	**100**	% Silt	**4**	**1**	**55**
1.00	**16**	**13**	**100**	% Clay	**1**	**1**	**4**
0.425	**12**	**7**	**100**	Activity	**9.0**	**5.0**	**0.0**
0.250	**10**	**5**	**97**				
0.150	**7**	**4**	**92**	% Soil Mortar	**19**	**18**	**100**
0.075	**5**	**3**	**75**				
0.060	**5**	**2**	**59**	Grading Modulus	**2.64**	**2.72**	**0.25**
0.050	**4**	**2**	**54**	Moisture Content (%)	**N / T**	**N / T**	**N / T**
0.035	**3**	**1**	**39**	Relative Density (SG)*	**3.131**	**3.145**	**3.356**
0.020	**3**	**1**	**25**				
0.006	**2**	**1**	**14**	Unified (ASTM D2487)	**GP-GC**	**GP**	**ML**
0.002	**1**	**1**	**4**	AASHTO (M145-91)	**A - 2 - 4**	**A - 1 - a**	**A - 4**

Remarks: *: Determined
N / T: Not Tested

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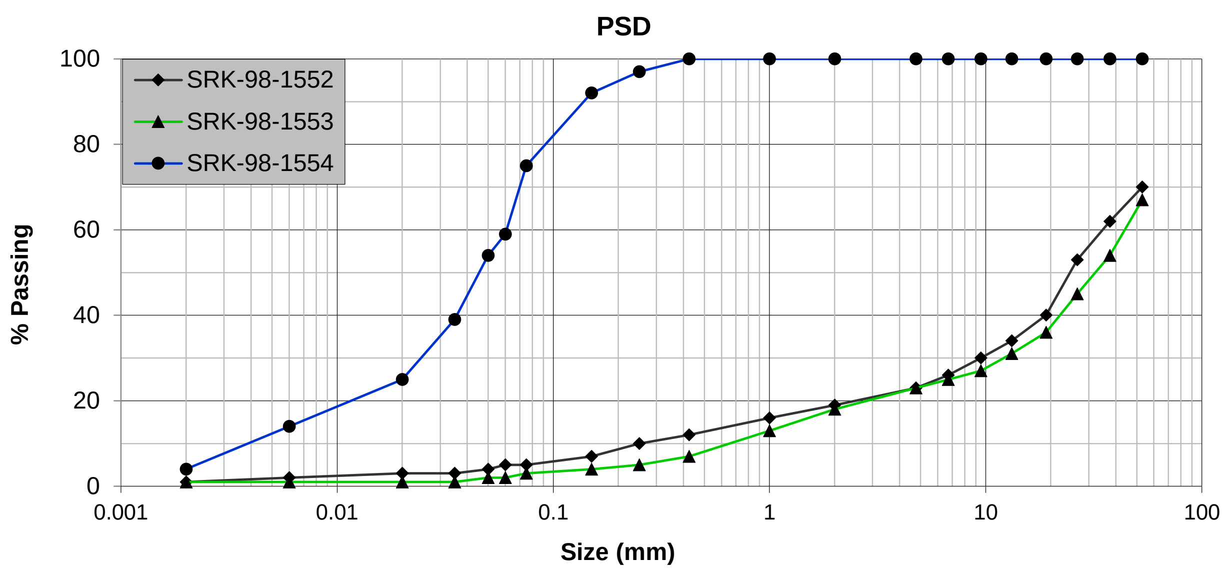
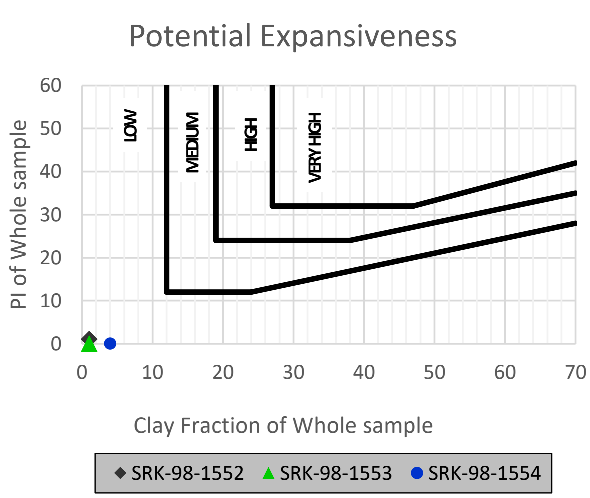
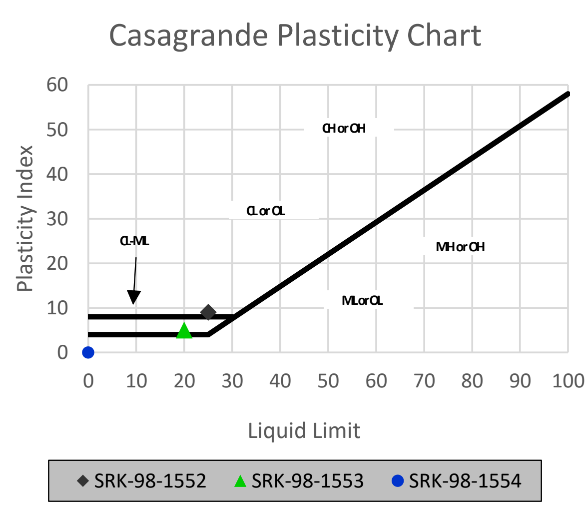
Project Name:	552477: SMC TSF Ext.
Job Number:	SRK-98
Date:	2020-08-25
Method:	SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR	Sheet Ref: R-STL-011-Rev02







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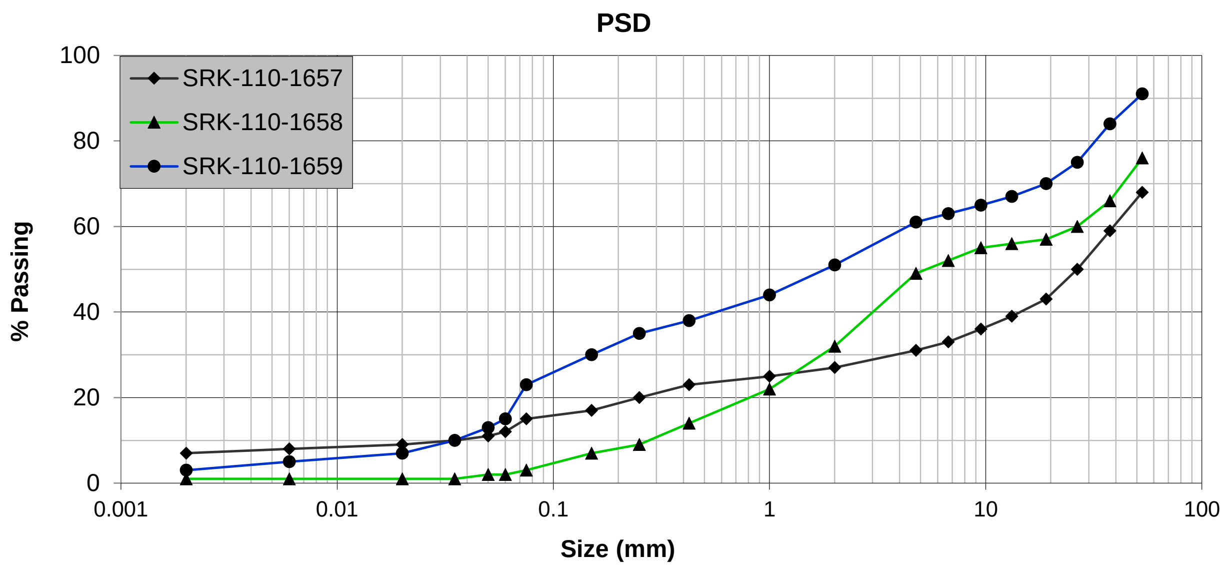
Client Name: SRK Consulting
Project Name: 560333: Mareesburg TSF Phase 4
Job Number: SRK-110
Date: 2021-03-03
Method: SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

