Evaluating the functionality of different kimberlite mine wastes as alternative to building material

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DECLARATION

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LIST OF ABBREVIATIONS

AAR	Alkali-aggregate reaction
AASHTO	American Association of State Highway and Transportation Officials
Agg.	Aggregate
AIV	Aggregate Impact Value
ASR	Alkali-Silica Reaction
ASTM	American Society for Testing and Materials
BIC	Bushveld Igneous Complex
BIS	Bureau of Indian Standard
BSI	British Standards Institution
COLTO	Committee of Land Transportation Officials
CPHT	Carats per hundred tons
CRD	Coarse Residue Deposits
FRD	Fine Residue Deposits
HK	Hypabyssal Kimberlite
IMC	International Building Code
ISO	International Organisation for Standardisation
MoRTH	Ministry of Road Transport and Highways
NWU	North West University
PSD	Particle Size Distribution
P-XRF	Portable X-ray Fluorescence
REE	Rare Earth Elements
SABS	South African Bureau of Standards
SANS	South African National Standards
SCP	Safety Critical Product
TK	Tuffisitic Kimberlite
TKB	Tuffisitic Kimberlite Breccia
TSF	Tailings Storage Facility

UGW	Under-Ground Waste
VK	Volcaniclastic Kimberlite
WRD	Waste Residue Deposits
XRD	X-ray Diffraction
XRF	X-ray Fluorescence

ABSTRACT

Kimberlite diamond mines tend to produce vast amounts of rock-derived waste that are ultimately stored and rehabilitated at high cost to the mining company. Diamond mine rock waste does not always contain the same cocktail of hazardous elements typically associated with other mining commodities' rock waste. Repurposing this material in a creative, optimised way could lead to value creation. Instead of rehabilitation, this project suggests that using various types of rock waste could replace aggregate or other components in the manufacture of building-related products. This could allow mining companies, building material manufacturers and the local community to work together to produce an environmentally friendly and economically viable product. Previous studies have found that kimberlite waste could be used in a range of products, from aggregates to cement to clinker bricks and more. The few studies that have been done have mostly concerned themselves with local bureau of standards requirements, using various testing methodologies. This project investigates mine rock waste from five Southern African sites, examining 25 different materials. The tests conducted followed the South African Board of Standards (SABS) and other key quality bureau methods to assess compliance for a safety-critical product, with a focus on aggregate compliance tests due to time constraints. Information from different textural tests, aggregate impact value (AIV), chemistry (XRF), and mineralogy (XRD) helps assess the potential usage of 25 different materials. Results showed that all materials met SANS 1083/1090 density requirements, but most tailings failed on grading, fineness modulus and dust content due to excessive fines. Waste rocks graded well and achieved acceptable Aggregate Impact Values. Mineralogy was the dominant limiting factor: high phyllosilicate and clay content made most tailings and waste rocks unsuitable for concrete aggregate. Only a dolomite-dominant group and a feldspar/pyroxene-rich Voorspoed group showed conditional potential. Unsuitable materials often contained clay or phyllosilicate minerals suited to light aggregate or clay brick production, a viable beneficiation pathway.

Keywords: Kimberlite; Tailings; Sustainable mining; Aggregate; Concrete; SABS; Clay.

OPSOMMING

Kimberliet-diamantmyne produseer gewoonlik groot hoeveelhede rotsafval wat teen die einde van n myn se lewe teen hoë koste deur die mynmaatskappy gestoor en gerehabiliteer word. Diamantmyn rots afval bevat nie altyd dieselfde mengsel van gevaarlike elemente wat meer bekend is in ander mynbou kommoditeite se rotsafval nie. Die hergebruik van hierdie materiaal op 'n kreatiewe en doeltreffende manier kan tot waardeskepping lei. In plaas van rehabilitasie stel hierdie projek voor dat die gebruik van die verskillende tiepes rotsafval moontlik as 'n plaasvervanger vir aggregaat, of ander komponente in die vervaardiging van bouverwante produkte gebruik kan word. Dit kan mynmaatskappye, boumateriaalvervaardigers en die plaaslike gemeenskap in staat stel om saam te werk om 'n omgewingsvriendelike en ekonomies lewensvatbare produk te produseer. Vorige studies het bevind dat kimberliet-afval moontlik in 'n verskeidenheid produkte gebruik kan word, wat wissel van aggregate tot sement tot klinkerstene en vele meer. Die paar studies wat gedoen is, het verskeie tiepes toetsmetodologieë gevolg, meestal gemoeid met hul plaaslike buro vir standaardevereistes. Hierdie projek ondersoek mynrotsafval van vyf verskillende Suider-Afrikaanse lande en kyk na 25 verskillende geologiese materiale. Die toetse wat uitgevoer is, het die Suid-Afrikaanse Raad van Standaarde (SABS) en ander belangrike kwaliteitsburo-metodes gevolg om voldoening aan 'n veiligheidskritieke produk te bepaal, waar die fokus op aggregaat-nakomingstoetse geplaas is weens tydsbeperkings. Inligting gebaseer op verskillende tekstuurtoetse, aggregaat-impakwaarde (AIV), chemie (XRF) en mineralogie (XRD) help om die potensiële gebruik van die 25 verskillende materiale te bepaal. Resultate het getoon dat alle materiale aan SANS 1083/1090 digtheids vereistes voldoen het, maar die meeste mynuitskot het misluk op gradering, fynheidsmodulus en stof inhoud as gevolg van oormatige fynstowwe. Afvalgesteentes het goed gegradeer en aanvaarbare Aggregaat-impakwaardes behaal. Mineralogie was die dominante beperkende faktor: hoë filosilikaat- en klei-inhoud het die meeste mynuitskot en afvalgesteentes ongeskik gemaak vir betonaggregaat. Slegs 'n dolomiet-dominante groep en 'n veldspaat/pirokseen-ryke Voorspoed-groep het voorwaardelike potensiaal getoon. Ongeskikte materiale het dikwels klei- of filosilikaatminerale bevat wat geskik is vir ligte aggregaat- of kleibaksteenproduksie, 'n lewensvatbare veredelingsroete.

Sleutelwoorde: Kimberliet; Mynuitskot; Volhoubare mynbou; Aggregaat; Beton; SABS; Klei.

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Chapter 1: Introduction

1.1 Background

Humans have been using the available mineral resources for thousands of years to construct features, some of which can still be viewed today, whilst others not so much (Courland, 2022:23). Numerous types of materials have been used to construct features throughout the years and were, for most of human history, related to their intended purpose and the available resources. The 16th-century explorer Francisco de Orellana made claims of massive and sophisticated cities along the Amazon River, which were for years accepted as make-believe and inspired numerous expeditions for their search (Rostain *et al*., 2024:183). It was only recently that studies were able to uncover these lost cities with the help of LIDAR, proving their existence and that their heavy reliance on perishable wood material was to blame for their disappearing act (Rostain *et al*., 2024:183). The invention of concrete, however, changed this practice in its entirety as a more suitable method of construction that can outlast generations (Courland, 2022:23). The use of concrete made it possible to push the boundaries of what could be built, with prime examples of the Roman era still with us today after thousands of years (Courland, 2022:23).

Modernisation and urbanisation are still taking place at a considerable pace, which brings up questions about sustainability from an environmental and financial point of view (UN, 2025a). The products need to be of acceptable quality, but also need to be financially viable to be successful (UN, 2025a). The building blocks of most masonry units are composed of aggregate (either just fine or with coarse texture) and cement, and have become one of the staples of a modern building structure (CMA, 2005:4; AfriSam, 2021a:1-2). Both of these components that make up this masonry unit are sourced from the lithosphere and can potentially be viewed as a limited resource due to their limited availability and costs associated with their processing, influencing their accessibility (USGS, 2024).

Mines tend to target a specific ore, but in the process have to discard enormous amounts of waste rock derived from either stripping or tailings derived from processing phases of mining (Hodgson, 1981; Aslam, 2021:3; USGS, 2024). Kimberlite diamond mines tend to produce only a few carats of diamonds per hundred tons, and therefore leave behind an enormous pile of rock waste which will in almost all cases have to be rehabilitated to comply with environmental laws (Lynn *et al*., 1998:238-239; Damarupurshad, 2006; Field *et al*., 2008:35-68; Aslam, 2021:3; Tanner & Möhr-Swart, 2007:8-9). This increases the overall processing cost of the mine and endangers the longevity of the mining project if thorough pre-emptive planning isn't undertaken (Tanner & Möhr-Swart, 2007:54-55). Other issues might arise which

endanger people living close to it, like the tailings dam failure events of Jagersfontein Mine, South Africa and Williamson Mine, Tanzania, both of which occurred in 2022 and took lives (Motsau & van Wyk, 2022:29; Marais *et al*., 2024:2).

An alternative to rehabilitation is to repurpose the waste by turning it into another product or to find use for it as a replacement in existing products (Tanner & Möhr-Swart, 2007:20). This has the advantage in that it might be financially viable, thereby increasing profits and minimalizing wastage with the same initiative, achieving sustainability in other words. Re-assessment of tailings are becoming more common in the mining industry, with focus on carbon sequestration and rare-earth mining being evaluated for the diamond sector (Chakravarthy *et al*, 2020:1-2; Mervine *et al*., 2020:761-764; Jones, 2023:4-7; Rifkhan *et al*., 2024:3).

Highly weathered materials, such as those found in tailings dams, are characterised by three main types of mineral groups, namely: silicate clays, Fe- and Al-oxide clays, and resistant primary minerals that might have industrial applications (Weil & Brady, 2017:55; Chaurasiya & Markandeya, 2021:534-537). The diamond mining industry is not as shiny as it used to be, with numerous factors to blame. Finding an alternative income source, especially by re-utilising one of its negative resources and turning it into a positive one, might be a welcome relief for this highly pressured industry. This concept of waste-to-resource can help create a circular economic model with wide-reaching impacts.

1.2 History of diamond mining

Diamonds have been known since antiquity and were first historically mined from alluvial gravels in India by at least 800 BCE, according to the astronomer Ptolemy (Bruton, 1978:23) or at least 200 AD by Kautilya (Rangarajan, 1992:819), and Borneo by about 960 AD (Legrand, 1980:182; Tavernier, 1676) (Janse & Sheahan, 1995:95; Lynn *et al*., 1998:232). By the 1790's, alluvial diamonds were found in parts of Brazil (Bardet, 1976; Janse & Sheahan, 1992:75; Legrand, 1980:182) and Venezuela, thereby dethroning India as the major producer globally for the time being (Lenzen, 1970; Legrand, 1980:28; Janse & Sheahan, 1995:95; Janse, 2007:117). This was the case until the discovery of South Africa's vast diamond deposits during the 1860s (Janse & Sheahan, 1995:89). It was only then that South Africa became a major player in the diamond market, when, during the 1870s, diamonds were becoming available for a much larger audience (Janse, 1995:104). This was thankfully due to discovery of their primary source rock a few years later, which took the name "kimberlite" as a tribute to the town of its discovery (Lewis, 1888; Wagner, 1914:78; Field *et al*., 2008:35; Janse & Sheahan, 1995:85; Scott Smith *et al*., 2018:47). Since then, many research and man hours have been dedicated to understand these features fundamentally and to identify their possible

locations and diamond bearing potential. Kimberlite mining contributed to almost all of the diamonds mined in these early periods until the 1910s to 1960s, when alluvial accounted for 96% of diamond production during this period (Janse, 2007:104). This only changed when a new focus was set on kimberlite exploration again, and on not only South Africa but also across the world (Janse, 2007:105).

1.3 Study area

Southern Africa has a host of diamond bearing kimberlites (Wagner, 1914:1-4; Field *et al*., 2008:33). There are currently 15 large scale kimberlite mines that have been, or is still, in production in this region with numerous smaller scale ones in the region (Field *et al*., 2008:33). The diversity found between individual kimberlites of different sites, and even found in the same structure make it a difficult geological feature to describe accurately (Skinner, 1989:530). A study like this is therefore reliant on the availability of testing material from various mines to ensure that a thorough consensus can be made on the potential of kimberlite tailings. Of the five mines studied, only two granted permission for their names to be mentioned in this thesis: Koffiefontein and Voorspoed. Therefore, all reasonable steps were taken to withhold any information that could aid in identifying the three remaining mines that preferred to remain anonymous. All that can be revealed is that all the mines studied were from Southern Africa.

1.4 Problem statement and substantiation

In the current mining industry, environmental aspects are becoming a more pressing issue as legislation is continually amended to enforce ethical practices (Tanner & Möhr-Swart, 2007:63-64; Marais et al., 2024:8). This can impose enormous financial strain on the company and severely impact the mine's lifespan. One of the pressing issues is the handling of mine wastes like the various types of rock material that ultimately form part of the tailings storage facility (TSF) (Tanner & Möhr-Swart, 2007:122-124; Motsau & van Wyk, 2022:4; Marais *et al*., 2024:4). These wastes are commonly rehabilitated at high costs to the mining company and must be monitored regularly (Tanner & Möhr-Swart, 2007:122-124; Motsau & van Wyk, 2022:4; Marais *et al*., 2024:4). If alternate uses can be devised for these wastes, the mine can potentially rid itself of one major issue surrounding mines, literally, and turn a profit in doing so.

Repurposing kimberlite tailings, or host-country waste rock, as replacements in certain building materials can help reduce overall CO_2 emissions from the mining sector and make the diamond mining sector a more environmentally and economically sustainable business model. Studies such as Swami et al. (2007), Chakravarthy et al. (2020), Otieno & Ndoro (2020), Pashkevich & Alekseenko (2020), and Chaurasiya & Markandeya (2021) indicate the

potential for using kimberlite tailings in various building materials. The above-mentioned studies, and others like them, have gotten satisfactory results and suggested that further studies should be conducted to verify their claims. The tests conducted by the above-mentioned studies also stressed the importance of using standardised methods to assess their properties to make them replicable and closely resemble the conditions under which they will be when assessed for quality clearance (Swami *et al*., 2007:131; Chakravarthy *et al*., 2020:4; Otieno & Ndoro, 2020:1260-1261; Pashkevich & Alekseenko, 2020:3; Chaurasiya & Markandeya, 2021:536). Most of the studies presumably made use of fresh kimberlite tailings, which disregards the highly weatherable nature of the material. The studies typically focus only on a specific mine, disregarding inter and intra mine variability of the kimberlite orebody and any other possibly useful rock material. Limited integration between mineralogical properties and safety standards were also of concern. The regulatory body of South Africa is known as the South African Board of Standards (SABS) and is responsible for quality assurance and conformity compliance of any material sold on the market by upholding the South African National Standards (SANS) documents (SABS, 2025).

1.5 Research aims

To establish if kimberlite-derived tailings and country-rock derived waste from diamond mines comply with concrete aggregate quality standards under SANS 1083, 1090, and 794 requirements.

1.6 Research objectives

1. To evaluate aggregate qualities by conducting the required tests, as recommended by SANS 1083, 1090, and 794.
2. To evaluate if country-rock derived waste materials are more suitable than kimberlite-derived tailings in concrete.
3. To evaluate how mineralogical variability influences aggregate performance.
4. To establish if other building material products might be possible.

1.7 Basic hypothesis

Kimberlite-derived tailings will show lower mechanical performance and higher weathering susceptibility than country-rock derived waste rock due to elevated phyllosilicate and altered mineral content. Therefore kimberlite-derived tailings will be expected to be unsuitable for use in concrete, whilst country-rock derived waste will be expected to be much more suitable.

Chapter 2: Literature study

2.1 Kimberlite characteristics

Kimberlites are known to be a highly complex geological material with mineralogy and structure being almost unique to each locality, especially for Group II kimberlites (Mitchell, 1986:9; Wooley *et al*., 1996:177; Mitchell, 2006; Field *et al*., 2008:36; Scott Smith *et al*., 2018:47; Sarkar *et al*., 2023:2). Their hybrid nature has led to various interpretations and classifications over the years (Field *et al*., 2008:36; Scott Smith *et al*., 2018:47). In-depth petrographic investigations are typically necessary when studying kimberlites due to mineralogical complexity, the presence of xenoliths, deuteric or metasomatic alteration and typical magma contamination processes (Skinner & Clement, 1982:305; Scott Smith *et al*., 2018:47). It is therefore important to make use of abundant samples and thorough examination of the rock suite before recognizing it as a kimberlite, because sometimes not all of the typomorphic minerals are present in a single sample (Scott Smith *et al*., 2018:47).