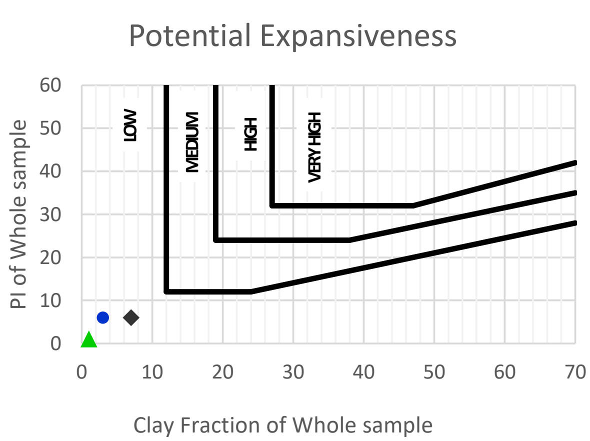
FOUNDATION INDICATOR							**Sheet Reference: R-STL-011 Rev02**
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**			
Sample	TPA15	TPA15	TPA16	Sample	TPA15	TPA15	TPA16
Depth (m)	0.5 - 0.8	1.4 - 1.7	1.2 - 1.5	Depth (m)	0.5 - 0.8	1.4 - 1.7	1.2 - 1.5
Lab No	SRK-110-1657	SRK-110-1658	SRK-110-1659	Lab No	SRK-110-1657	SRK-110-1658	SRK-110-1659
53.0	**68**	**76**	**91**	Liquid Limit (%)	**52**	**27**	**37**
37.5	**59**	**66**	**84**	Plastic Limit (%)	**26**	**18**	**20**
26.5	**50**	**60**	**75**	Plasticity Index (%)	**26**	**9**	**17**
19.0	**43**	**57**	**70**	Linear Shrinkage (%)	**14.5**	**4.5**	**8.5**
13.2	**39**	**56**	**67**	PI of whole sample	**6**	**1**	**6**
9.5	**36**	**55**	**65**				
6.7	**33**	**52**	**63**	% Gravel	**73**	**68**	**49**
4.75	**31**	**49**	**61**	% Sand	**15**	**30**	**36**
2.00	**27**	**32**	**51**	% Silt	**5**	**1**	**12**
1.00	**25**	**22**	**44**	% Clay	**7**	**1**	**3**
0.425	**23**	**14**	**38**	Activity	**3.7**	**9.0**	**5.7**
0.250	**20**	**9**	**35**				
0.150	**17**	**7**	**30**	% Soil Mortar	**27**	**32**	**51**
0.075	**15**	**3**	**23**				
0.060	**12**	**2**	**15**	Grading Modulus	**2.35**	**2.51**	**1.88**
0.050	**11**	**2**	**13**	Moisture Content (%)	**13.7**	**8.4**	**9.3**
0.035	**10**	**1**	**10**	Relative Density (SG)*	**2.754**	**2.879**	**2.658**
0.020	**9**	**1**	**7**				
0.006	**8**	**1**	**5**	Unified (ASTM D2487)	**GC**	**GP**	**GC**
0.002	**7**	**1**	**3**	AASHTO (M145-91)	**A - 2 - 7**	**A - 2 - 4**	**A - 2 - 6**

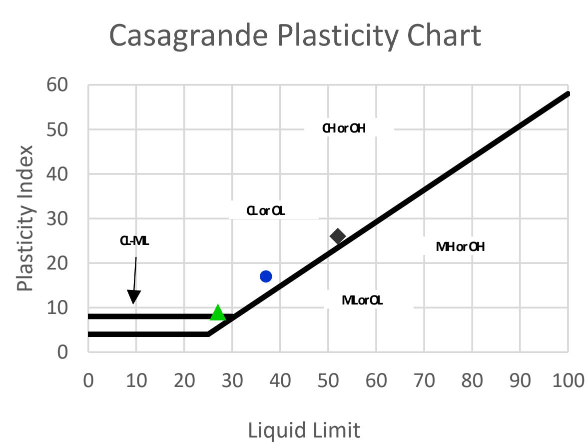
Remarks: *: Determined
N / T: Not Tested

Client Name: SRK Consulting
Project Name: 560333: Mareesburg TSF Phase 4
Job Number: SRK-110
Date: 2021-03-03
Method: SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR	Sheet Reference: R-STL-011 Rev02







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Job Number: SRK-110
Date: 2021-03-03
Method: SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

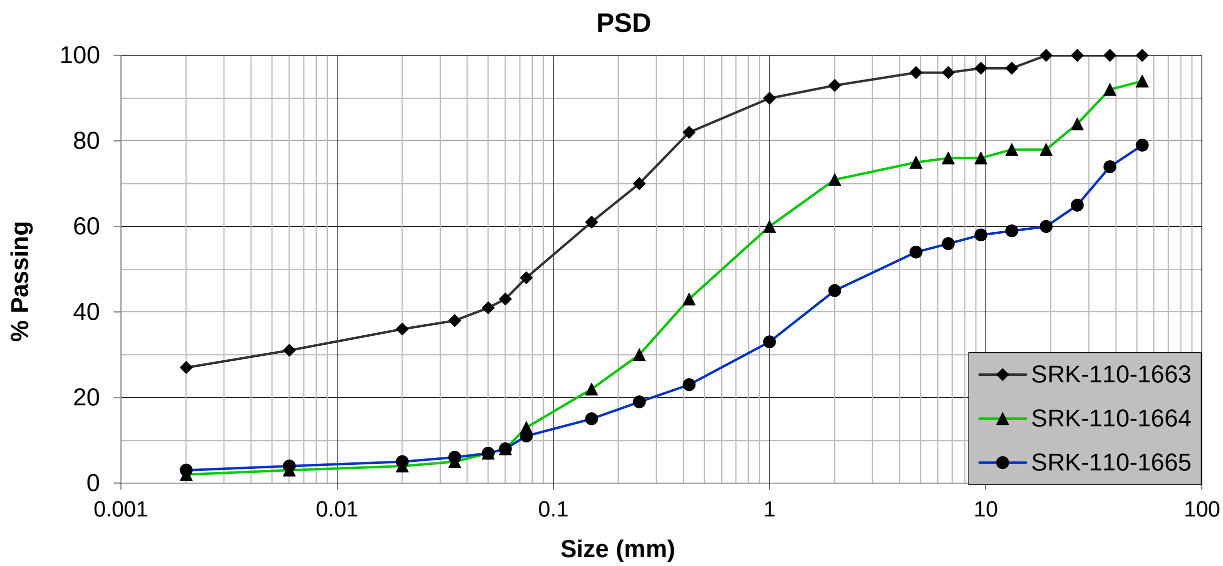
FOUNDATION INDICATOR						**Sheet Reference: R-STL-011 Rev02**	
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**			
Sample	TPB03	TPB04	TPB05	Sample	TPB03	TPB04	TPB05
Depth (m)	4.2 - 4.4	2.7 - 3.0	1.5 - 1.8	Depth (m)	4.2 - 4.4	2.7 - 3.0	1.5 - 1.8
Lab No	SRK-110-1663	SRK-110-1664	SRK-110-1665	Lab No	SRK-110-1663	SRK-110-1664	SRK-110-1665
53.0	**100**	**94**	**79**	Liquid Limit (%)	**55**	**29**	**37**
37.5	**100**	**92**	**74**	Plastic Limit (%)	**22**	**17**	**19**
26.5	**100**	**84**	**65**	Plasticity Index (%)	**33**	**12**	**18**
19.0	**100**	**78**	**60**	Linear Shrinkage (%)	**24.5**	**6.5**	**9.0**
13.2	**97**	**78**	**59**	PI of whole sample	**27**	**5**	**4**
9.5	**97**	**76**	**58**				
6.7	**96**	**76**	**56**	% Gravel	**7**	**29**	**55**
4.75	**96**	**75**	**54**	% Sand	**50**	**63**	**37**
2.00	**93**	**71**	**45**	% Silt	**16**	**6**	**5**
1.00	**90**	**60**	**33**	% Clay	**27**	**2**	**3**
0.425	**82**	**43**	**23**	Activity	**1.2**	**6.0**	**6.0**
0.250	**70**	**30**	**19**				
0.150	**61**	**22**	**15**	% Soil Mortar	**93**	**71**	**45**
0.075	**48**	**13**	**11**				
0.060	**43**	**8**	**8**	Grading Modulus	**0.77**	**1.73**	**2.21**
0.050	**41**	**7**	**7**	Moisture Content (%)	**23.1**	**21.2**	**21.2**
0.035	**38**	**5**	**6**	Relative Density (SG)*	**2.77**	**2.833**	**2.857**
0.020	**36**	**4**	**5**				
0.006	**31**	**3**	**4**	Unified (ASTM D2487)	**SC**	**SC**	**GP-GC**
0.002	**27**	**2**	**3**	AASHTO (M145-91)	**A - 7 - 6**	**A - 2 - 6**	**A - 2 - 6**

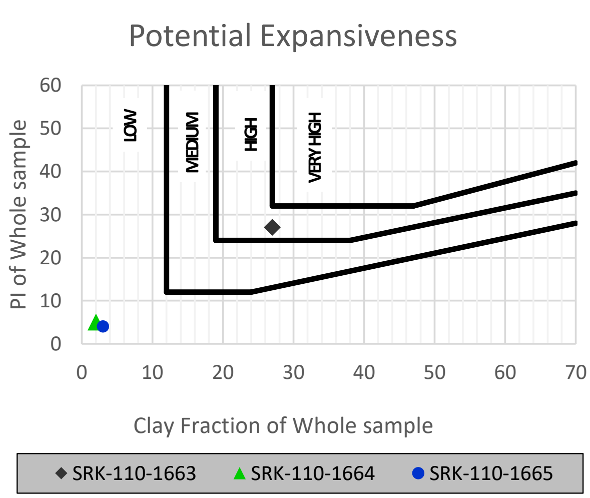
Remarks: *: Determined
N / T: Not Tested

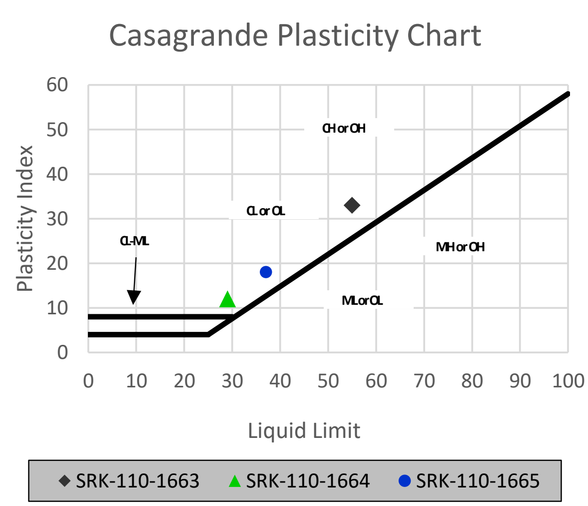
Client Name:	SRK Consulting
Project Name:	560333: Mareesburg TSF Phase 4
Job Number:	SRK-110
Date:	2021-03-03
Method:	SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR

Sheet Reference: R-STL-011 Rev02







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Job Number: SRK-110
Date: 2021-03-03
Method: SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR							**Sheet Reference: R-STL-011 Rev02**
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**			
Sample	TPA09	TPA10	TPA12	Sample	TPA09	TPA10	TPA12
Depth (m)	1.8 - 2.2	1.8 - 2.1	0.5 - 0.7	Depth (m)	1.8 - 2.2	1.8 - 2.1	0.5 - 0.7
Lab No	SRK-110-1654	SRK-110-1655	SRK-110-1656	Lab No	SRK-110-1654	SRK-110-1655	SRK-110-1656
53.0	**97**	**92**	**100**	Liquid Limit (%)	**29**	**-**	**62**
37.5	**91**	**92**	**100**	Plastic Limit (%)	**19**	**-**	**27**
26.5	**78**	**83**	**100**	Plasticity Index (%)	**10**	**SP**	**35**
19.0	**68**	**75**	**100**	Linear Shrinkage (%)	**5.0**	**0.5**	**27.0**
13.2	**68**	**75**	**100**	PI of whole sample	**2**	**-**	**28**
9.5	**67**	**75**	**98**				
6.7	**65**	**73**	**97**	% Gravel	**58**	**55**	**9**
4.75	**61**	**69**	**96**	% Sand	**38**	**43**	**44**
2.00	**42**	**45**	**91**	% Silt	**3**	**1**	**19**
1.00	**29**	**28**	**84**	% Clay	**1**	**1**	**28**
0.425	**20**	**17**	**80**	Activity	**10.0**	**0.0**	**1.3**
0.250	**15**	**10**	**74**				
0.150	**10**	**6**	**67**	% Soil Mortar	**42**	**45**	**91**
0.075	**7**	**4**	**55**				
0.060	**4**	**2**	**47**	Grading Modulus	**2.31**	**2.34**	**0.74**
0.050	**3**	**2**	**45**	Moisture Content (%)	**8.0**	**5.7**	**25.1**
0.035	**2**	**1**	**42**	Relative Density (SG)*	**2.825**	**2.911**	**2.766**
0.020	**2**	**1**	**38**				
0.006	**1**	**1**	**31**	Unified (ASTM D2487)	**SW-SC**	**SW**	**CH**
0.002	**1**	**1**	**28**	AASHTO (M145-91)	**A - 2 - 4**	**A - 1 - a**	**A - 7 - 6**