2.1.1 Classification system of kimberlites

For the reader's convenience, a short history of kimberlite classification is given as background information and recommends Scott Smith *et al*. (2018) or any of the other works mentioned here for further reading, if so required. At first, the hard rock source material hosting the diamonds were referred to as an “eruptive tuff” in 1872 by Professor E. Cohen (Wagner, 1914:78; Mitchell, 1995; Field *et al*., 2008:35) but was later recognised as being unique and subsequently called a “kimberlite” by Professor H.C. Lewis in 1887 (Lewis, 1888; Wagner, 1914:78; Field *et al*., 2008:35; Janse & Sheahan, 1995:85; Scott Smith *et al*., 2018:47). It was Wagner (1914) who was able to give the first classification framework for the grouping of kimberlites and grouped them as either “basaltic” or “micaceous”. The classification was based on their composition and structure (Wagner, 1914:78). They are referred to as “basaltic kimberlite” for the mica-poor variety, which Professor H.C. Lewis first described, whilst the “micaceous or lamprophyric kimberlite” is rich in mica and devoid of augite (Wagner, 1914:78-107). Williams (1932) and Holmes & Theobald (1937) also contributed to the earliest terminology related to kimberlites. Only much later did other important advances happen, as those were made by Dawson (1962, 1971, 1980), Mitchell (1970, 1986, 1995), Hawthorne (1975), Clement and Skinner (1985) and Field and Scott Smith (1998), to name a few (Scott Smith *et al*., 2018:i).

Smith (1983) amended the principles of Wagner (1914), renaming the “basaltic” to Group I kimberlites and the “micaceous” to Group II kimberlites. This interpretation divided kimberlites

into the Group I kimberlites as the olivine-rich monticellite-serpentine-calcite kimberlites with less than 5% mica content, and Group II kimberlites as micaceous kimberlites with more than 50% mica content (Smith, 1983; Lynn *et al*., 1998:236). The isotopic affinities of the different groups of kimberlites, as indicated by their Nd, Sr and Pb signatures, coincided with the original groupings made by Wagner (1914) and were firmly established by subsequent studies (Smith *et al*., 1985; Skinner, 1989; Wooley *et al*., 1996; Pearson *et al*., 2019:387-392). The kimberlite Group I indicated slightly depleted Sr-Nd signatures compared to bulk earth and radiogenic Pb signatures, whilst kimberlite Group II indicated a significant Sr-Nd enrichment signature compared to bulk earth, with no unradiogenic Pb signatures (Smith, 1983; Mitchell, 1995:250; Field *et al*., 2008:36; Pearson *et al*., 2019:391). The classification of kimberlites was later amended by Mitchell (1995:376) to the same groupings as used by Smith *et al.* (1985). However, it discouraged any close relationship between Group I and Group II kimberlites, as Group II kimberlites had more similar properties with lamproites than with Group I kimberlites.

It was recommended by Mitchell (1995:250,376) that the term “orangeites” should be used instead of Group II kimberlites as originally proposed by Wagner (1928). Both the terms “Group II kimberlite” and “orangeites” are accepted by the IUGS classifications as valid, as long as it is recognised that they are vastly different from Group I kimberlites (Woolley *et al*., 1996:184). The study by Kononova et al. (2011) examined the chemical relationships among 540 potassic rocks using R-factor analyses. Amongst the various important findings, the Sr-Nd relationship between the kimberlites and lamproites indicated the closer relationship of Southern African lamproites to Australian lamproites than Group I kimberlites, meriting the concept of orangeites to be the accepted classification of South African lamproites (Kononova *et al*., 2011:43). This coincides with findings of Mitchell and Bergmann (1991) (Winter, 2014:441).

The glossary of Scott Smith *et al*. (2018) is considered to be the most recent publication on the terms related to kimberlites that are widely accepted. The currently accepted classification, according to Scott Smith *et al*. (2018:47), is the term kimberlite for Group I kimberlites and will follow the definition of Lewis (1887;1888), whilst lamproite will replace the Group II kimberlite and orangeite as the accepted name for the material typically described as the micaceous kimberlite, as described by Wagner (1914).

2.1.2 Definition of kimberlite and lamproite

To truly appreciate the complexity and diversity of kimberlites, it is necessary to understand the properties that define and group them. As previously mentioned, the mineral diversity of kimberlites varies greatly between the various types and locations, and even within the same structure (Mitchell, 1986:9-11; Field *et al*., 2008:37). The mineralogical diversity and properties

have been refined with each passing study (Lewis, 1888; Wagner, 1914; Mitchell, 1970; Clement & Skinner, 1982; Mitchell, 1995; Morkel, 2006). A kimberlite, according to Lewis (1888:2), was initially defined as the 'diamond-bearing matrix' or as a 'diamond-bearing peridotite'. The kimberlites at the time of Lewis (1888) descriptions were that of Bultfontein, De Beers, Kimberley, Du Toitspan, Koffiefontein and Jagersfontein, which are all today classified as Group I Kimberlite or simply kimberlite (Smith, 1983; Field *et al*., 2008:34). Even then some of the scientists acknowledged the complexity of the geologic material and the possible frustrations it will possibly cause in scientific circles of the future (Lewis, 1888:3-5).

A lot has changed over the years on the interpretation of kimberlites, mostly based on their mineralogical, chemical, textural, genetic and other characteristics that set them apart from other geological materials (Lewis, 1888; Wagner, 1914; Skinner & Clement, 1982:304; Smith, 1983; Mitchell, 1995; Wooley *et al*., 1996:177; Kononova *et al*., 2011:34; Scott Smith *et al*., 2018:45-46). The definition of kimberlites made by Skinner & Clement (1982:305) was the first most widely accepted definition (Field *et al*., 2008:36). This was further developed by Mitchell (1986) to help describe the mineralogical diversity associated with a magmatic material originating from extraordinary depths, that incorporates host rocks, to form a hybrid material with unique properties. Mitchell's (1986:9-11) definition is considered more petrologically complete, as the role of the constituent mineral's composition is emphasised more (Field *et al*., 2008:36). The current understanding and most accepted terminology for kimberlites were compiled by Scott Smith *et al*. (2018:45-46).

For the ease of the reader, the latest definition of a kimberlite is given, though not in full, as according to Scott Smith (2018:45-46):
"Kimberlites are a group of volatile-rich (H_2O and CO_2 commonly up to or > 5 and 10 wt.%, respectively), potassic (low Na_2O/K_2O ratios < 0.5; < ~0.5 wt.% Na_2O; up to ~3 wt.% K_2O), ultrabasic, olivine-rich (~50 modal %), silica-undersaturated igneous rocks derived from a deep asthenospheric mantle source and typically exhibit a distinctive inequigranular texture resulting from the presence of macrocrysts set in a finer-grained matrix. The matrix to the macrocrysts consists of microphenocrysts of olivine and less common phlogopite and Mg-Cr-Ti-rich spinels set in a groundmass which might contain monticellite, phlogopite-kinoshitalite solid solutions, perovskite, spinel, apatite, carbonate (calcite and/or dolomite) and serpentine. Feldspar, feldspathoids, clinopyroxene and amphibole are not typomorphic minerals and are not found in contamination-free kimberlites … kimberlites are particularly susceptible to weathering, especially in tropical environments"

The above-mentioned definition only includes the properties of kimberlites and not of lamproites (Mitchell, 1995; Wooley *et al*., 1996; Kononova *et al*., 2011:34; Scott Smith, 2018:vi; Sarkar *et al*., 2023:1-2). The definition of a lamproite is more difficult to constrain, especially on a global scale, as they differ considerably between localities (Kononova *et al*., 2011:43; Sarkar *et al*., 2023:1-2). It is for this reason that both the definition of orangeites and lamproites will be given, as this study focused on South African examples which are proven to be more similar to lamproites than kimberlites, but does differ from other examples globally and could in some cases be considered "transitional kimberlites" (Mitchell, 1995; Wooley *et al*., 1996:179; Kononova *et al*., 2011:43; Sarkar *et al*., 2023:8).

The definition of an orangeite, according to Mitchell (1995:14), is:
"Orangeites are a clan of ultrapotassic peralkaline volatile-rich (dominantly H_2O-rich) rocks, characterised by the presence of phlogopite macrocrysts and microphenocrysts, together with groundmass micas, which vary in composition from phlogopite to tetraferriphlogopite. Rounded olivine macrocrysts and euhedral primary olivines are common, but are not always major constituents. Characteristic primary groundmass phases include diopside, commonly zoned to and mantled by titanian aegirine, spinels ranging in composition from Mg-chromite to Ti-magnetite, Sr- and REE-rich perovskite, Sr-rich apatite, REE-rich phosphates (monazite, daqingshanite), potassian barian titanates belonging to the hollandite group, potassium triskaidecatitanates, Nb-rutile, and Mn-ilmenite. These are set in a mesostasis that may contain calcite, dolomite, ancylite, and other rare-earth carbonates, witherite, norsethite, and serpentine. Evolved members of the group contain groundmass sanidine and potassium richterite. Zirconium silicates (wadeite, zircon, kimzeyitic garnets, Ca-Zr silicate) are common as late-stage groundmass minerals. Quartz may occur rarely as a mesostasis mineral. Barite is a common secondary mineral.
Orangeites may be distinguished from kimberlites by the absence of monticellite, magnesian ulvöspinel, and Ba-rich micas belonging to the barian phlogopite-kinoshitalite series. In addition, orangeites, in common with kimberlites and lamproites, do not contain melilite, alkali feldspar, plagioclase, kalsilite, or nepheline."

The definition of a lamproite, according to Wooley *et al*. (1996:179-180), based on Mitchell & Bergman (1991), is:
"Lamproites are characterized by the presence of widely varying amounts (5-90 vol.%) of the following primary phases: (1) titanian (2-10 wt% TiO), aluminum-poor (5-12 wt% Al_2O) phenocrystic phlogopite, (2) titanian (5-10 wt% TiO) groundmass poikilitic "tetraferriphlogopite", (3) titanian (3-5 wt% TiO) potassium (4-6 wt% K_2O) richterite, (4) forsteritic olivine, (5) aluminum-poor (<1 wt% Al_2O_3*), sodium-poor (<l wt% Na_2O) diopside, (6)*

non stoichiometric iron-rich (14 wt% Fe_2O_3*) leucite, and (7) iron-rich sanidine (typically 1-5 wt%* Fe_2O_3*). The presence of all the above phases is not required to classify a rock as a lamproite. Any one mineral may be dominant, and this, together with the two or three other major minerals present, suffices to determine the petrographic name. Minor and common accessory phases include priderite, wadeite, apatite, perovskite, magnesiochromite, titanian magnesiochromite, and magnesian titaniferous magnetite; less commonly, but characteristically, jeppeite, armalcolite, shcherbakovite, ilmenite and enstatite are also present. The presence of the following minerals precludes a rock from being classified as a lamproite: primary plagioclase, melilite, monticellite, kalsilite, nepheline, Na-rich alkali feldspar, sodalite, nosean, hauyne, melanite, schorlomite or kimzsyite. Lamproites conform to the following chemical characteristics: molar* $K_2O/Na_2O > 3$*, i.e., ultrapotassic, (2) molar* $K_2O/Al_2O_3 > 0.8$ *and commonly > 1, (3) molar* $(K_2O + Na_2O)/Al_2O_3$ *typically > 1 i.e., peralkaline, (4) typically <10 wt% each of FeO and CaO, TiO, 1-7 wt%, >2000 and commonly >5000 ppm Ba, >500 ppm Zr, >1000 ppm Sr and >200 ppm La."*

2.1.3 Differences

Some of the most important differences between kimberlites and lamproites are that kimberlites have a lower K and H_2O composition, a higher CO_2 composition and more geochemically depleted Sr-Nd isotope signature than lamproites (Smith, 1983; Mitchell, 1995:15; Pearson *et al*., 2019:391; Kononova *et al*., 2011:43). Other important differences, especially between kimberlites and orangeites based on mineralogy, was summarised by Mitchell (1995:11-13) by making use of Mitchell (1986:9-11) and Skinner (1989). Orangeites are characterised by the absence of Cr-poor titanium pyrope garnets, enstatite, Mg-ilmenites and subcalcic diopside macrocrysts, as well as Ba-rich aluminous micas, monticellite, magnesian ulvospinels and some other spinel species related to kimberlites being absent (except in very rare cases) (Mitchell, 1995:11-13). Other important differences are that orangeites contain primary microphenocrystalline diopside in the groundmass, with sanidine and potassium richterite being rare, micas that have evolved from phlogopite to tetraferriphlogopite, K-Ba titanates, zirconium silicates, REE-enriched perovskites, and apatite crystals, as opposed to kimberlite specimens, and a more diverse carbonate assemblage (Mitchell, 1995:11-13). From a mineralogical point of view, the differences between orangeites and lamproites remain, such as the abundance of primary carbonate in orangeites compared to lamproites, which have it only in rare occurrences, and the absence of fluorine in orangeites (Mitchell, 1995:376).

It is important to remember that these described properties might sound narrow and tightly confined, but the complex nature of kimberlites and lamproites is what makes it difficult to

comprehend and hard to explain without causing disagreements (Skinner & Clement, 1982:305; Taylor, 1998:893; Scott Smith *et al*., 2018:48; Sarkar *et al*., 2023:1-2).

2.2 Characteristics of Southern African kimberlites and lamproites

The understanding and diversity of minerals found across various diamond deposits have changed considerably over the years and have contributed to the development of detailed mineralogical data for most mines (Wagner, 1914:89; Kononova *et al*., 2011:38; Scott Smith *et al*., 2018:I). There are many kimberlites and lamproites in Southern Africa, but only a few have been mined or studied extensively (Field *et al*., 2008:35; de Wit *et al*., 2016:199). The article by Field et al. (2008) is recommended, as it describes the history, geology, and diamond statistics of 15 large-scale and 19 small-scale diamond mines in Southern Africa. Another, more recent investigative review of African kimberlites was conducted by de Wit *et al*. (2016) and is also highly recommended. Only the mines investigated during this study will be discussed in detail.

2.2.1 Brief geology of selected Southern African kimberlites and lamproites

2.2.1.1 Koffiefontein

The mine is situated right next to the town of its name's sake. The kimberlite material from Koffiefontein was described by Wagner (1914:89) as having a distinct blue-grey colour and containing fragments of country rocks such as shale, granite, and pegmatite, with no floating reefs present. Much later Clement (1982:64) described Koffiefontein as having three different kimberlite facies namely, i) KOF1, which makes out most of the kimberlite pipe and is classified as a Tuffisitic Kimberlite Breccia (TKB), ii) KOF2, which is found in the West Dyke Extension and is very similar to KOF1 apart from diamond grades, and, iii) KOF3, which is found in the East Dyke Extension and is classified as a hypabyssal facies kimberlites. Another important observation of Clement (1982:69) was that a large floating reef of various lithologies from the Karoo Supergroup is enclosed within the main pipe. The study of Naidoo *et al*. (2004) is very comprehensive and detailed on the geology of the Koffiefontein pipe. It was proved that the pipe was formed by at least three separate magma batches, as their chemical signatures differed (Naidoo *et al*., 2004:181). There are seven separate emplacement sequences identified by Naidoo *et al*. (2004:178-180), which start with the formation of the West and East Fissure intruding into a country rock containing shale, mudstone, dolerite and granite as two distinct pipe structures. This was followed by a large intrusion between the separate fissures known as the Speckled East Kimberlite, which was followed shortly afterwards by the Speckled West Kimberlite, which almost destroyed the former. This large volcanic event led to structural failure on the south, east, and north facies, which brought large amounts of

country rock into the mixture, giving rise to the Mudstone Breccia. The final magmatic activity took the form of a hypabyssal plug, emplaced within the Speckled West Kimberlite and cross-cutting post-emplacement dykes.