Remarks: *: Determined
N / T: Not Tested

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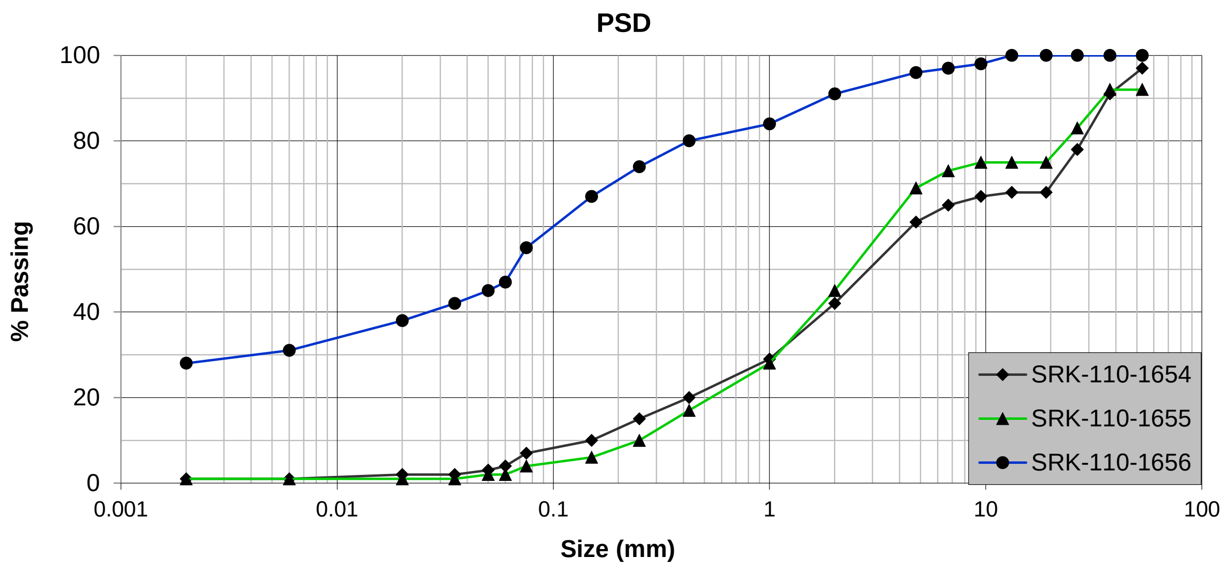
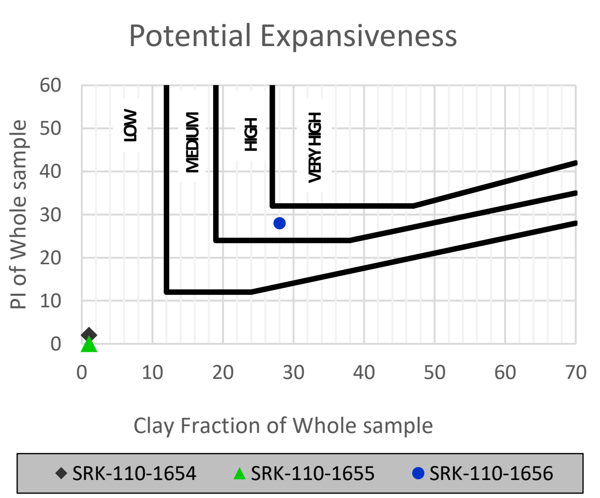
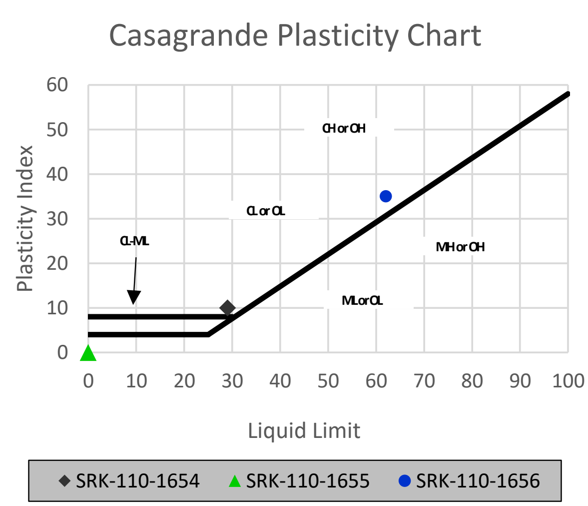
Project Name:	560333: Mareesburg TSF Phase 4
Job Number:	SRK-110
Date:	2021-03-03
Method:	SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR	**Sheet Reference: R-STL-011 Rev02**







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Job Number: SRK-110
Date: 2021-03-03
Method: SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR

Sheet Reference: R-STL-011 Rev02

Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				Atterberg Limits & Classification			
Sample	TPA04	TPA06	TPA07	Sample	TPA04	TPA06	TPA07
Depth (m)	0.9 - 1.2	1.2 - 1.6	1.0 - 1.5	Depth (m)	0.9 - 1.2	1.2 - 1.6	1.0 - 1.5
Lab No	SRK-110-1651	SRK-110-1652	SRK-110-1653	Lab No	SRK-110-1651	SRK-110-1652	SRK-110-1653
53.0	**89**	**94**	**80**	Liquid Limit (%)	**-**	**32**	**27**
37.5	**88**	**82**	**77**	Plastic Limit (%)	**-**	**19**	**18**
26.5	**83**	**72**	**71**	Plasticity Index (%)	**SP**	**13**	**9**
19.0	**80**	**59**	**68**	Linear Shrinkage (%)	**0.5**	**6.5**	**4.5**
13.2	**79**	**57**	**63**	PI of whole sample	**-**	**2**	**2**
9.5	**79**	**56**	**60**				
6.7	**77**	**53**	**55**	% Gravel	**56**	**63**	**61**
4.75	**73**	**51**	**50**	% Sand	**41**	**34**	**35**
2.00	**44**	**37**	**39**	% Silt	**2**	**2**	**3**
1.00	**27**	**24**	**33**	% Clay	**1**	**1**	**1**
0.425	**17**	**17**	**23**	Activity	**0.0**	**13.0**	**9.0**
0.250	**11**	**10**	**15**				
0.150	**8**	**7**	**10**	% Soil Mortar	**44**	**37**	**39**
0.075	**5**	**5**	**7**				
0.060	**3**	**3**	**4**	Grading Modulus	**2.34**	**2.41**	**2.31**
0.050	**3**	**2**	**3**	Moisture Content (%)	**10.8**	**12.4**	**11.0**
0.035	**2**	**1**	**2**	Relative Density (SG)*	**2.885**	**2.812**	**2.868**
0.020	**1**	**1**	**1**				
0.006	**1**	**1**	**1**	Unified (ASTM D2487)	**SW-SM**	**GP-GC**	**GP-GC**
0.002	**1**	**1**	**1**	AASHTO (M145-91)	**A - 1 - a**	**A - 2 - 6**	**A - 2 - 4**