2.2.1.2 Kimberlite 2

Due to the sensitive nature of the geology, it has to be simplified to prevent identification. For this project, the typical country rock types at this mine are gneiss, dolerites, and metasediments such as quartzite, schist, and carbonates (Kent, 1980; Field *et al*., 2008; de Wit, 2016). The kimberlite is classified as a Group I kimberlite and has a great variety within the mine (Field *et al*., 2008; de Wit, 2016).

2.2.1.3 Kimberlite 3

Due to the sensitive nature of the geology, it has to be simplified to prevent identification. For this project, the country rock types typical of this mine are sedimentary rocks such as sandstone, mudstone, and carbonates (Kent, 1980; Field *et al*., 2008; de Wit, 2016). The kimberlite is classified as a Group I kimberlite and has a great variety within the mine (Field *et al*., 2008; de Wit, 2016).

2.2.1.4 Kimberlite 4

Due to the sensitive nature of the geology, it must be simplified to prevent identification. For this project, the typical country rock types at this mine are dolerite and sedimentary rocks such as sandstone and quartzite (Field *et al*., 2008; de Wit, 2016). The kimberlite is classified as a Group I kimberlite and has a great variety within the mine (Field *et al*., 2008; de Wit, 2016).

2.2.1.5 Voorspoed

The Voorspoed mine is situated about 190 km southwest of Johannesburg and is one of three pipes and six dykes in the Kroonstad district, with the nearby Lace mine pipe also a major producer of diamonds (Wagner, 1914:112). It has since been determined that there are 11 pipes in total in this Kroonstad cluster, of which the Voorspoed and nearby Lace pipes are the only economically viable “kimberlites” (Stiefenhofer, 2013:6; Field *et al*., 2008:55; de Wit *et al*., 2016:210). The Voorspoed pipe intruded a country rock comprising sedimentary, specifically shales and sandstones of the Ecca Group found at the surface and igneous rocks of the Karoo Supergroup (Wagner, 1914:5; de Wit *et al*., 2016:210). The “kimberlite” pipe emplaced through an existing dyke and an amygdaloidal basalt volcano plug of the Drakensberg group, which provided for the structural weakness for magma flow to occur (Wagner, 1914:5-7; Stiefenhofer, 2013:6; de Wit *et al*., 2016:210). The basalt lava of the Drakensberg Group is typically black or red in colour, with amygdales that are, in most cases, filled with the secondary mineral

zeolite and, in rare instances, quartz (Wagner, 1914:5-7; Kent, 1970:540; McCarthy & Rubidge, 2013:210). The study by Stiefenhofer (2003) examined the country rock and the Voorspoed pipe in detail. However, unfortunately, it was not accessible to this study because it was an internal document of De Beers. The comprehensive study done by Phillips *et al*. (1998) is, however, available and focuses on the pipe.

The Voorspoed pipe has been described as a micaceous kimberlite by Wagner (1914:113), and has been proven to belong to the Group II Kimberlite, or orangeite, or lamproite group through Sr-Nd signature testing (Smith, 1983; Mitchell, 1995:123; Phillips *et al*., 1998:300; Field *et al*., 2008:55; Stiefenhofer, 2013:6; de Wit *et al*., 2016:2016). The Voorspoed pipe contains two types of Tuffisitic Kimberlite Breccia (TKB), one type of Tuffisitic Kimberlite (TK) and seven types of Hypabyssal Kimberlite (HK) facies (Phillips *et al*., 1998:300-302; Stiefenhofer, 2003; Field *et al*., 2008:55). The two TKB facies can be described as being a hard rock containing abundant xenoliths and autoliths in a dark fine-grained matrix, which are distinguished from each other primarily by their main xenolithic composition with the 'normal' being dominated by Karoo Supergroup rocks and HK facies autoliths, whilst the 'basalt-rich' variety contains additional basalt xenoliths which pushes the country rock representation to over 80% (Phillips *et al*., 1998:301). The TK facies is much like the above-mentioned facies, except that it has fewer than 30% xenoliths, which are also much smaller in size (Phillips *et al*., 1998:301). The seven HK facies are distinguished from each other by their mineralogical and textural features. They can be readily distinguished from TKB and TK by their higher abundance of phlogopite, serpentine, and carbonate (Phillips *et al*., 1998:301-302). Further studies by Stiefenhofer (2003) pointed out that evidence of graded bedding, pyroclastic textures and the distribution of the basalt breccia in the pipe suggests that it would more accurately be defined as a Volcaniclastic Kimberlite (VK) than a TK (Field *et al*., 2008:55-56; Stiefenhofer, 2013:6; de Wit *et al*., 2016:210). The chemistry of the Voorspoed lamproite pipe, however, differs from that of other well-known South African lamproites such as Lace, Swartruggens, and Finsch and shows closer resemblance to that of the Postmasburg lamproite (Mitchell, 1995:122-126).

2.2.2 Mineralogy of South African kimberlites and lamproites

The previously given definitions of kimberlites and orangeites already specify the minerals typically associated with their assemblages and do not constitute a complete list; only olivine is required for identification (Skinner & Clement, 1982:304). Kimberlites and orangeites often incorporate large amounts of country rock into their matrix as xenoliths. They are altered before mining, which, however, changes the diversity of minerals that could end up in waste-disposal dams. The scope of this study assesses both diamond-bearing ore rock and country

rock. Minerals typically encountered in kimberlite tailings dams are provided in Table 2-1, and should not be assumed as being an exhaustive mineral list. This table was compiled from previous works to form a compact and summarised characteristics sheet (Wagner, 1914:52-53; Frick, 1970; Dawson, 1980:65-109; Skinner & Clement, 1982:304; Mitchell, 1986:137-274; Howe, 1997:50; Klein & Dutrow, 2007:331-550; Morkel, 2006:6; Strydom, 2015:12-14). These mentioned works, especially that of Wagner (1914), Dawson (1980), Skinner & Clement (1982), Mitchell (1986) are advised if more information is required on the detailed mineralogy of kimberlites and to a lesser degree orangeites, where Mitchell & Bergman (1991), Mitchell (1995) and Howe (1997) would be more appropriate.

Table 2-1 Most noteworthy of mineral appearances in kimberlites and orangeites, with some important characteristics of their occurrence (compiled from Wagner, 1914:52-53; Frick, 1970; Dawson, 1980:65-109; Skinner & Clement, 1982:304; Mitchell, 1986:137-274; Howe, 1997:50; Klein & Dutrow, 2007:331-550; Morkel, 2006:6; Strydom, 2015:12-14).

Mineral:	Chemical Formula:	Observed:
Olivine (Mostly Forsterite)	$(Mg, Fe)_2SiO_4$	Groundmass, phenocrysts and macrocrysts
Monticellite (Rare Olivine group)	$CaMgSiO_4$	Groundmass and phenocryst
Phlogopite (Mica group)	$KMg_3(AlSi_3O_{10})(F,OH)_2$	Groundmass and phenocryst
Serpentine (1:1 Clay group)	$(Mg,Fe)_3Si_2O_5(OH)_4$	Groundmass
Perovskite	$CaTiO_3$	Groundmass
Calcite (Carbonate group)	$CaCO_3$	Groundmass and phenocryst
Garnet	$(Mg,F,Ca)_3Al_2(SiO_4)_3$	Groundmass and phenocryst
Ilmenite	$(Fe,Mg)TiO_3$	Groundmass and phenocryst
Pyroxene	(Fe,Ca,Mg)2Si2O6	Groundmass (minor), phenocryst and mantle xenolith
Spinel group (Spinel, Chromite and magnetite)	$MgAl_2O_4$, $FeCr_2O_4$ and Fe_3O_4	Groundmass and minor phenocrysts
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	Groundmass
Chlorite (2:1:1 clay group)	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2 \cdot (Mg, Fe)_3(OH)_6$	Rare groundmass
Clay groups	Assorted	Weathering of kimberlite
Biotite (Mica group)	$K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$	Residual, in Country rock xenolith or weathering
Brucite	$Mg(OH)_2$	Weathering of kimberlite
Pyrite (Sulphates)	FeS_2	Late stage in mantle xenoliths or olivine weathering
Zirconium	$ZrSiO_4$	Groundmass and phenocryst
Rutile	TiO_2	Groundmass and phenocryst
Pectolite	$NaCa_2Si_3O_8(OH)$	Groundmass
Quartz	SiO_2	Country rock xenolith
Feldspar	$(Ca,Na,K)(Al,Si)_2Si_2O_8$	Country rock xenolith

Table 2-1: (continued)

Composition:	Nature:	Weathers to:
Major	Primary	Serpentine, magnetite and haematite
Major/Trace	Primary	Calcite
Major/Minor	Primary	Calcite, chlorite and serpentine
Major	Alteration	Clay minerals
Minor	Primary	Resistant
Major/Trace	Primary or alteration	Other carbonates
Minor/Trace	Primary	Resistant
Minor/Trace	Primary	Resistant
Minor	Primary	Serpentine, chlorite, calcite and rarely amphibole
Major/Trace	Mantle xenoliths, primary or alteration	Perovskite to sphene
Minor/Trace	Primary	Calcite
Minor/Trace	Rare primary, mostly alteration	Smectite and vermiculite
Major/Trace	Alteration, mostly 2:1 clays	Smectite and vermiculite
Minor/Trace	Alteration or Country rock contamination	Smectite and vermiculite
Minor/Trace	Alteration	Metal hydroxides
Minor/Trace	Primary or alteration	Metal hydroxides/sulphides
Trace	Primary	Resistant
Minor/Trace	Primary, minor alteration	Resistant
Minor/Trace	Rare primary, mostly alteration	Clay minerals
Minor/Trace	Contamination, sometimes alteration	Clay minerals
Minor/Trace	Contamination	Clay minerals

2.3 Weathering of minerals associated with South African kimberlites and lamproites

2.3.1 Weathering principles

The factors influencing weathering have been studied well and have been identified a long time ago by Jenny (1941) as being the function of parent material, topography, organisms, climate and time, where the main mechanisms are described as physical weathering (disintegration) or chemical weathering (decomposition) (Rai & Kittrick, 1989:180; Weil & Brady, 2017:54-60). The mineralogy and texture are the most characteristic influences on the weathering of a parent material, where mafic minerals are much more susceptible than felsic minerals, and finer-grained materials are more susceptible than coarse-grained materials to weathering (Goldich, 1938:55; Weil & Brady, 2017:60-70). The topography is usually related to the landscape setting and slope of the material, where it either increases or retards the effects of climate on weathering by affecting water penetration into soils, the groundwater table, aspect, and wind susceptibility (Jenny, 1994:89-97; Weil & Brady, 2017:80-82). The type of organism will usually determine the extent of influence, where micro-organisms can help to increase weathering through chemical excretion, plants changing cation environments and rock material disintegration through root activity, and animals (as well as humans) that excavate and physically alter the rock material (Jenny, 1994:197-238; Weil & Brady, 2017:75-80). The climate can drive chemical and physical weathering by influencing temperature, rainfall, evaporation, humidity, and wind, especially favouring chemical weathering when water and temperature are high and physical weathering when temperature changes and wind are frequent (Jenny, 1994:104-190; Weil & Brady, 2017:73-75). The last, but also important, factor of time is crucial as the state of weathering tends to increase as it gets more evolved, as the above-mentioned act on each other to form distinctive weathering horizons with characteristic properties ranging from less weathered near the parent rock and more evolved further away (Jenny, 1994:31-50; Weil & Brady, 2017:83-84).

2.3.2 Mineralogical alteration trends

The susceptibility of minerals to weathering can best be described using the famous Goldich stability series diagram, figure 2-1, which points out that mineral susceptibility coincided with the mineral crystallisation trend of Bowen's reaction series for igneous rocks (Bowen, 1922:190; Goldich, 1938:56; Jackson *et al*., 1948:1240; Rai & Kittrick, 1989:180; Winter, 2014:130). This indicates that minerals which crystallise in equilibrium with a composition, temperature and pressure far removed from conditions at the Earth's surface become metastable once exposed to surface conditions, making them highly susceptible to

weathering. Minerals formed at the highest temperatures and/or pressures are therefore typically the most prone to weathering (Goldich, 1938:56; Rai & Kittrick, 1989:180; Jenny, 1994:69; Weil & Brady, 2017:55).

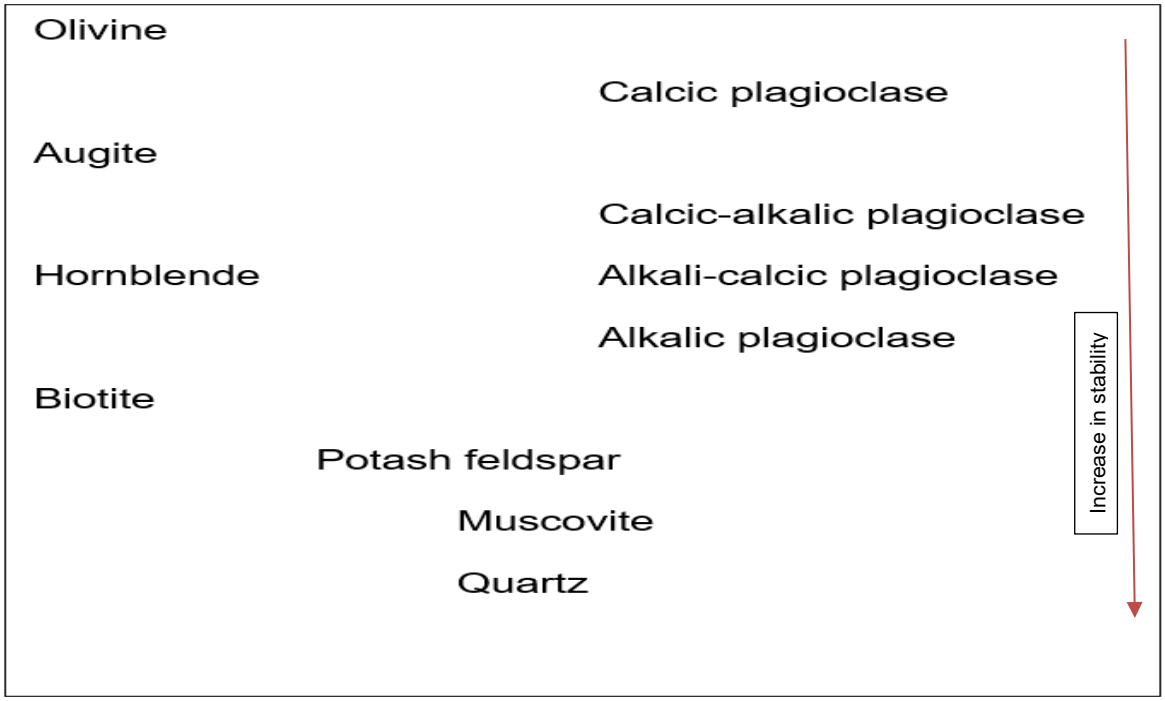


Figure 2-1: The Goldich diagram indicates that mineral stability against weathering increases moving downward (Adapted from Goldich, 1938:56).

Weathering of minerals lead to the chemical decomposition of the original crystal structure due to instability caused by ion release, or substitution, leading to the synthesis of a new mineral species that is more stable under the given environment with time (Goldich, 1936:57; Weil & Brady, 2017:54). The current understanding of mineral weathering and alteration to a more stable product can be summarised in figure 2-2. This figure indicates well-established trends and aligns with findings from many other researchers (Jackson *et al*., 1948:31-33; Millot, 1970:97; Rai & Kittrick, 1989:181; Hseu *et al*., 2007:398-399; Weil & Brady, 2017:362). The trend indicates that the initial mineral type will primarily affect the pathway and diversity of clay minerals, which will alter with time. Primary mica minerals tend to follow the illite/chlorite to vermiculite to smectite trend, whilst mafic minerals can directly alter to smectite if the conditions are right. These smectites can then alter to kaolinite if weathering persists. Felsic minerals tend to weather directly to kaolinite. All of these can weather to Fe- and Al-oxide forms if weathering is very severe and continues.