Remarks: *: Determined
N / T: Not Tested

Specialised Testing Laboratory (Pty) Ltd
Asphalt | Aggregate | Bitumen | Geotechnical
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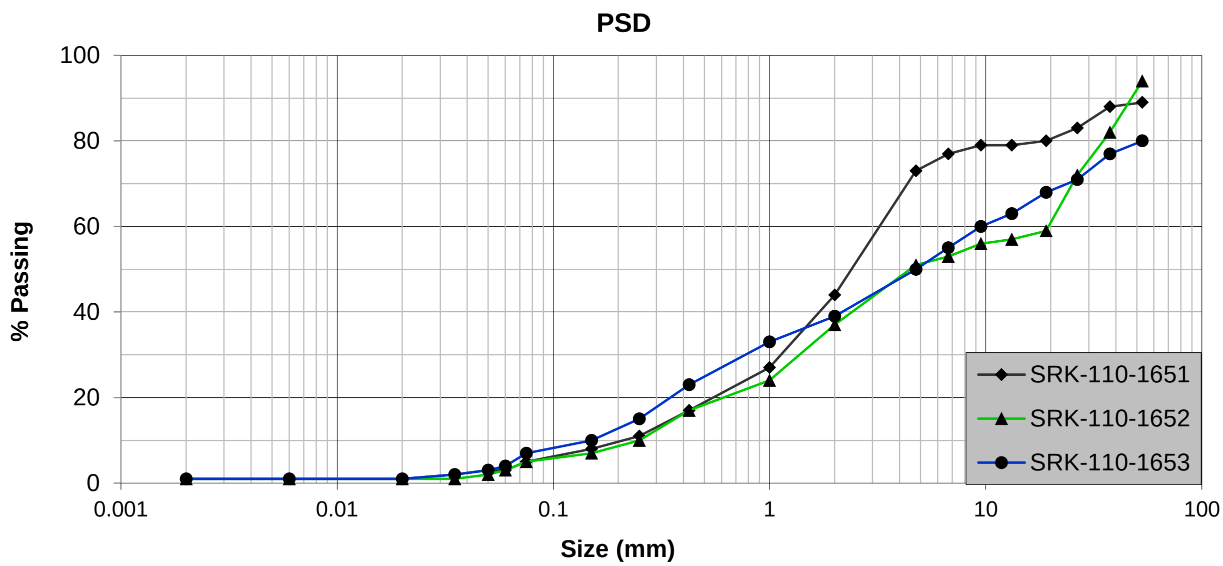
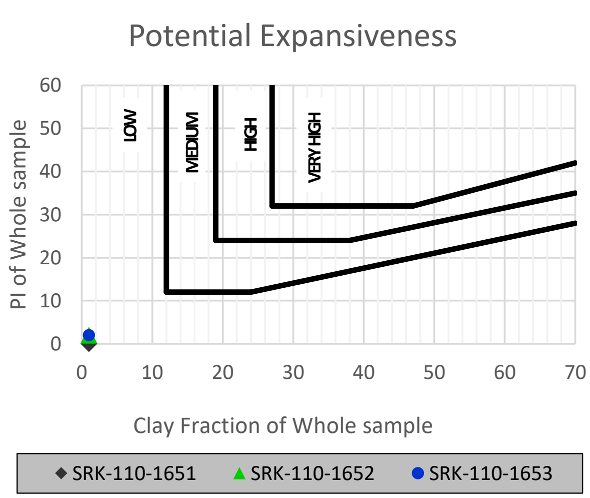
www.stlab.co.za

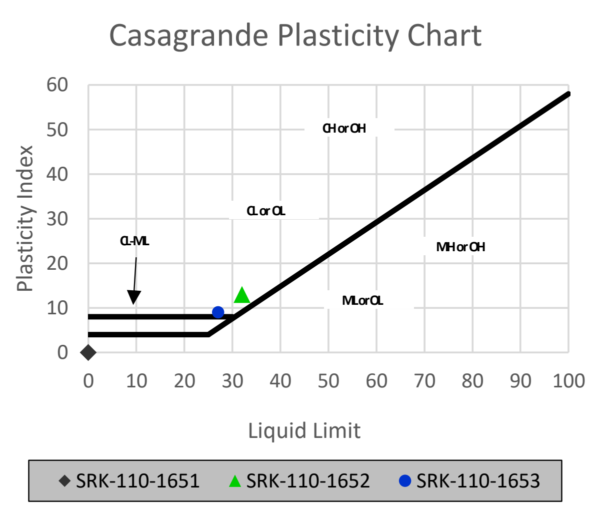
Quality | Excellence | On Time

Client Name: SRK Consulting
Project Name: 560333: Mareesburg TSF Phase 4
Job Number: SRK-110
Date: 2021-03-03
Method: SANS 3001 GR1, GR3, GR10 GR12 & BS 1377 (where applicable)

FOUNDATION INDICATOR	**Sheet Reference: R-STL-011 Rev02**







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FOUNDATION INDICATOR							Sheet Reference: R-STL-011 Rev02
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**			
Sample	TPB03	TPB04	TPB05	Sample	TPB03	TPB04	TPB05
Depth (m)	4.2 - 4.4	2.7 - 3.0	1.5 - 1.8	Depth (m)	4.2 - 4.4	2.7 - 3.0	1.5 - 1.8
Lab No	SRK-110-1663	SRK-110-1664	SRK-110-1665	Lab No	SRK-110-1663	SRK-110-1664	SRK-110-1665
53.0	**100**	**94**	**79**	Liquid Limit (%)	**55**	**29**	**37**
37.5	**100**	**92**	**74**	Plastic Limit (%)	**22**	**17**	**19**
26.5	**100**	**84**	**65**	Plasticity Index (%)	**33**	**12**	**18**
19.0	**100**	**78**	**60**	Linear Shrinkage (%)	**24.5**	**6.5**	**9.0**
13.2	**97**	**78**	**59**	PI of whole sample	**27**	**5**	**4**
9.5	**97**	**76**	**58**				
6.7	**96**	**76**	**56**	% Gravel	**7**	**29**	**55**
4.75	**96**	**75**	**54**	% Sand	**50**	**63**	**37**
2.00	**93**	**71**	**45**	% Silt	**16**	**6**	**5**
1.00	**90**	**60**	**33**	% Clay	**27**	**2**	**3**
0.425	**82**	**43**	**23**	Activity	**1.2**	**6.0**	**6.0**
0.250	**70**	**30**	**19**				
0.150	**61**	**22**	**15**	% Soil Mortar	**93**	**71**	**45**
0.075	**48**	**13**	**11**				
0.060	**43**	**8**	**8**	Grading Modulus	**0.77**	**1.73**	**2.21**
0.050	**41**	**7**	**7**	Moisture Content (%)	**23.1**	**21.2**	**21.2**
0.035	**38**	**5**	**6**	Relative Density (SG)*	**2.77**	**2.833**	**2.857**
0.020	**36**	**4**	**5**				
0.006	**31**	**3**	**4**	Unified (ASTM D2487)	**SC**	**SC**	**GP-GC**
0.002	**27**	**2**	**3**	AASHTO (M145-91)	**A - 7 - 6**	**A - 2 - 6**	**A - 2 - 6**

Remarks: *: Determined
N / T: Not Tested

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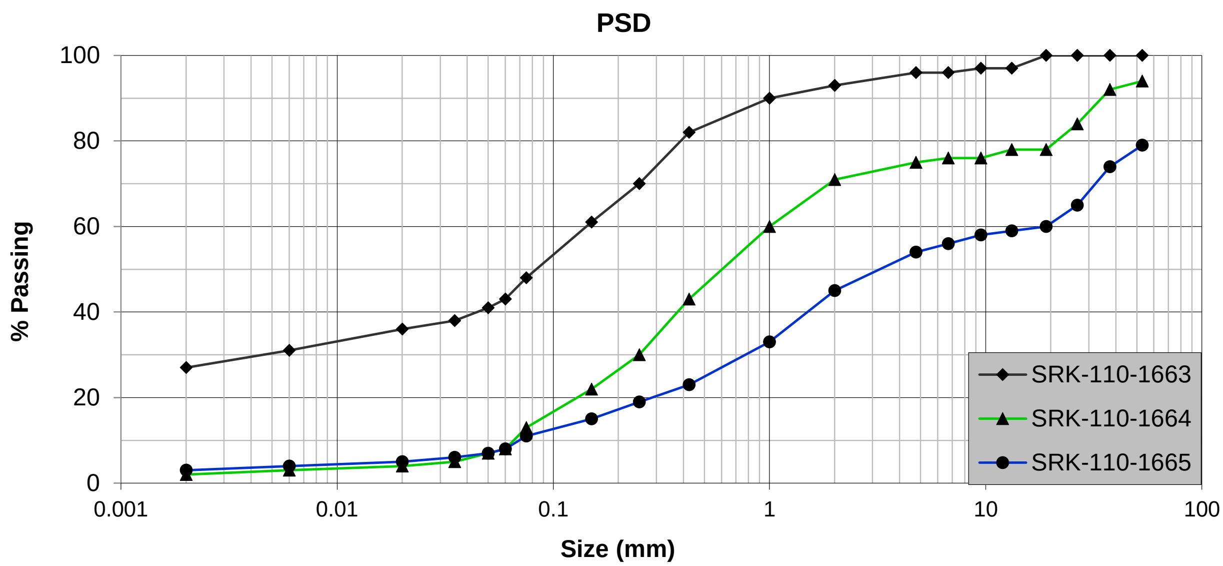
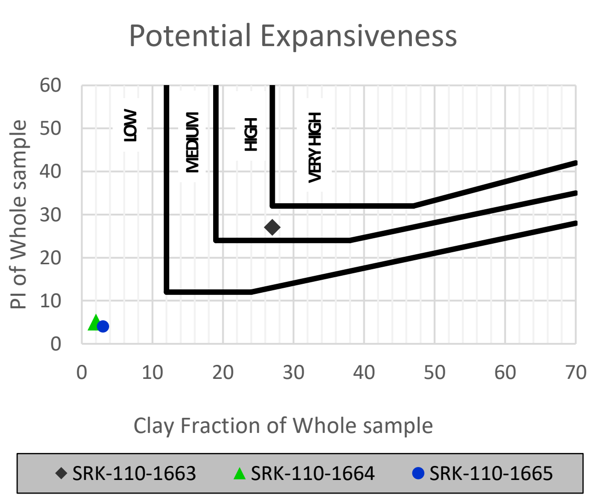
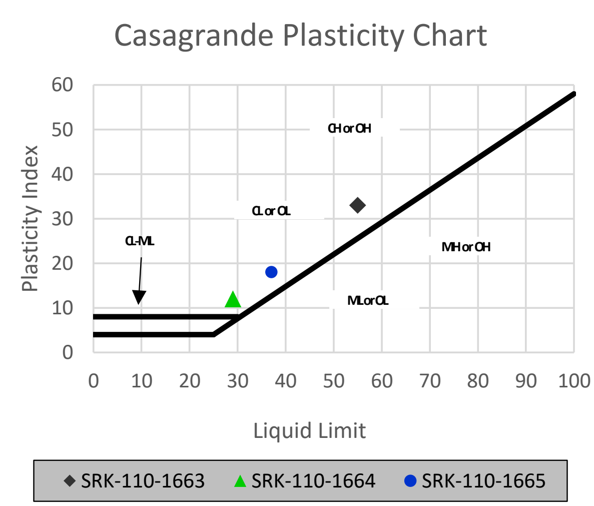
FOUNDATION INDICATOR	Sheet Reference: R-STL-011 Rev02







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FOUNDATION INDICATOR				**Sheet Reference: R-STL-011 Rev02**			
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**			
Sample	TPB05	TPC08		Sample	TPB05	TPC08	
Depth (m)	0.3 - 0.5	1.0 - 1.2		Depth (m)	0.3 - 0.5	1.0 - 1.2	
Lab No	SRK-110-1666	SRK-110-1667		Lab No	SRK-110-1666	SRK-110-1667	
53.0	**100**	**100**		Liquid Limit (%)	**69**	**71**	
37.5	**100**	**100**		Plastic Limit (%)	**27**	**28**	
26.5	**100**	**100**		Plasticity Index (%)	**42**	**43**	
19.0	**100**	**100**		Linear Shrinkage (%)	**30.5**	**29.5**	
13.2	**100**	**100**		PI of whole sample	**37**	**40**	
9.5	**100**	**100**					
6.7	**100**	**100**		% Gravel	**1**	**1**	
4.75	**100**	**100**		% Sand	**42**	**42**	
2.00	**99**	**99**		% Silt	**13**	**14**	
1.00	**96**	**98**		% Clay	**44**	**43**	
0.425	**89**	**93**		Activity	**1.0**	**1.0**	
0.250	**78**	**81**					
0.150	**71**	**71**		% Soil Mortar	**99**	**99**	
0.075	**60**	**62**					
0.060	**57**	**57**		Grading Modulus	**0.52**	**0.46**	
0.050	**55**	**55**		Moisture Content (%)	**42.2**	**8.8**	
0.035	**51**	**51**		Relative Density (SG)*	**2.735**	**2.757**	
0.020	**48**	**48**					
0.006	**46**	**45**		Unified (ASTM D2487)	**CH**	**CH**	
0.002	**44**	**43**		AASHTO (M145-91)	**A - 7 - 6**	**A - 7 - 6**	