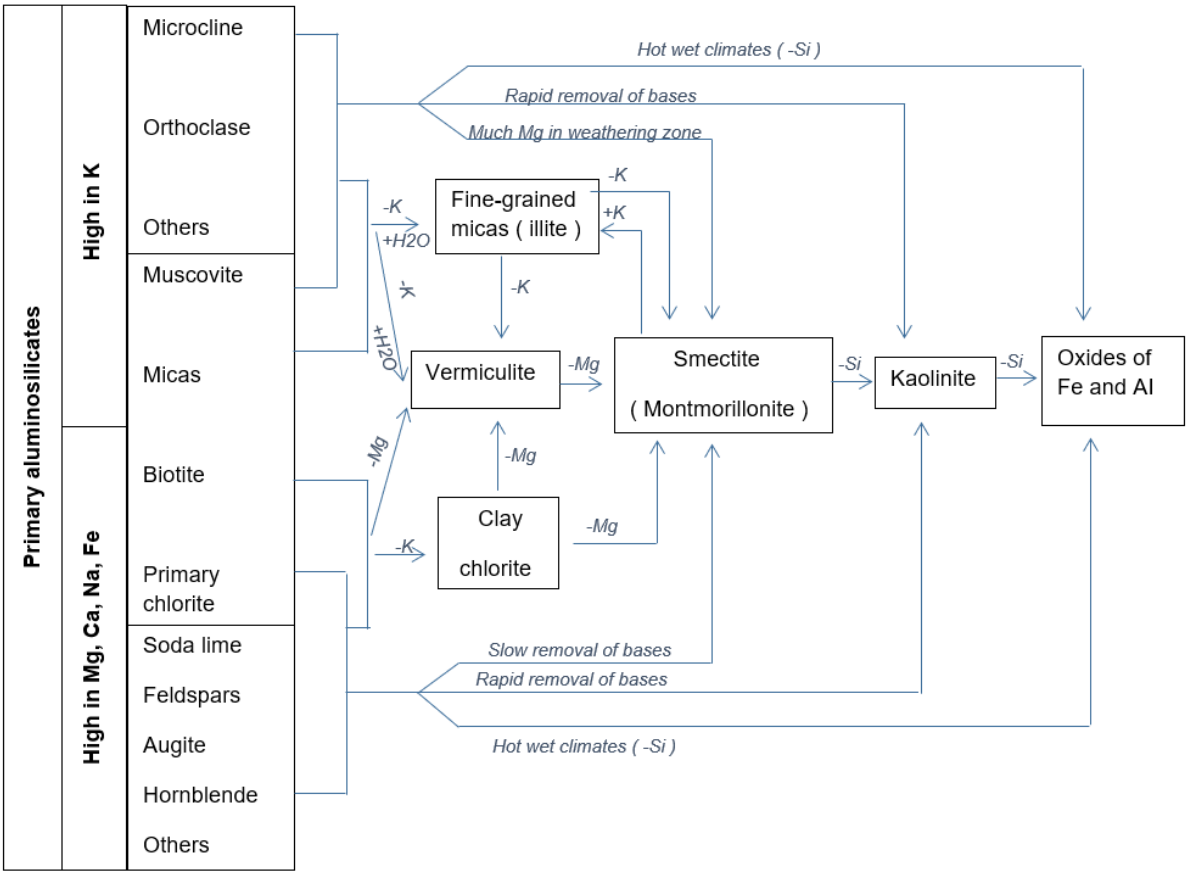


Figure 2-2: Formation sequence of clay minerals and metal oxides through weathering (Adapted from Weil & Brady, 2017:362).

This, however, is only a simplified representation, and minerals such as olivine and phlogopite, the bulk minerals of kimberlites and orangeites, can be better described using Figure 2-3. The most common alteration procedure affecting ultramafic rocks is serpentinization, which firstly affects olivine and then the more resistant orthopyroxene to ultimately form serpentine (Deschamps *et al*., 2013:119-120; Petrounias *et al*., 2022:2). The alteration of mafic primary minerals like olivine and pyroxene to serpentine leads to the removal of cations like Al_2O_3 and CaO from the original crystal structure leading to a mineral product with decreased density (to 2550 kg/m^3) and increased LOI (10-12%) (Deschamps *et al*., 2013:101; Petrounias *et al*., 2022:2). This process alters the Mg-rich silicate minerals of the ultramafic rocks into phyllosilicate members that are much softer and flaky (Deschamps *et al*., 2013:97; Petrounias *et al*., 2022:2). The olivine first alters to form serpentine (1:1 clay), then vermiculite (2:1 clay), then smectite (2:1 clay). Some studies differ on whether vermiculite is in fact an intermediary between serpentine and smectite (Kresten, 1973; Dawson, 1980:106-107; Bonifacio *et al*., 1997; Hseu *et al*., 2007:398), whilst others indicate that serpentine weathers directly to smectite (Wildman *et al*., 1968; Allen & Hajek, 1989:240; Lee *et al*., 2003:1315). It has been established that vermiculite can be formed from serpentine in well-drained profiles whilst

smectites form in poorly drained profiles, meaning that vermiculite could exist as an intermediary phase through the chlorite route (Rai & Kittrick, 1989:185; Bonifacio *et al*., 1997; Lee *et al*., 2003:1313). Therefore, the intermediate (chlorite/vermiculite) or direct conversion of serpentine to smectite is both possible, and the weathering conditions will impact which route is preferred. The phlogopite undergoes a simple conversion from a mica mineral to a 2:1 clay; it first alters to chlorite (2:1:1 clay), then to vermiculite (2:1 clay), then to smectite (2:1 clay).

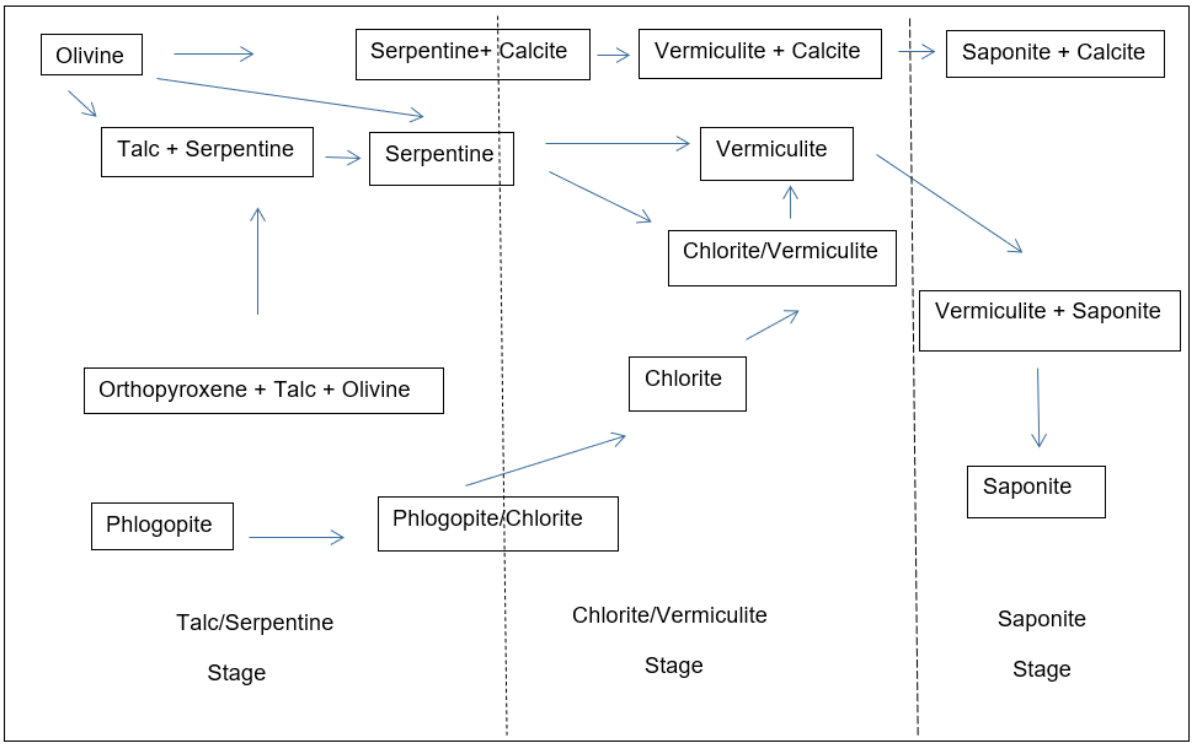


Figure 2-3: Alteration sequence of mafic minerals typically associated with kimberlites (Adapted from Kresten, 1973).

The pseudomorphic serpentine can go through an intermediary amorphous stage where neoformation occurs, which is caused by the precipitation of elements like Mg, Fe and Ca from the olivine dissolution process to form a new structure like smectite, instead of a kaolinite clay structure (Borchardt, 1989:697; Allen & Hajek, 1989:240; Lee *et al*., 2003:1315). The unique weathering environment created by tailings dams, along with the chemical composition of the minerals in it, allows the serpentine to weather/neoform to smectite and to remain stable for a very long time due to the restricted leaching environment (Borchardt, 1989:697; Rai & Kittrick, 1989:185; Lee *et al*., 2003:1315; Massoura *et al*., 2006:29). This will create similar weathering profiles like that found in lateritic deposits where kaolinite or vermiculite content is highest on the top of the weathering profile and decreases rapidly with depth to a much more smectite rich bottom (Millot, 1970:97; Allen & Hajek, 1989:240; Hseu *et al*., 2007:399). The formation environment of clays from ultramafic rocks, like kimberlites, is important to consider as it

determines the mineralogy and related chemical and physical properties (Petrounias *et al*., 2022:18). It will determine the engineering properties and suitability for use in concrete (Petrounias *et al*., 2022:18).

Clay groups like smectite and vermiculite exhibit characteristic swelling abilities whilst the other clay groups do not (Morkel & Vermaak, 2006:150; Chen *et al*., 2022:3185; Weil & Brady, 2017:355). This is primarily due to the formation of negative charges on the platelike structures through isomorphous substitution of Si^{4+} by Al^{3+} in the tetrahedral sheet and Al^{3+} by Mg^{2+} in the octahedral sheet (Weil & Brady, 2017:355). Swelling happens because in the 2:1 structure, and due to isomorphous substitution, the adjacent layers are weakly bound by only oxygen-to-oxygen and cation-to-oxygen bonds which allows for easy attraction of exchangeable cations and water molecules to the interlayer area leading to swelling (Chen *et al*., 2022:3185; Weil & Brady, 2017:355). There are additionally two types of swelling mechanisms, where crystalline swelling is caused by the hydration of exchangeable cations in a dry clay and osmotic swelling is caused by large differences in the ion concentrations near the interlayer surface and pore water (Morkel & Vermaak, 2006:150; Chen *et al*., 2022:3189).

2.4 Diamond mining process

The processing of kimberlite and lamproites are expensive and are typically associated with the processing of millions of tons of ore at a very low grade that is typically in the order of a few carats per hundred tons (cpht) with a few exceptions having grades as high as 200 cpht in certain kimberlite facies (Lynn *et al*., 1998:238-239; Damarupurshad, 2006; Field *et al*., 2008:35-68; Aslam, 2021:3). The two main processing activities are the crushing of ore and the concentration of economical minerals, in this case diamonds (Hodgson, 1981; Aslam, 2021:3). The process of diamond extraction can be illustrated using the generic flowsheet developed by Hodgson (1981), as illustrated by figure 2-4. The flowsheet indicates the progressive crushing and gravity-based concentration of ore rock to concentrate diamonds, making recovery based on hygroscopic or X-ray properties of diamonds possible.

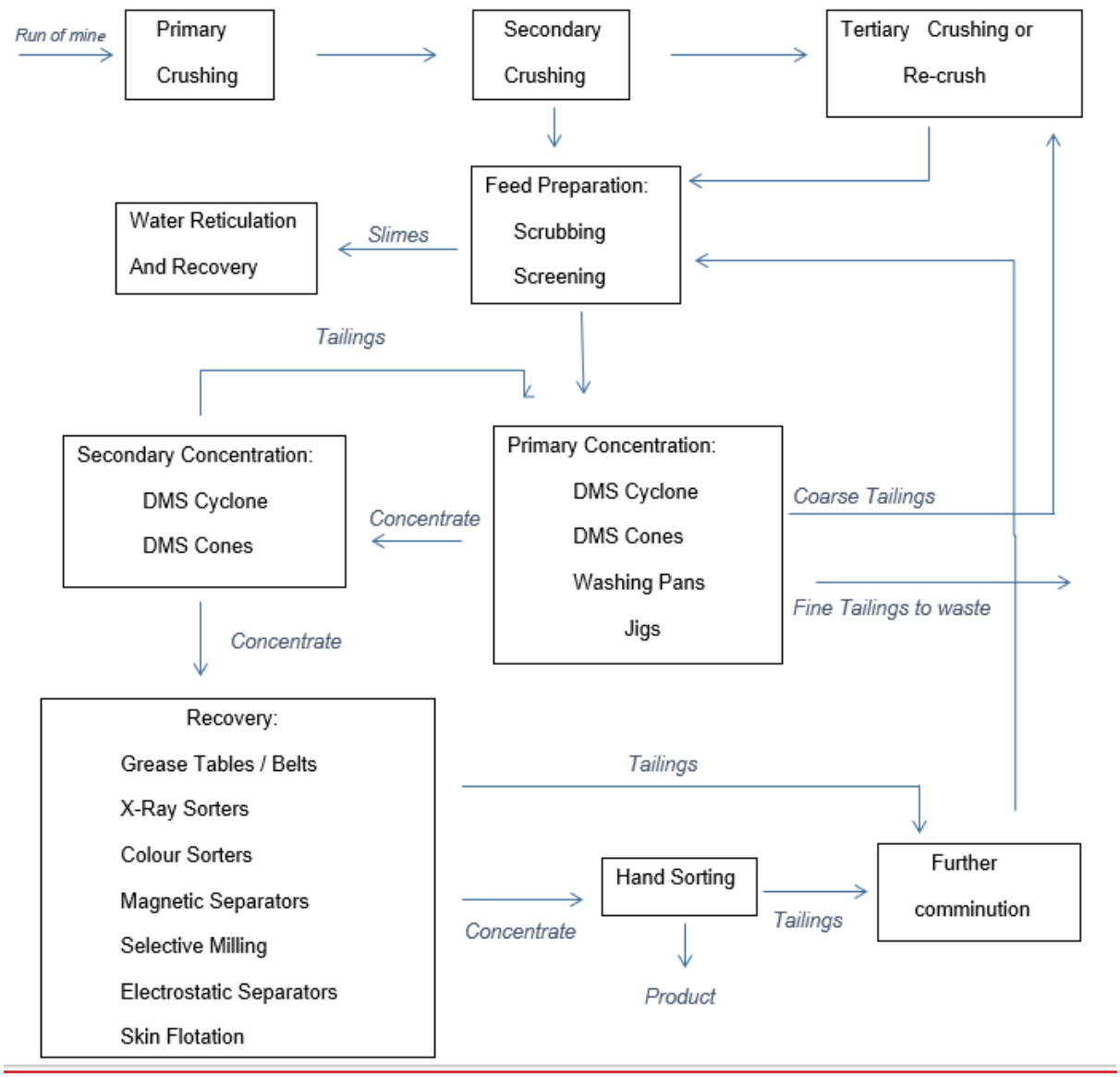


Figure 2-4: Generic diamond processing flowsheet (Adapted from Hodgson, 1981).

The unwanted waste material, also known as gangue, can be found in different forms, with the ‘slimes’ that are too small to process due to being lost to water and the tailings that are typically larger than 1mm in diameter which have undergone processing (Morkel, 2006:1; Aslam, 2021:5; Motsau & van Wyk, 2022:3). The tailings itself can be separated into the ‘fines’ and the ‘coarse’ tailings, which have historically been stored separate but is being stored together in modern times (Morkel, 2006:1; Strydom, 2015:2; Motsau & van Wyk, 2022:3). It is most common for the slimes to be disposed with the fines to form the Slime’s Dam or Fine Residue Deposit (FRD) with some fines and coarse tailings used to construct the Coarse Residue Deposit (CRD), whilst more recent examples only use one large disposal site to store wastes from processing and recycling of water (Morkel, 2006:1; Strydom, 2015:2; Du Plessis, 2025). Other rock wastes that are not processed, but are moved to get access to the ore are

usually termed waste rock and are stored as Waste Residue Deposit's (WRD's) across the mining site, if not used to help construct the previously mentioned FRD or CRD walls, and could have origins from open pit or underground activity (Du Plessis, 2025).