Remarks: *: Determined
N / T: Not Tested

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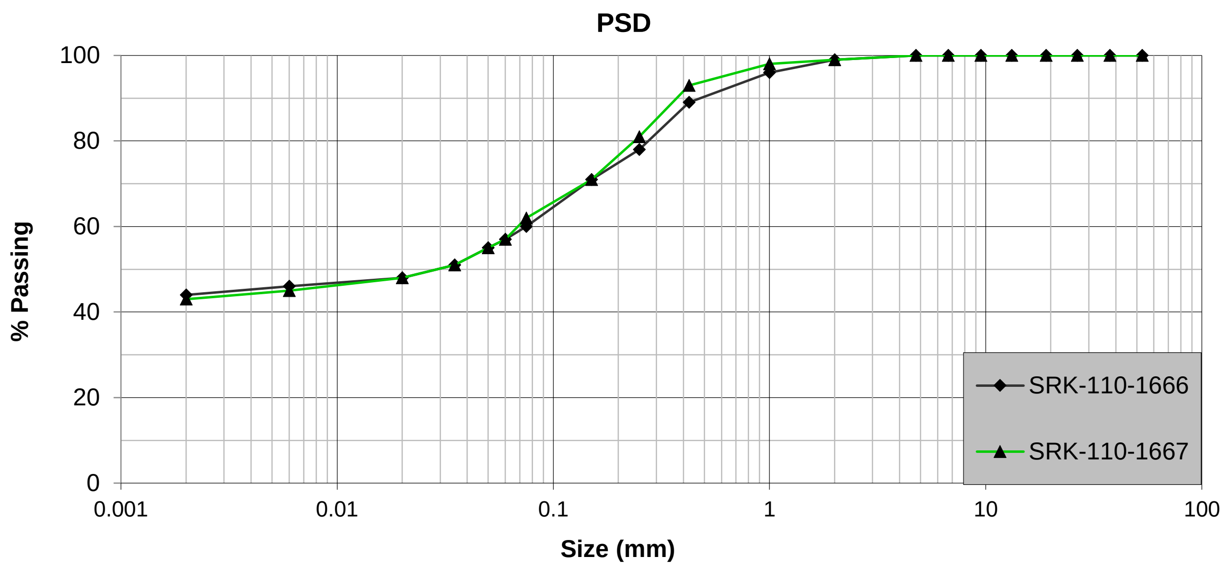
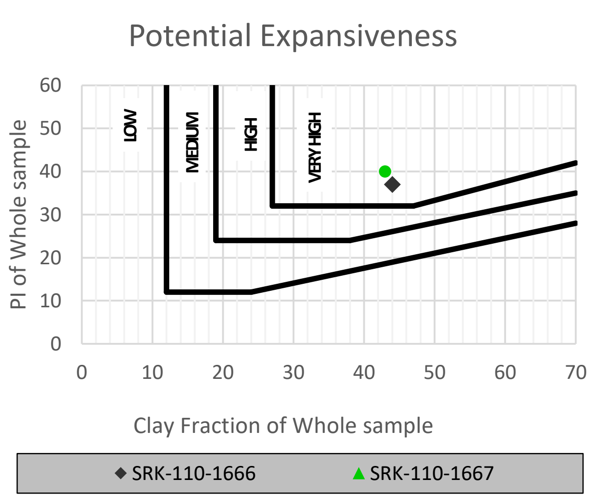
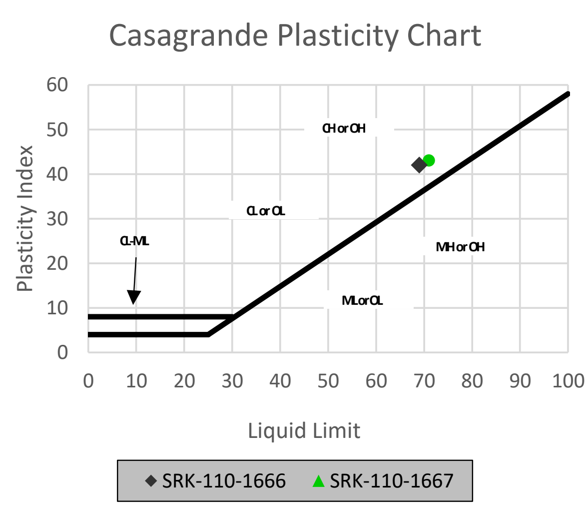
FOUNDATION INDICATOR

Sheet Reference: R-STL-011 Rev02







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FOUNDATION INDICATOR								Sheet Reference: R-STL-011 Rev02
Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**				
Sample	TPA09	TPA10	TPA12	Sample	TPA09	TPA10	TPA12	
Depth (m)	1.8 - 2.2	1.8 - 2.1	0.5 - 0.7	Depth (m)	1.8 - 2.2	1.8 - 2.1	0.5 - 0.7	
Lab No	SRK-110-1654	SRK-110-1655	SRK-110-1656	Lab No	SRK-110-1654	SRK-110-1655	SRK-110-1656	
53.0	**97**	**92**	**100**	Liquid Limit (%)	**29**	**-**	**62**	
37.5	**91**	**92**	**100**	Plastic Limit (%)	**19**	**-**	**27**	
26.5	**78**	**83**	**100**	Plasticity Index (%)	**10**	**SP**	**35**	
19.0	**68**	**75**	**100**	Linear Shrinkage (%)	**5.0**	**0.5**	**27.0**	
13.2	**68**	**75**	**100**	PI of whole sample	**2**	**-**	**28**	
9.5	**67**	**75**	**98**					
6.7	**65**	**73**	**97**	% Gravel	**58**	**55**	**9**	
4.75	**61**	**69**	**96**	% Sand	**38**	**43**	**44**	
2.00	**42**	**45**	**91**	% Silt	**3**	**1**	**19**	
1.00	**29**	**28**	**84**	% Clay	**1**	**1**	**28**	
0.425	**20**	**17**	**80**	Activity	**10.0**	**0.0**	**1.3**	
0.250	**15**	**10**	**74**					
0.150	**10**	**6**	**67**	% Soil Mortar	**42**	**45**	**91**	
0.075	**7**	**4**	**55**					
0.060	**4**	**2**	**47**	Grading Modulus	**2.31**	**2.34**	**0.74**	
0.050	**3**	**2**	**45**	Moisture Content (%)	**8.0**	**5.7**	**25.1**	
0.035	**2**	**1**	**42**	Relative Density (SG)*	**2.825**	**2.911**	**2.766**	
0.020	**2**	**1**	**38**					
0.006	**1**	**1**	**31**	Unified (ASTM D2487)	**SW-SC**	**SW**	**CH**	
0.002	**1**	**1**	**28**	AASHTO (M145-91)	**A - 2 - 4**	**A - 1 - a**	**A - 7 - 6**	