2.5 Reutilization of diamond mine waste

There is a growing global concern about the sustainable and responsible use of natural resources for the sake of future generations and biodiversity protection (UN, 2025b). The mining of mineral resources is a necessary but unfortunately destructive activity that humanity cannot do without (Siegel, 2013:8-10; Dold, 2020:4; USGS, 2024). Many different solutions have been postulated for what to do with the end-of-mine landscape and mining waste that is ultimately left after a resource has been extracted (Pearman, 2009; Finucane & Tarnowy, 2019:488-493; Dold, 2020:3; USGS, 2024). For especially kimberlite mine waste there are solutions like carbon sequestration which look promising as it is low risk and requires no additional cost, apart from funding studies, by the mining company as well as to help convey the image of a responsible and ethical mine practice that is invested in greenhouse gas control (Chakravarthy *et al*, 2020:1-2; Mervine *et al*., 2020:761-764; Jones, 2023:4-7). Apart from carbon sequestration, other solutions have been explored for a wide range of secondary uses, leading to the production of countless research papers on sustainable resource use (Chanturiya *et al*., 2018:7-13; Pashkevich & Alekseenko, 2020:1-3; Chaurasiya & Markandeya, 2021:533-538; Rifkhan *et al*., 2024:3). One of these solutions has had historical success, like the use of gold tailings as building aggregate (Preethi *et al*., 2017:32; Andrews *et al*., 2022:8; Zhang *et al*., 2025:12). This project, however, will focus on some of the works that have advanced the understanding of kimberlite tailings as a building material substitute. The next section could not possibly assess or include all of the available studies on this topic due to the sheer number of them, and some of the more noteworthy breakthrough or review studies will be discussed to give a sense of the potential and setbacks faced.

2.5.1 Previous Kimberlite tailings replacement studies

The use of gold mine tailings for such endeavours has been documented. However, studies on the use of kimberlite mine tailings are still in their infancy, with the study by Swami et al. (2007) being among the earliest published works on the topic.

In their study, they used the Bureau of Indian Standards (BIS) tests and procedures to assess kimberlite tailings from the Panna mines in India for use as an aggregate in road construction. This was done to satisfy the requirements of the Ministry of Road Transport and Highways (MoRTH) and the Indian Road Congress for a material to be used in road construction (Swami

et al., 2007:131). All necessary tests were conducted according to the BIS and assessed against the relevant criteria (Swami *et al*., 2007:131). Properties like specific gravity, relative gravity, dry density, water absorption, proctor compaction test, moisture content, California bearing ratio (CBR), flakiness index, elongation index, soundness, LA abrasion value, aggregate impact value (AIV), stripping value, particle size distribution (PSD), loss of ignition (LOI) and chemical composition were assessed to determine appropriate use (Swami *et al*., 2007:132). It was found to perform satisfactorily in three of the four layers that make up a bituminous road. However, serious issues related to water absorption and soundness tests (weathering ability) make it most appropriate for application in areas with a low water table, low to medium rainfall, and low heavy-vehicle traffic (Swami *et al*., 2007:132-133). Overall, it was considered a marginal aggregate because it has potential for certain uses but still needs to be tested and assessed thoroughly before each use (Swami *et al*., 2007:134). A section of bituminous road was constructed and performed well after one year (Swami *et al*., 2007:234).

The study of Pashkevich and Alekseenko (2020:5) investigated three different uses for the slime component of the tailings dam at the Lomonosov mine, Russia. Considering the high clay, mostly saponite, content of the tailings, one of the options was clinker-clay bricks. The clay brick capability was tested by performing uniaxial compression tests on samples that have been moulded with the help of a little bit of cement and have been treated at different temperatures (Pashkevich & Alekseenko, 2020:8). It was found that optimal strength was at 900ºC with almost 15MPa, but that acceptable strength could also be achieved at 800ºC with 13.5MPa (Pashkevich & Alekseenko, 2020:8). The solid content was also found to have a significant effect on the compression strength of the final product (Pashkevich & Alekseenko, 2020:8). They also experimented with Portland Cement manufacturing and found that a satisfactory product could be made from 70wt% limestone, 20-25wt% of the slime's slurry and 5-10wt% slag ash from a coal powerplant (Pashkevich & Alekseenko, 2020:9). This is on the condition that the tailings waste contains no sulphur or phosphorus (Pashkevich & Alekseenko, 2020:9). The study got positive results, but was hampered by the economic viability as the mine is situated in a remote part of the country (Pashkevich & Alekseenko, 2020:3).

The study by Chakravarthy *et al*. (2020:1-3) investigated the feasibility of using carbon-sequestered kimberlite (valorisation) as a cement replacement in concrete. The study in this case produced a finely ground, valorised kimberlite with varying degrees of treatment to assess the effects of moisture, temperature, and CO_2 content on performance (Chakravarthy *et al*., 2020:3-4). Bricks were moulded and compression tested according to the requirements of ASTM C67, where kimberlite replaced cement at different ratios (Chakravarthy *et al*.,

2020:7). The untreated kimberlite was found to have performed much worse than the industry control with -10% and -30% strength respectively for 10% and 20% replacement for cement (Chakravarthy *et al*., 2020:14). The valorised kimberlite produced on average better results than the untreated kimberlite and in some cases even the industrial control (Chakravarthy *et al*., 2020:11-14). The higher the valorised treatment of the kimberlite, the higher the compressive strength of the brick was noted (Chakravarthy *et al*., 2020:14). The most likely explanation for this finding is that the amorphous silica created by the carbonation of silicates is inducing a pozzolanic effect, which is similar to the mechanism associated with cement reaction (Chakravarthy *et al*., 2020:14-15). Even though the treated kimberlite is superior to the untreated kimberlite, the latter still has satisfactory properties for certain classes of use according to ASTM C67 and can therefore be used as an additive (Chakravarthy *et al*., 2020:10-15).

The study by Otieno and Ndoro (2020:1260-1261) investigated the feasibility of using kimberlite tailings from the Cullinan mine as an aggregate in concrete. The study used tailings waste replacement ratios ranging from 0% to 40%, 60%, and 100% of the control (andesite) aggregate (Otieno & Ndoro, 2020:1260-1261). Properties such as PSD, slump, compression strength, and durability were tested (Otieno & Ndoro, 2020:1261-1263). The PSD revealed that the fine tailings were finer than the andesite crusher sand and had a more continuous grading texture (Otieno & Ndoro, 2020:1261). The increase in kimberlite replacement indicated higher slump and decreased workability (Otieno & Ndoro, 2020:1262). The compression tests indicated that an 40% kimberlite replacement as an aggregate did not severely impact the strength of the concrete, but that strength does, however, drop drastically with higher replacement (Otieno & Ndoro, 2020:1263-1264). The durability index highlighted problems with gas permeability in kimberlite aggregate batches, but states that this should be studied further and replicated (Otieno & Ndoro, 2020:1264). The study states the importance of further studies investigating a broader range of commonly considered controls to compare their differences and to investigate shrinkage, creep, weathering susceptibility and possibly microscopic analyses of microstructure (Otieno & Ndoro, 2020:1265).

The study by Chaurasiya and Markandeya (2021:531) investigated a wide range of uses for kimberlite tailings, focusing on the tailings waste produced by the Panna mines in India, with support from the government's mineral development enterprise. Characteristics such as chemical composition, PSD, optical properties, mineralogical (XRD and AMA-EDS), and moisture absorption were tested in bulk (Chaurasiya & Markandeya, 2021:532-533). The part of their project that examined building materials included ceramic tiles, mosaic tiles, glazed tiles, cold-bonded tiles, and bricks (Chaurasiya & Markandeya, 2021:536). All of the mentioned

showed satisfactory results with minimal alteration required for substitution (Chaurasiya & Markandeya, 2021:536). The glazed tiles show great potential, as they achieve a higher-quality product at a lower treatment temperature than products on the market, indicating economic potential (Chaurasiya & Markandeya, 2021:536).

2.5.2 Importance of clay in the building industry

The use of clay in everyday life is often overlooked in favour of other commodities that tend to outshine it as a viable investment. It can be used for numerous applications across a broad range of fields, such as agriculture, pharmaceutics, food processing, waste containment, construction materials, and a wide range of manufactured products (Chanturiya *et al*., 2018:7-13; Pashkevich & Alekseenko, 2020:3; Chaurasiya & Markandeya, 2021:534-537). The study by Chanturiya *et al*. (2018:14) investigated methods for extracting clay minerals from recycled water from diamond mine tailings and found that cryogenic treatment and electrochemical separation can produce a very pure clay mineral concentrate suitable for even specialised products. The type of clay is also important to note, as they have vastly different properties and therefore different preferred uses (He et al., 1995:1701; Singh, 2022:17). There are countless examples of clay in use, some of which have already been discussed.

The important study by He et al. (1995) quantified this by evaluating the pozzolanic potential of different clay types for use as a cement replacement. Relatively pure samples of illite, sepiolite, Ca-montmorillonite, Na-montmorillonite, kaolinite and mixed-layer mica/smectite were used to evaluate their properties (He *et al*., 1995:1692). All of their chemical compositions complied with the ASTM C 618 guideline requirements in that the sum of SiO_2 + Fe_2O_3 + Al_2O_3 should exceed 70% (He *et al*., 1995:1692). Calcined clays met the ASTM moisture and loss-on-ignition requirements and also drastically improved pozzolanic properties (He *et al*., 1995:1692). The study found that kaolinite and Ca-montmorillonite were optimally calcined at 650ºC and 830ºC, respectively, to produce a product with compressive strength 20% higher than that of conventional Portland cement (He *et al*., 1995:1697). The study found that Na-montmorillonite and mixed-layer mica/smectite were optimally calcined at 830ºC and 960ºC, respectively, to produce a product with compressive strength 10% higher than that of conventional Portland cement (He *et al*., 1995:1697). The study found that illite and sepiolite were optimally calcined at 930ºC and 830ºC, respectively, to produce a product with a compressive strength 20% lower than that of conventional Portland cement (He *et al*., 1995:1697). It was further suggested by He *et al*. (1995:1701) that kaolinite can also be calcined to a 10% stronger than conventional Portland cement at 550ºC to make it even more economically viable, and that the Na-montmorillonite could also have proved better than its Ca counterpart due to higher initial amorphous silica content. It was also noted in this study

that pozzolanic properties can be assessed using XRD and alkali-soluble silica. However, they cannot be used to predict the exact compressive strength (He *et al*., 1995:1701).

Another important clay mineral, especially in its exfoliated form, is that of vermiculite which has a broad range of building material applications (The Vermiculite Association, 2014:1; Rashad, 2016:61). The organization brochure of the Vermiculite Association (2014) and the review study of Rashad (2016) give meaningful and approved applications of this mineral already wide in use in the industry. Common examples of its use include building boards, specialist plaster, roof and floor screeds, and insulated concrete products (The Vermiculite Association, 2014:1-3). The addition of exfoliated vermiculite offers advantages such as reducing product density and improving thermal insulation, soundproofing, workability, and fire resistance (Rashad, 2016:54-60). This, however, worsens water absorption, mechanical strength, and porosity issues, but can be counteracted by the addition of other additives (Rashad, 2016:54-60).

2.6 Regulation of product quality

A Safety Critical Product (SCP) is typically described as being a component which has the potential to cause serious injury or death if a single failure of the component's properties should occur (Duquenne & Ragusa, 2021:3; DCA, 2025). These types of products are tested regularly to ensure regulatory compliance and to ensure they meet the desired quality and performance standards (Duquenne & Ragusa, 2021:3; DCA, 2025). Internationally recognised organisations dedicated to the standardisation of products such as building materials include the International Organisation for Standardisation (ISO), the American Society for Testing and Materials (ASTM), the American Association of State Highway and Transportation Officials (AASHTO), and the International Building Code (IBC). The South African Bureau of Standards (SABS) is responsible for the regulation and standardisation of SCPs and other products in South Africa through the development and maintenance of the South African National Standards (SANS) documents.

2.6.1 South African National Standards (SANS) for building materials

In South Africa, the SABS follows a structured compliance framework that hierarchically organises documents from the final product's qualities to the individual testing method procedures that define how they should be tested, and all the possible documents in between (SABS, 2025). Usually, the failure of even a single test can lead to the total disqualification of a product to enter the market, or in special cases that can prove otherwise, be assigned to a lower classification of uses based on its lower performance or conformity (SANS, 1990:22;

SANS, 2009b:7; SANS, 2013:ii; SABS, 2025). Any construction project is thoroughly examined from planning through to the end phases to ensure the quality of craftsmanship and products used, as stipulated by the SANS 10400 document (SANS, 1990:22; CMA, 2005:77).

A concrete masonry unit is regulated under SANS 1215, where it is described as a brick made from cement, water and aggregate that is preformed and set to harden to a specified dimension for use in construction (SANS, 2008a:3-17; CMA, 2005:4; AfriSam, 2021a:1-2). A concrete paving block is similar in composition to the previously mentioned, apart from being regulated by SANS 1058 and is used in pavements and driveways (SANS, 2012a:4). Concrete is regulated by the SANS 10100 document series, which is pre-ceded and post-ceded by numerous documents that require full compliance (CMA, 2005:89; AfriSam, 2021b:107). The SANS 10100-2 document states that the applicable aggregate is regulated by SANS 1083, cement by the SANS 50197 series, and water by SANS 51008 (SANS, 2014a:13-15). Other important standards related to aggregate use include SANS 1090, which addresses fine aggregate in plaster and mortar, and SANS 794, which addresses low-density aggregates (SANS, 2009a:3; SANS, 2009b:10-23; AfriSam, 2021b:52).

2.6.2 Aggregate quality compliance

The documents of SANS 1083, SANS 1090 and SANS 794 are used to denote the appropriate qualities and methods of testing that should take place to assess the aggregate's suitability for use (SANS, 2013; SANS, 2009a; SANS, 2009b; CMA, 2005:89; AfriSam, 2021b:53). Apart from the methods outlined in these mentioned guidelines, the AfriSam group also makes use of other supplementary SABS approved methods to assess the properties of aggregates that might influence their usefulness, as recommended by the previously mentioned SANS documents for materials that warrant further investigation (SANS, 2013:ii; SANS, 2009a: ii; SANS, 2009b: ii; AfriSam, 2021b:53). To navigate this overlapping and at times confusing regulative set of frameworks, summaries will be given in table form. Table 2-2 simplifies the outline of the different methods used and their most important features (SANS, 2013; SANS, 2009a; SANS, 2009b; AfriSam, 2021b:53). It should be noted that a few of the mentioned methods were not made available for this study by the SABS because they could not provide them when requested. The criteria given in SANS 1083 (for fine and coarse aggregate), SANS 1090 and SANS 794, which indicate conforming properties, will also be summarised in table form, as indicated in tables 2-3, 2-4, 2-5 and 2-6, respectively.

Table 2-2: The summary of the appropriate SANS methods for determining aggregate properties, as recommended by SANS 1083, SANS 1090, SANS 794 and AfriSam (SANS, 2013; SANS, 2009a; SANS, 2009b; AfriSam, 2021b:53).

SANS	Name	Material (Bulk or fraction)	Fraction type	Establishes	Group
197	Preparation of test samples of aggregate	Bulk		Preparation method	
201	Sieve analyses, fines content and dust content of aggregates*	Bulk		PSD, Fines, Dust content	Physical
202	Chloride content of aggregates	Bulk (500g)		Chloride content	Chemical
794	Aggregates of low density	Bulk (3 or 15L)	Fine:<4,75mm and Coarse:>4,75mm	Bulk density***	Physical
		Bulk (300g max)		Grading*	Physical
		Bulk (Container specific)		Soundness	Physical
		Bulk (Container specific)		Insulating properties	Physical
		Bulk (Container specific)		Shrinkage****	Physical
		Bulk (125ml)		Organic impurity in fine aggregate**	Chemical
		Bulk (Not specified)		Sulphur trioxide content	Chemical
		Bulk (2g)		Sulphide sulphur content	Chemical
		Bulk (1g)		Loss of Ignition	Chemical
		Bulk (750g)		Iron content	Chemical
5832	Organic impurity in fine aggregate**	Bulk (125ml)		Organic impurity	Chemical
5833	Detection of sugar in fine aggregate	Bulk (50g)		Sugar content	Chemical
5834	Soluble deleterious impurity in fine aggregate	Bulk (Not specified)		Effect of soluble deleterious materials	Physical
5835	Estimation of the effect of fine aggregate on the water requirement of concrete	Bulk (10L)		Water requirement	Physical
5838	Sand equivalent value of fine aggregate	Not available			
5841	Aggregate crushing value of coarse aggregate	Fraction (3kg)	8-11,2mm	ACV	Physical
5842	FACT value (10% fine aggregate crushing value) of coarse aggregate	Fraction (3kg)	8-11,2mm	FACT	Physical
5843	Water absorption of aggregates	Bulk (1kg)		Water absorption	Physical
5844	Particle density and relative densities of aggregate	Bulk (500g)		Particle and Relative Density	Physical
5845	Bulk densities of void content of aggregates***	Bulk (Container specific)	Class: <4,75mm 37,5mm 75mm	Bulk density and Void content	Physical
5846	Abrasion resistance of coarse aggregates (LA Machine method)	Not available			
5847	Flakiness index of coarse aggregate	Not available			
5848	Polished-stone value of aggregates	Not available			
5849	Total water-soluble salt content of fines in aggregate	Bulk (400g)		Water-soluble salts content	Chemical
5851	Liquid limits of fines in aggregates for base-course	Fraction (Bulk containing 300-400g <425µm)	<425µm	Liquid limit	Physical
5854	pH Value of fines in aggregate for base-course	Fraction (Bulk containing 300-400g <425µm)	<425µm	pH	Chemical
6239	Aggregate impact value of coarse aggregate	Fraction (5kg)	9,5-13,2mm	AIV	Physical
6240	Electrical conductance of fine aggregate	Fraction (Container specific)	<6,7mm and <425µm	EC	Chemical
6242	Acid insolubility of aggregates	Bulk (Bulk 200g, cone to 10g)		Insolubility in acid	Chemical
6243	Deleterious clay content of fines in aggregate (Methylene blue adsorption indicator test)	Fraction (Bulk 1kg and sieve)	<75µm	Deleterious swelling clay	Chemical
6254	Mortar tests – Initial drying shrinkage and wetting expansion of mortar****	Bulk (Container specific)		Shrinkage	Physical

Table 2.2: (Continued)

Type of observation	Justification	Follows	Precedes	Reference
Preparation	Preparation step		Many	SANS, 2006b
Weighing and sieving	Afrisam, SANS 1083, SANS 1090	197		SANS, 2008b
Titration	Afrisam, SANS 1083, SANS 1090	197		SANS, 2006c
Weighing	Afrisam			SANS, 2009b
Weighing and sieving				
Inspect for pop-outs				
Thermal conductivity				
Length change				
Indicator test				
Precipitation				
Complex titration				
Weight				
Titration				
Indicator test	Afrisam, SANS 1083, SANS 1090	197	5833	SANS, 2006d
Titration	Afrisam, SANS 1083	197, 5832		SANS, 2006e
Compression (Mortar)	Afrisam, SANS 1083	197, 5863		SANS, 2006f
Theoretical and trial slump	Afrisam	197, 201, 1083, 5821-1	5845, 5862	SANS, 2006g
	Afrisam			SANS, 2006h
Compression (dry and wet)	Afrisam, SANS 1083		197, 5842	SANS, 2008c
Compression (dry and wet)	Afrisam, SANS 1084	5841		SANS, 2006i
Weighing	Precedes other		5844	SANS, 2008d
Weighing	Afrisam	197, 5843	5845	SANS, 2014b
Weighing, rodding, jigging (uncompacted or compacted)	Afrisam	197, 201, 5835, 5844		SANS, 2006j
	Afrisam			SANS, 2006k
	Afrisam, SANS 1083			SANS. 2008e
	Afrisam			SANS, 2008f
Dissolve and precipitate	Afrisam	197		SANS, 2008g
Slump test	Precedes other	197, 201	5854, 6240	SANS, 2002
pH	Afrisam	197, 201 5851		SANS, 2006l
Tamping (Abrasion resistance)	Afrisam	197		SANS, 2012b
EC	Afrisam	197, 5851		SANS, 2008h
Dissolving and weigh	Afrisam	197		SANS, 2008i
Titration	Afrisam	197, 5832		SANS, 2008j
Length change	SANS 1090			SANS, 2006m

Table 2-3: SANS 1083 conformity matrix for fine aggregate for concrete (SANS, 2013:7-8).

1	2	3	4
Property	**Class**		
	Fine aggregate derived from the natural disintegration of rock and any mixture (blend) of this class and fine aggregate derived from the mechanical crushing or milling of rock	**Fine aggregate derived from the mechanical crushing or milling of rock**	**Test method subclause**
Grading, mass percentage that passes sieves[1] that have square apertures of nominal size 5 000 µm 4 750 µm 150 µm	 92 – 100 90 – 100 5 – 25		6.2
Dust content, material that passing a 75 µm sieve[1], mass percentage, max.	5[2]	10[2]	6.3
Methylene blue adsorption value[3], max.	0,7		6.4
Clay content[4], material of particle size smaller than 5 µm, mass percentage, max.	2,0		6.5
Fineness modulus	1,2 – 3,5		6.6
Chloride content[5], expressed as Cl^-, mass percentage, max.	Fine aggregate for concrete for prestressing : 0,01 normal reinforced concrete : 0,03 non-reinforced concrete : 0,03		6.7
Organic impurities	The colour of the liquid above the fine aggregate shall not be darker than the colour of the reference solution, except that this requirement shall not be applicable if the fine aggregate complies with the requirement for soluble deleterious impurities.	–	6.8
Presence of sugar	Free from sugar unless the fine aggregate complies with the requirement for soluble deleterious impurities.	–	6.9
Soluble deleterious impurities	The strength of specimens made with the fine aggregate shall be at least 85 % of that of the specimens made with the same fine aggregate after it has been washed, except that this requirement shall not be applicable if the fine aggregate complies with the requirements both for organic impurities and for the presence of sugar.	–	6.10

1) Complying with SANS 3310-1 or SANS 3310-2.
2) These limits may be exceeded under certain circumstances (see 4.2.3).
3) Applicable only if dust content exceeds limit given in the table (see 4.2.3).
4) Applicable only if dust content and methylene blue adsorption values exceed the relevant limits given in the table (see 4.2.3). For the purpose of this requirement, the clay content is defined as –5 µm material which might not all be clay minerals. The clay content of this –5 µm fraction is likely to be appreciable if the methylene blue adsorption value exceeds the relevant limit given in the table.
5) Caution must be exercised on sites where fine aggregate is prepared (or delivered) for the making of prestressed and other concrete for which the chloride content is specifically restricted (see the table). Stockpiles of such fine aggregate should be kept well apart from other fine aggregate and should properly marked. Suppliers of fine aggregate derived from the crushing or milling of rock are cautioned that, whereas the parent rock could be relatively free from chlorides, washing of such aggregate with water that contains an excessive amount of chlorides could cause the chloride content of the resulting fine aggregate to exceed the specified limits.

Table 2-4: SANS 1083 conformity matrix of coarse aggregate for concrete (SANS, 2013:9).

1	2	3	4	5	6	7	8	9	10
Property	**Requirement**								**Test method subclause**
	Nominal size of aggregate								
	mm								
Grading[1], mass percentage of material that passes sieves[2] of nominal aperture size, mm	75,0	53,0	37,5	26,5	19,0	13,2	9,5	6,7	6.2
75,0	100	100							
53,0	0 – 50	85 – 100	100						
50,0	0 - 43	70 - 85	98 - 100						
37,5	0 – 25	0 – 50	85 – 100	100					
28,0	0 - 7	0 - 28	15 - 55	90 - 100					
26,5	0 – 5	0 – 25	0 – 50	85 – 100	100				
20,0		0 – 7	0 - 28	15 - 55	90 - 100				
19,0		0 – 5	0 – 25	0 – 50	85 – 100	100			
14,0			0 - 7	0 - 28	15 - 55	90 - 100			
13,2			0 – 5	0 – 25	0 – 50	85 – 100	100		
10,0				0 - 7	0 - 28	15 - 55	9 - 100		
9,5				0 – 5	0 – 25	0 – 55	85 – 100	100	
7,1					0 - 9	0 - 30	25 - 58	92 - 100	
6,7					0 – 5	0 – 25	0 – 55	85 – 100	
5,0						0 - 7	0 - 28	15 - 55	
4,75						0 – 5	0 – 25	0 – 55	
2,36							0 – 5	0 – 25	
2,0							0 - 4	0 - 28	
1,18								0 – 5	
1,0								0 - 4	
Dust content, material that passes a 75 µm sieve[2], mass percentage, max.	2								6.3
Aggregate crushing value (ACV)[3], of less than 13,2 mm and more than 9,5 mm fraction (dry), mass percentage, max.	29								6.11
10 % FACT value, of less than 13,2 mm and more than 9,5 mm fraction (dry), kN, min.	Coarse aggregate for use in concrete subject to surface abrasion, structural elements of reinforced or prestressed concrete (or both): 110								6.12
Flakiness index, max.	35								6.13

1) Other gradings are permitted if so required (see annex A). Such a grading shall be specified in terms of the appropriate nominal sizes specified in the table.
2) Complying with SANS 3310-1 or SANS 3310-2.
3) Optional alternative to the 10 % FACT value.

Table 2-5: SANS 1090 conformity matrix of fine aggregate for plaster and mortar (SANS, 2009a:6).

1		2	3	4
Property		**Type**		**Test method subsection**
		Fine aggregate for plaster	**Fine aggregate for mortar**	
Grading, mass percentage passing sieves[1] that have square apertures of nominal size, µm	4 750	100	100	6.2
	2 360	90 – 10	90 – 100	
	1 180	70 – 0	70 – 100	
	600	40 – 10	40 – 100	
	300	5 – 0	5 – 85	
	150	5 – 90	5 – 35	
		65		
		20		
Dust content, material passing a 75 µm sieve[1], mass percentage, max.		7,5[2]	12,5[2]	6.3
Methylene blue adsorption value[3]		0,7		6.4
Clay content[4], material of particle size smaller than 5 µm, mass percentage, max.		2,0		6.5
Organic impurities		The colour of the liquid above the fine aggregate shall not be darker than the colour of the reference solution, except that this requirement shall not be applicable if the fine aggregate complies with the requirement for soluble deleterious impurities.		6.6
Soluble deleterious impurities		The strength of mortar specimens made with the fine aggregate shall not be less than 85 % of that of the specimens made with the same fine aggregate after it has been washed.		6.7
Drying shrinkage of mix, %, max.[5]		0,10	0,12	6.8

1) Complying with SANS 3310-1 or SANS 3310-2.

2) These limits may be exceeded under certain circumstances (see 4.3).

3) Applicable only if dust content exceeds limit given in the table (see 4.3).

4) Applicable only if dust content and methylene adsorption value exceed the relevant limits given in the table (see 4.3). For the purpose of this requirement, the clay content is defined as the −5 µm material which might not all be clay minerals. The clay content of this −5 µm fraction is likely to be appreciable if the methylene blue adsorption value exceeds the limit given in the table.

5) These limits may be raised to 0,12 % and 0,14 % respectively, provided that the exposure conditions are known to be mild or, historically, the safe use has been validated.

Table 2-6: SANS 794 conformity matrix for low-density aggregates (SANS, 2009b:4-6).

1	2	3	4	5	6	7	8
Property	% (m/m) passing the sieve				Average thermal conductivity W/(mK), max		Test method subclause
mm	Fine aggregate	Nominal 13,2mm aggregate	Nominal 19,0mm aggregate	Nominal 26,5mm aggregate	At 20ºC	At 400ºC	
Grading							6.2
37,5				100			
26,5			100	85-100			
19,0		100	85-100	0-50			
13,2		85-100	0-50	0-25			
9,5		0-55	0-25	0-5			
6,7		0-25	0-5				
4,75	100	0-10					
2,36	90-100						
0,15	0-10						
Bulk density	Not exceed 1000 kg/m^3						6.1
Soundness	No pop-outs. Exception for clinker aggregates, where 6mm max is allowed.						6.3.1-2
Insulation	Oven-dry bulk density of concrete or plaster specimen (kg/m^3)		Up to 480		0,115	0,175	6.4
			From 480 to 800		0,215	0,3	
			from 800 to 1450		0,5	-	
Shrinkage	Not exceed 0,06%						6.5
Organic impurity	Do not generate a darker colour than the standard colour. May be ignored if compressive tests prove discolouration due to non-harmful impurities.						7.1
Sulphur Trioxide content	Not exceed 1,0% (m/m)						7.2
Sulphide sulphur content	Not exceed 2,0% (m/m)						7.3
Loss of ignition	Not exceed, a) 5% (m/m) for all aggregates other than clinker and b) 25% (m/m) for clinker in precast masonry units.						7.4
Iron content	Not exceed 7,5mg ferric oxide per kilogram						7.5

2.6.3 Long-term durability implications

Concrete is the most frequently used structural material, which consists of cement, water and aggregate (AfriSam, 2021b:28; Petrounias *et al*., 2022:1). The cement and water components help to bind the aggregate into a stable unit, where the aggregate ideally functions as an inert filler in concrete, where it can constitute up to 80% of the total mixture (Petrounias *et al*., 2022:2). The durability of concrete can therefore be defined as the period of time for which the concrete remains stable and reasonably fulfills the function for which it was created for (AfriSam, 2021b:129). The four factors influencing durability of concrete is: the structural design, the construction practices, quality of ingredients, and the environment (AfriSam, 2021b:129). Deterioration of concrete can happen due to one, or more, of the following reasons namely, corrosion, sulphate attack, Alkali-silica reaction (ASR), acid attack, and wearing of surface (AfriSam, 2021b:130).

2.6.3.1 Corrosion

Corrosion is when the reinforcing steel in concrete starts to corrode, leading to cracks and decrease in strength (AfriSam, 2021b:131). This is caused when the protective ferric oxide layer of the steel is lost due to the loss of alkalinity by the ingress of carbon dioxide and the subsequent movement of ions like chloride to the susceptible surfaces (AfriSam, 2021b:131). To reduce the risk of corrosion the infiltration and movement of carbon dioxide, oxygen, chloride and water should be minimalized by increasing the distance of the steel from the surface as much as possible, and to select and prepare the concrete in the appropriate manner (AfriSam, 2021b:131).

2.6.3.2 Sulphate attack

Sulphate attack is when diffusion of sulphate occurs and causes the hydration products in the cement to be altered in such a way that it leads to concrete deterioration (AfriSam, 2021b:135; Nadir & Ahmed, 2022:662). The source of sulphate can originate from the aggregate, the water used or the environment (AfriSam, 2021b:135). The new hydration products (like gypsum) can induce swell and shrink cycles due to fluctuating water availability, leading to cracking and ultimate deterioration of concrete (AfriSam, 2021b:135; Nadir & Ahmed, 2022:662). Sulphate attack can occur during the curing stage of concrete setting, or due to later diffusion of sulphate from seasonal groundwater movement (AfriSam, 2021b:135; Nadir & Ahmed, 2022:662). Other factors influencing the susceptibility of a concrete to sulphate attack is the concentration of sulphate in contact with concrete, the type of sulphate (as not all types are equally deleterious), and the type of cement used (AfriSam, 2021b:135).

2.6.3.3 ASR

Alkali-silica reaction (ASR), also known as Alkali-aggregate reaction (AAR), occurs when a combination of reactions take place between aggregate and alkalis in the concrete mix and leads to expansions taking place and cracks forming, leading to concrete deterioration (AfriSam, 2021b:137; Ghanem *et al*., 2010:1101). ASR can only occur when all the necessary criteria are met like, sufficient number of alkalis, sufficient amount of reactive silica aggregate, and sufficient amount of water (AfriSam, 2021b:137; Ghanem *et al*., 2010:1102). This being said, all three criteria mentioned can still take place at the same time and ASR will still not take place if the pH is not above 13 (AfriSam, 2021b:137). In high concentrations the K^+ and Na^+ tend to form hydroxides, and the Ca^{2+} ions tend to form carbonates, all of which contributes to the rise in pH (Gaucher & Blanc, 2012:3). ASR is an endothermic reaction and has been found to be accelerated by increased temperature and alkalinity (Ghanem *et al*., 2010:1108). ASR can successfully be prevented by careful planning, by controlling the total alkali content of the concrete mix and the use of specific types of cements that reduce risk (AfriSam, 2021b:139).