Remarks: *: Determined
N / T: Not Tested

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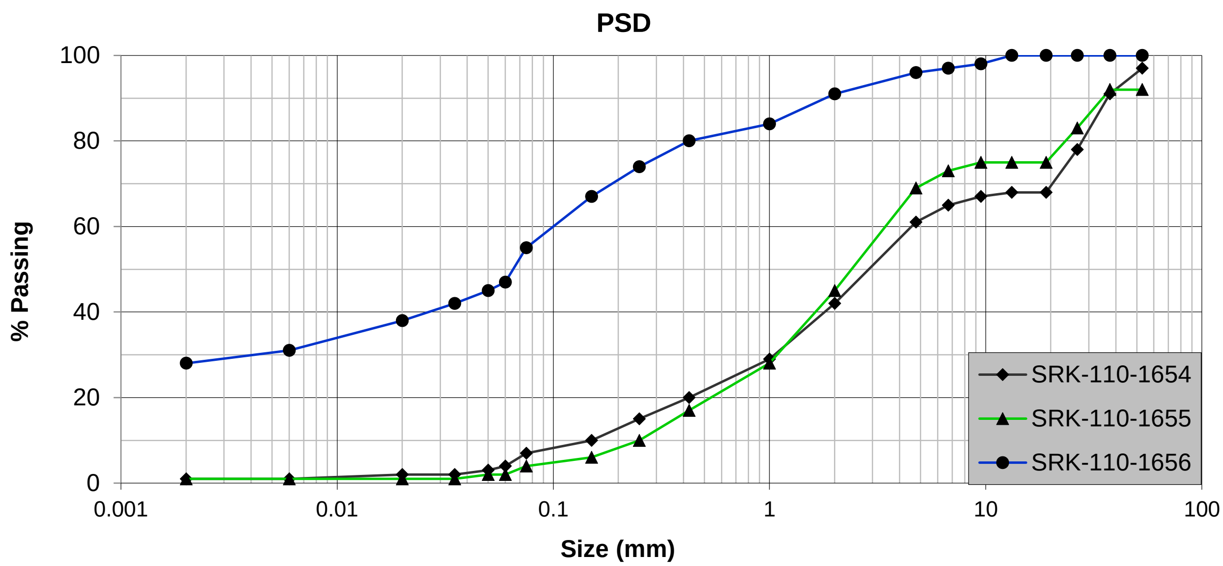

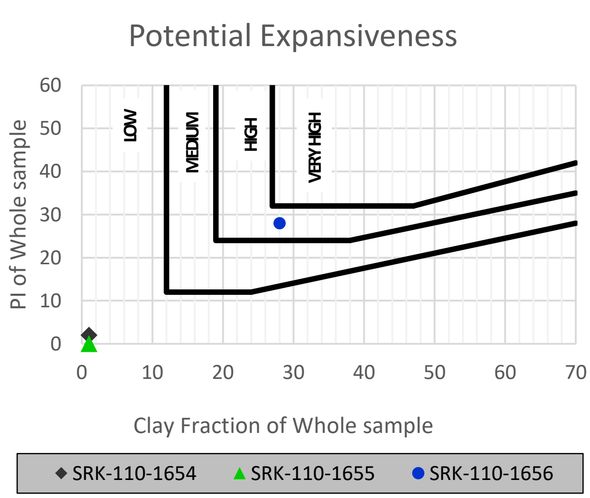

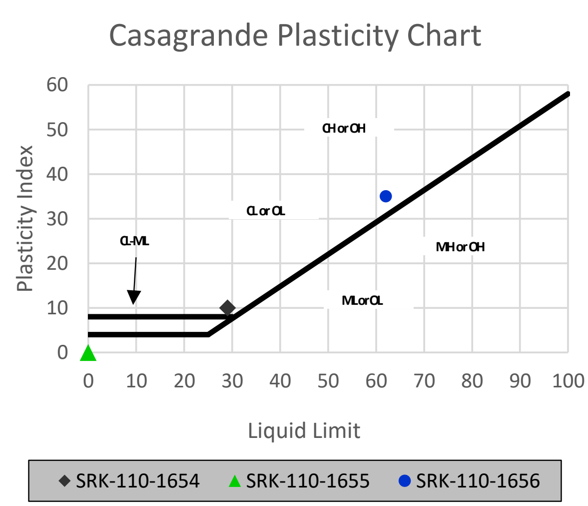

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Grading & Hydrometer Analysis (Particle Size (mm) & % Passing)				**Atterberg Limits & Classification**			
Sample	TPA01	TPA01	TPA04	Sample	TPA01	TPA01	TPA04
Depth (m)	0.2 - 0.4	1.0 - 1.4	0.3 - 0.5	Depth (m)	0.2 - 0.4	1.0 - 1.4	0.3 - 0.5
Lab No	SRK-110-1648	SRK-110-1649	SRK-110-1650	Lab No	SRK-110-1648	SRK-110-1649	SRK-110-1650
53.0	**62**	**100**	**100**	Liquid Limit (%)	**38**	**-**	**69**
37.5	**53**	**100**	**100**	Plastic Limit (%)	**17**	**-**	**31**
26.5	**50**	**100**	**100**	Plasticity Index (%)	**21**	**SP**	**38**
19.0	**47**	**100**	**100**	Linear Shrinkage (%)	**10.0**	**0.5**	**29.0**
13.2	**45**	**99**	**100**	PI of whole sample	**6**	**-**	**35**
9.5	**44**	**99**	**99**				
6.7	**43**	**98**	**98**	% Gravel	**61**	**18**	**3**
4.75	**42**	**98**	**98**	% Sand	**26**	**77**	**39**
2.00	**39**	**82**	**97**	% Silt	**8**	**4**	**14**
1.00	**34**	**48**	**95**	% Clay	**5**	**1**	**44**
0.425	**29**	**28**	**93**	Activity	**4.2**	**0.0**	**0.9**
0.250	**25**	**17**	**86**				
0.150	**21**	**12**	**77**	% Soil Mortar	**39**	**82**	**97**
0.075	**17**	**8**	**64**				
0.060	**13**	**5**	**58**	Grading Modulus	**2.15**	**1.82**	**0.46**
0.050	**12**	**4**	**56**	Moisture Content (%)	**18.4**	**10.0**	**38.5**
0.035	**10**	**3**	**52**	Relative Density (SG)*	**2.856**	**2.957**	**2.71**
0.020	**9**	**2**	**50**				
0.006	**6**	**1**	**46**	Unified (ASTM D2487)	**GC**	**SW-SM**	**CH**
0.002	**5**	**1**	**44**	AASHTO (M145-91)	**A - 2 - 6**	**A - 1 - b**	**A - 7 - 5**

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