2.6.3.4 Acid attacks

Acid attacks occur when the concrete is exposed to an acid and durability is compromised by the dissolving of cement paste and any calcareous minerals found in the aggregate (AfriSam, 2021b:140). All concretes are technically vulnerable to acid attacks, where the greater the amount of acid involved leads to a greater degree of susceptibility (AfriSam, 2021b:140). It is generally recommended to use special cements if the concrete is expected to be subject to acid exposure, but other qualities of concrete like cement content, water ratio, curing and quality control have been found to sometimes outweigh cement type in importance (AfriSam, 2021b:140). Other measures that can help to minimalize acid attack is by adding a protective waterproof barrier sealant to the concrete surface, or laying an additional concrete layer above the concrete that is used for structural integrity purposes (AfriSam, 2021b:140). These methods help to prevent contact to the concrete and the acids' ability to affect structural integrity (AfriSam, 2021b:140).

2.6.3.5 Wearing of surface

The wearing of concrete surfaces can occur through different processes like abrasion, cavitation or erosion (AfriSam, 2021b:130). The use of aggregate that contains compromised materials, like secondary minerals, can severely impact the durability of a concrete by introducing deleterious properties. The morphology, texture and mineralogy of especially altered rocks show strong correlations to decrease in engineering properties (Pomonis *et al*., 2007:956). Secondary minerals generally have an intense impact on mechanical properties due to their inappropriate

nature, caused by cleavage, internal layering, fibrous texture and hydrous tendencies (Pomonis *et al*., 2007:956; Petrounias *et al*., 2018:2). Ultramafic rocks are especially vulnerable to this due to high weathering ability and large amounts of soft minerals (Morkel & Vermaak, 2006:150; Petrounias *et al*., 2018:2). Petrology can be considered as an appropriate method to examine the durability of aggregate and its quality (Rhoades & Mielenz, 1947; Petrounias *et al*., 2022:2).

Chapter 3: Methodology

This research project uses experimentally acquired data, comparing it against the SABS criteria to classify each material's proposed usage class. The appropriate tests recommended by the SABS were used, and by following the SABS procedures for determining these characteristics, a more informed decision can be made regarding the use of kimberlite tailings as an alternative building material. A further advantage of this approach is that it makes the results relevant to industry and reproducible according to a widely recognised standard.

The tests were designed to investigate the extent to which the source of the kimberlite tailings (mine location) and the type of kimberlite waste material (Slimes, FRD, CRD and WRD) affect their suitability for use. Replicates were used in some cases to ensure the results were statistically significant, primarily in those tests where notable variation in the results was expected.

For aggregate suitability assessment, three SANS documents mention about 18 characteristics to be tested, with AfriSam encouraging the testing of about 15 additional aggregate properties. The SABS also advises on the additional 15 tests as encouraged by AfriSam. However, they are usually reserved for material that has not been tested before, or of which it is suspected that it might contain deleterious properties. Not all of the tests could be conducted in this project due to obstacles, such as a lack of information from SABS offices, inadequate equipment, safety concerns, time constraints, and other factors. It was decided to concentrate on the most appropriate tests that could be conducted at the NWU to identify if kimberlite tailing material and other mine-derived waste rocks show any potential in building material products based on their aggregate properties.

3.1 Study design

The characteristics of the kimberlite tailings material will be tested in much the same manner as under normal SABS laboratory conditions. The SABS does make provision for the replication of tests that differ from the set specifications, to ensure comparable results, and for the interpretation thereof if alterations to the methods are made. The tests were done chronologically, so the results of a previous test can be used more effectively and with greater information to inform the development of the project, as the numbering system does not always reflect the order of test execution. The procedures will focus either on bulk material properties or on specific particle size fraction properties.

All of the tests prescribed by the SABS are important, but some are irreplaceable for describing the properties of a material. Some helpful methods that were added included X-ray fluorescence

(XRF) and X-ray diffraction (XRD) to determine chemical and mineralogical properties, respectively.

3.1.1 Bulk physical properties

Measurements were taken to calculate bulk density and relative density of bulk samples, according to SANS 5845 and SANS 5844, respectively (SANS, 2006j; SANS, 2014b). The textural properties, such as grading, fines content, and dust content, were uncovered, as per SANS 201 (SANS, 2008b). This study sought to be efficient and thorough at the same time by incorporating different tests into a single experimental procedure, without affecting the validity of the results. Up to five replications per material type were used to increase statistical significance.

The procedures described in SANS 5845, SANS 5844, and SANS 201 were successfully combined into a single experimental trial that determined the bulk density, relative density, void content, textural grading, fineness modulus, and dust content of an aggregate for concrete purposes. This was done by using 200ml of kimberlite tailings material in a 250ml sealable graduated media bottle. A bulk density can be determined for both an air-dried material and, according to the standard, an oven-dried material at 100-110ºC to constant mass. The concept of using a container that can seal was introduced due to necessity, as the materials sometimes absorbed atmospheric moisture as soon as they came out of the oven, leading to weight changes. The sealing/bottling helped increase accuracy and better determine the point of dehydration. The relative density could then be calculated as it follows the same preparation to this point. De-ionised water is added to the same level as the aggregate or to the container's capacity, and this is noted. Shaking, rolling, or tapping of the material is required to dislodge trapped air and properly wet the sample. The determination of both bulk and relative density allows for the subsequent determination of void content, as mentioned in SANS 5845.

That said, the aforementioned bulk and relative density procedures also align with the preparation method described for texture determination in SANS 201, which determines the particle size distribution of materials. In this test method, the samples are wet sieved using 75µm and 1.18mm sieves and the wash water is carefully decanted after agitation. This is continued until the wash water is considered clear. After wet sieving is finished, the material retained on the sieves is added back to the container and dried again in an oven to constant mass. In the meantime, passing material from the wet sieving is also dried to a constant mass.

Continuing with SANS 201, the dried material is then dry sieved using sieve sizes corresponding to those outlined in the standard for fine and coarse aggregate (SANS, 2008b). The necessary observations are made, such as the weight of each particle size fraction, and are used to construct particle size distribution curves that outline the material's textural properties. Other textural

properties, as listed in SANS 201, such as fines and dust content, are also determined from the information gathered in this process. The void content of SANS 5845 can be used to determine the water requirement in aggregate accurately (SANS 5835) with the help of SANS 201. This SANS 5835 standard comprises a theoretical calculation, which is normally followed by experimental trials to validate the theoretical claim, but this project will not include such trials.

3.1.2 Fractional physical properties

The aggregate impact value (AIV) was calculated following the procedures described in SANS 6239 (SANS, 2012b:4-7). This simple method evaluates the resistance of a coarse aggregate to shock or impact events. It is recommended for frequent site control monitoring use for aggregates (SANS, 2012b:3). The standard specifies that a 5kg sample of 9,5mm to 11mm size fraction coarse aggregate should be impacted by a 13,5kg to 14kg hammer from a 380mm fall through the use of a special apparatus described in the document (SANS, 2012b:4-7). A similar apparatus, functionally the same as the one proposed, was built and used, with a cylindrical hammer with a handle to fall onto a solid steel pipe with a solid base, with the test sample inside. It should be noted that this project used about 250g per test sample with a cylinder height of 20mm, instead of the proposed 5kg, as per the standard, which supposedly gives a cylinder height of 50mm. The standard specifies that fewer samples can be used, if so required, as long as the fragment diameters of the aggregates are smaller than the aggregate packing height in a cylinder. Up to two replications were done for each type of material that had enough material of the specific particle size of concern to warrant investigation.

3.1.3 Bulk supplementary properties

As with the previous procedures, a well-mixed, appropriately sized bulk sample was used for XRF and XRD analyses. The bulk sample of each material type was evenly split until a final 200g bulk sample that was dried to 100-110ºC in an oven. The bulk samples of each material type were milled to a very fine, homogeneous powder, sieved, and milled repeatedly until all material passed through a 150µm sieve, then thoroughly mixed again to homogenise further. The material was then analysed at the NWU laboratory at G23 on the Potchefstroom campus for XRD. The material was also analysed in the B8 laboratory with the Portable X-ray Fluorescence (P-XRF) instrument.

3.2 Sampling collection and preparation

Material from Koffiefontein, Kimberlite 2, and Kimberlite 3 was collected by other parties (including the main supervisor), whilst we collected the materials from Kimberlite 4 and Voorspoed. The materials collected included all available kimberlitic/lamproitic mine wastes and a broad range of

accessible waste rocks. A list of their names and the code used in this project is indicated in Table 3-1.

Table 3-1: The full names and their code names of the 25 different geological materials tested.

Full Name	Code	Full Name	Code	Full Name	Code
Koffiefontein Coarse	Kof.C	Kimberlite 3 Carbonaceous	Kim3.Carb	Kimberlite 4 Fine Rock Deposit	Kim4.FRD
Koffiefontein Fine	Kof.F	Kimberlite 3 Calcrete	Kim3.Cal	Kimberlite 4 Coarse Rock Deposit	Kim4.CRD
Koffiefontein Slimes	Kof.S	Kimberlite 3 Laminated Sandstone	Kim3.LAS		
		Kimberlite 3 Quartzite	Kim3.QSH	Voorspoed Grey Mudstone	Voo.GMS
Kimberlite 2 Underground Waste	Kim2.UGW	Kimberlite 3 Coarse Rock Deposit White	Kim3.CRDW	Voorspoed Yellow Mudstone	Voo.YMS
Kimberlite 2 Coarse Rock Deposit	Kim2.CRD	Kimberlite 3 Coarse Rock Deposit Black	Kim3.CRDB	Voorspoed Fine Rock Deposit	Voo.FRD
Kimberlite 2 Fine Rock Deposit	Kim2.FRD	Kimberlite 3 Fine Rock Deposit 1	Kim3.FRD1	Voorspoed Coarse Rock Deposit	Voo.CRD
Kimberlite 2 Waste Rock Deposit 1	Kim2.WRD 1	Kimberlite 3 Fine Rock Deposit 7	Kim3.FRD7	Voorspoed Basalt	Voo.BAS
Kimberlite 2 Waste Rock Deposit 2	Kim2.WRD 2	Kimberlite 3 Fine Rock Deposit 8	Kim3.FRD8		
Kimberlite 2 Waste Rock Deposit 3	Kim2.WRD 3				

It was ensured that a representative sample of each material type was taken, with at least one 25L bucket per type, and sampled over a broad area to homogenise later in the lab on campus using a riffle splitter. It should be noted that in most cases, the waste rock samples also have much larger rocks on site due to their unprocessed nature. The collected samples were then prepared according to the SANS 197 specification, which is a prerequisite for most of the procedures used (2006b). Further sample preparation was performed in accordance with the SANS document that covers the procedure of interest. The samples destined for analyses were first dried using a Scientific™ model 222 160L economy oven at a temperature of 100-110ºC until weight change was less than 1%.

Samples for XRD and XRF analyses were then powdered using a ring mill to homogenise the material further and enable accurate measurements. A maximum particle size of 150 µm was determined by sieving and milling until all particles had passed through the sieve. The optimal particle size for these assessments is 75 µm, and it is assumed that most of the particles in the samples sent to the independent laboratory were within this size range.

For the samples that underwent XRD analyses, a PANalytical X'Pert Pro instrument was used. A back-loading method was used, with the samples loaded onto a spinner stage inside the XRD and scanned with X-rays generated by a Co X-ray tube. The results are detected using an X'Celerator detector, which creates a unique diffractogram for each sample and uses HighScore

Plus™ and the International Centre for Diffraction Data (ICDD) program to identify the minerals present.

Samples that underwent P-XRF analyses were scanned using a Thermo Scientific Nikon XL3t GOLDD+ P-XRF instrument. The P-XRF used the AllGeo setting and a NIST standard regularly to monitor calibration.

3.3 Data analysis

All of the data acquired through experimentation were analysed and interpreted according to the criteria for conformity as mentioned in SANS 1083, SANS 1090, SANS 794 and other SANS documents recommended by AfriSam (SANS, 2013; SANS, 2009a; SANS, 2009b; CMA, 2005:89; AfriSam, 2021b:53). Where replications were done for statistical purposes, the average value was used for interpretation and display purposes. The data was displayed in an illustrative manner to showcase differences among the various types of material and to compare them with the benchmark stipulated by the standard, or was presented in the manner recommended by the specific standard of interest. PAST™ software was used to conduct hierarchical clustering analyses to illustrate inter-mine relationships (Hammer *et al.,* 2001).

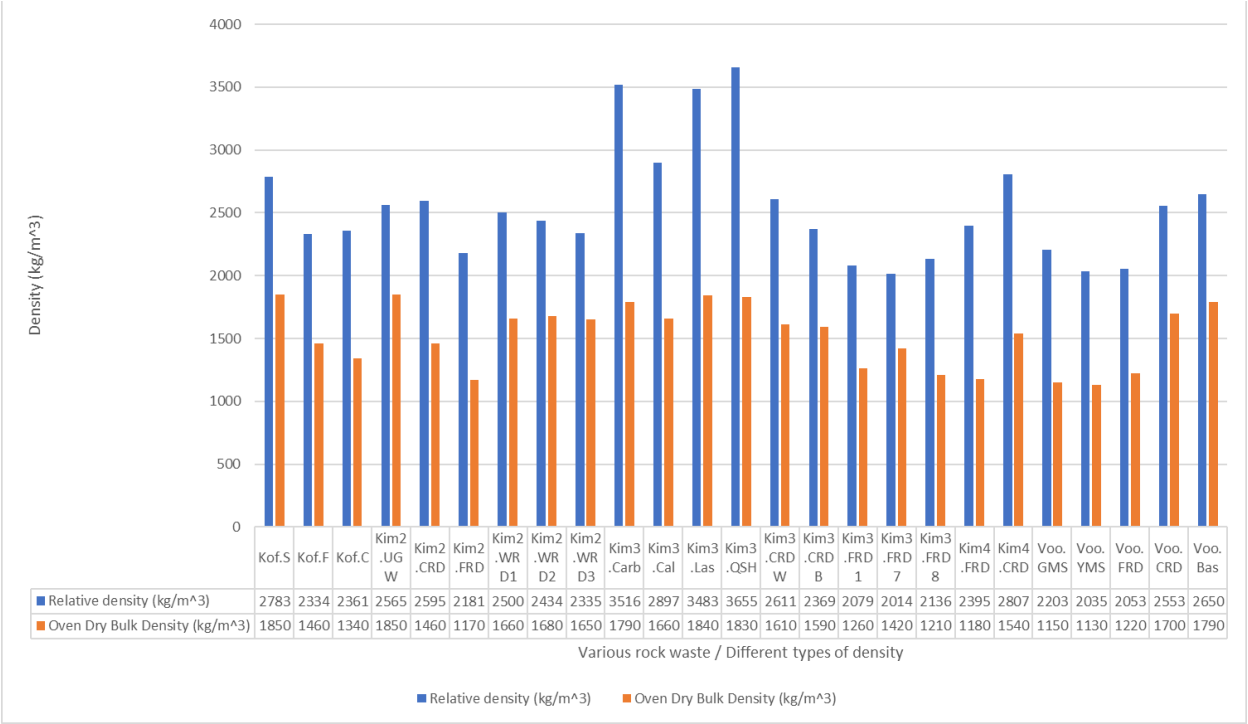
Interpretations will also be made in accordance with the specific SANS documents to evaluate the level of conformity of a material based on its performance in the tests conducted. Where it is found that the SANS documents are unsatisfactory to properly evaluate or assess a specific property, other documents from other international standards bureaus will be used to compensate for any shortfalls. The outcome of the tests help determine whether a specific material has potential for use and for which applications it is best suited.

Chapter 4: Results

The information was gathered from tests that used a single appropriately sized bulk sample or up to five separate replications from a common bulk sample with pre-mixed material, where statistical significance was important, and was then reworked to represent an average value for use in this document. The results of analyses on the physical properties including: density, void content, grading, fineness modulus, dust content, and AIV, as well as the mineralogy and chemical composition of the samples collected are presented here. Some sections have grouped the materials by mine site to focus on intra-mine relationships, whilst others discuss all 25 mine wastes together to support inter-mine relationships better.

4.1 Density

The apparent relative density and dry bulk density, according to SANS 5844 and SANS 5845, respectively, are presented on Figure 4-1 using data from Annexure A. The figure shows the average value for the material tested, based on up to 5 replications per material type. All of the tested materials had an apparent relative density between 2000 kg/m^3 and 3700 kg/m^3. The materials with the highest apparent relative density and that stood out compared to the other materials were the Kim3.Carb, Kim3.Las and Kim3.QSH. The rest of the materials tested had similar apparent relative densities, but still showed some variation among them. The FRDs across the different mines and weathered mudstones of Voorspoed had comparatively significantly lower apparent relative densities than the CRDs and remaining waste rocks. All of the materials tested had a dry bulk density in the range from 1000 kg/m^3 to just below 1900 kg/m^3. The materials still show the same types of trends as for apparent relative density, but there is now a smaller difference among the materials. All the waste rocks (except for the Voo. GMS and Voo.YMS) have similar dry bulk densities, which are also close to the CRDs of the different mines. The FRDs and the weathered mudstones of Voorspoed still have notably lower dry bulk densities than the rest of the materials.



	Kof.S	Kof.F	Kof.C	Kim2 .UG W	Kim2 .CRD	Kim2 .FRD	Kim2 .WR D1	Kim2 .WR D2	Kim2 .WR D3	Kim3 .Carb	Kim3 .Cal	Kim3 .Las	Kim3 .QSH	Kim3 .CRD W	Kim3 .CRD B	Kim3 .FRD 1	Kim3 .FRD 7	Kim3 .FRD 8	Kim4 .FRD	Kim4 .CRD	Voo. GMS	Voo. YMS	Voo. FRD	Voo. CRD	Voo. Bas
Relative density (kg/m^3)	2783	2334	2361	2565	2595	2181	2500	2434	2335	3516	2897	3483	3655	2611	2369	2079	2014	2136	2395	2807	2203	2035	2053	2553	2650
Oven Dry Bulk Density (kg/m^3)	1850	1460	1340	1850	1460	1170	1660	1680	1650	1790	1660	1840	1830	1610	1590	1260	1420	1210	1180	1540	1150	1130	1220	1700	1790

Figure 4-1: The apparent relative density and dry bulk density of the aggregate.

4.2 Void content

The void content, according to SANS 5845, is illustrated in Figure 4-2 using data from Annexure A. This figure shows the average value for the material tested, based on up to 5 replications per material. The void content ranges from 27.85% to 50.75% for the different materials. Void content is calculated from the apparent relative density and dry bulk density and will therefore follow similar trends observed in Figure 4-1 and Figure 4-2. The void content tends to increase with the fineness of the kimberlite tailings and is highest in materials with a very fine texture, such as the FRD and slimes component. The exceptions to these observations do exist when studying the waste rocks, where some of them also have very high void contents, but are rather coarse. The Kimberlite 2 waste rocks tend to have low void contents, whilst the waste rocks of Kimberlite 3 and Voorspoed tend to have higher void contents.

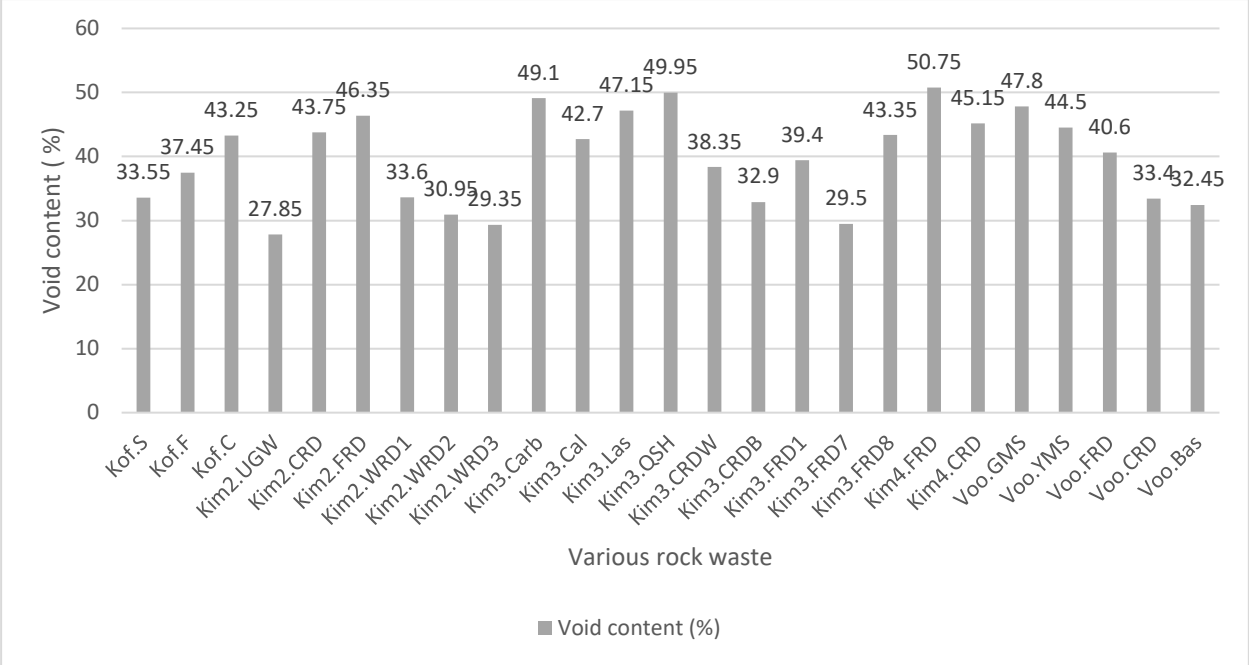


Figure 4-2: The void content of the aggregate.

4.3 Grading

Results are presented in Annexure B. The PSD assessment using the SANS 201 procedures to determine grading is illustrated using percent passing figures, as shown in Figures 4-3 to 4-8, based on the data in Annexure B. The SANS 201 explains that for “all-in” aggregates (fine plus coarse aggregate), they should be separated and tested accordingly (SANS, 2008b:13-14). Section 8 of this standard therefore requires grading and dust content to be based on the total materials, whilst the fineness modulus should be based on the <4.75mm proportion of the aggregate solely (SANS, 2008b:13-14). This, however, creates confusion, as there are no “all-in” aggregate specifications (SANS, 2008b:13-14). The results presented in Figure 4-3 show the average values for the material tested, based on up to 5 replications per material type. All of the studied mine rock wastes show the relative conformity of waste type to grading. There are typically four types of trends that can be identified, which, in most cases, coincide with a specific rock-type waste. The FRD8 of Kimberlite 3, the FRD of Voorspoed, and both weathered mudstones of Voorspoed indicate very fine grading, with between 87% and 91% of the material consisting of particles smaller than 75µm. The other FRDs have a very tight pattern and relatively well-sorted texture in most cases, with most particles within the 150µm and 1.18mm size fractions. A similar pattern is found for most of the CRDs, where most of the particles are above 1.18mm and in most cases smaller than 6.7mm, indicating a relatively well-sorted texture. Most of the waste rock types follow well-graded textural patterns, some being close to the textures of the CRD (like Kimberlite 2), and others having much coarser-grained textures, which also give a more well-sorted textural

pattern (like Kimberlite 3). The individual rock wastes of each mine are shown in figures 4-4 to 4-8, which more clearly illustrate the different trends and variations within a single mine setting.

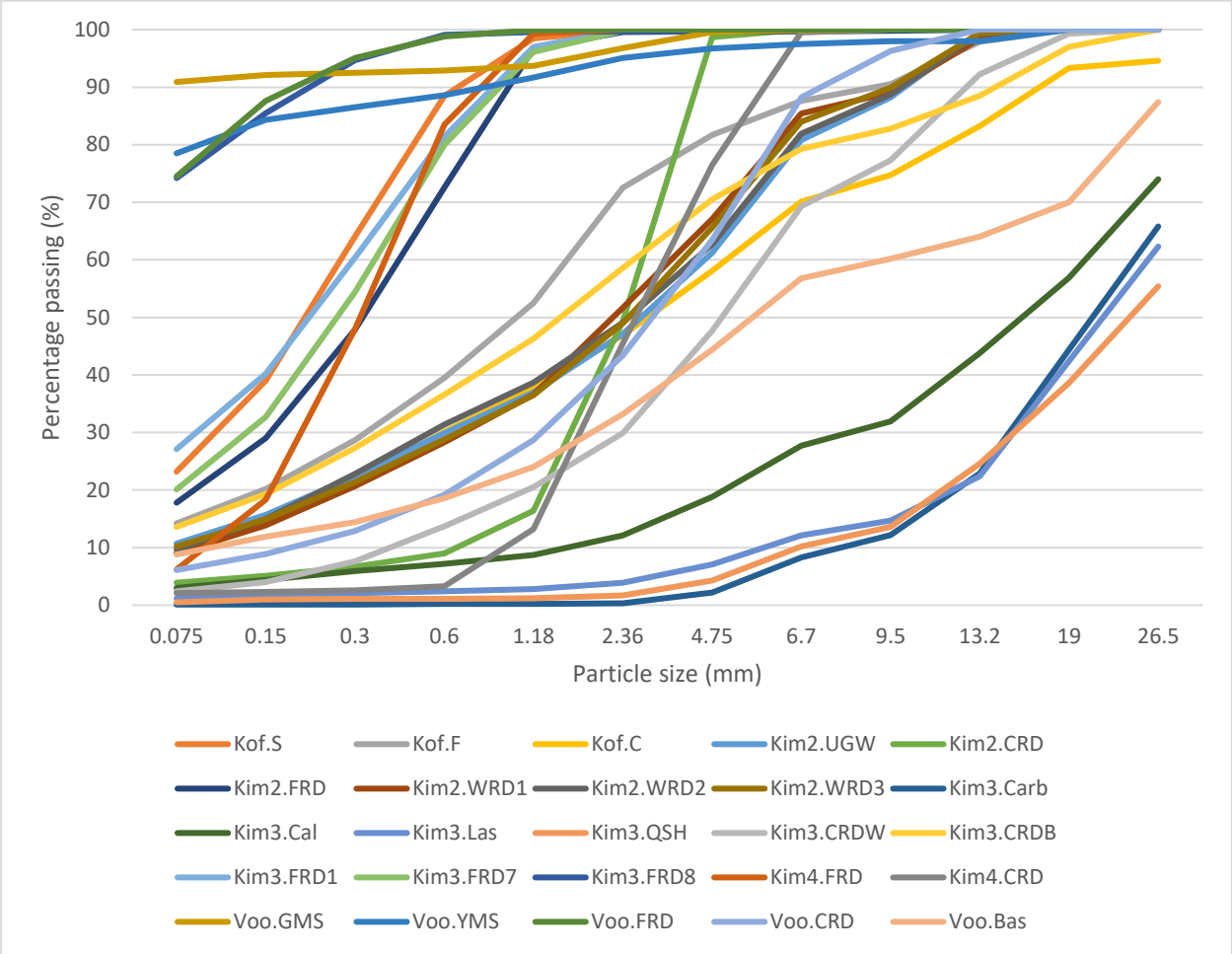


Figure 4-3: The grading of all the studied materials.

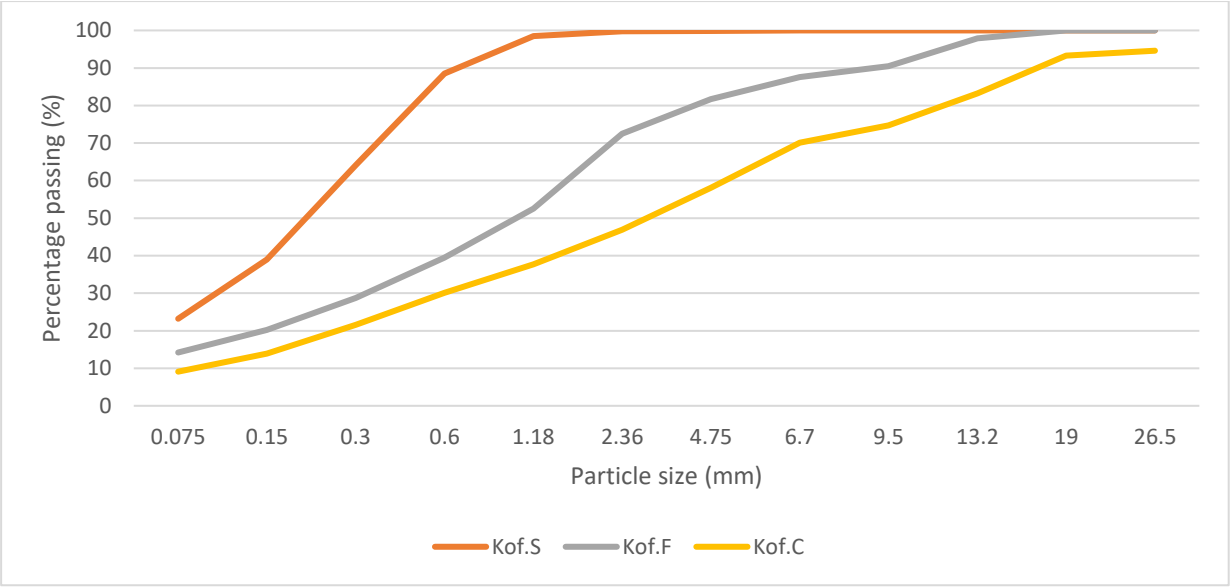


Figure 4-4: The grading of Koffiefontein mine waste.

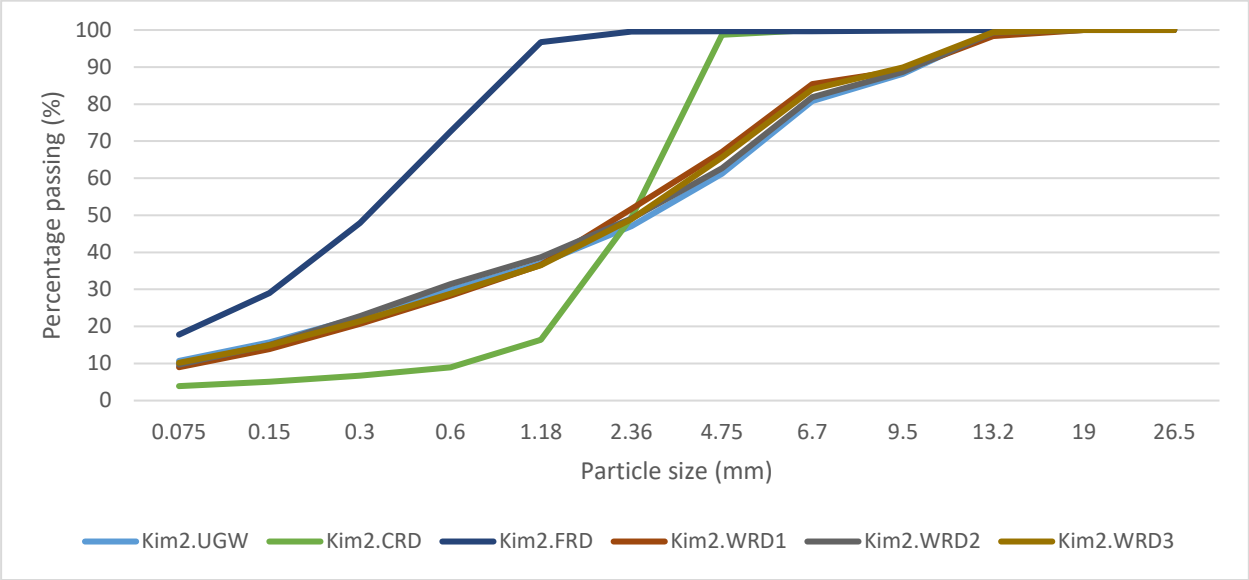


Figure 4-5: The grading of Kimberlite 2 mine waste.

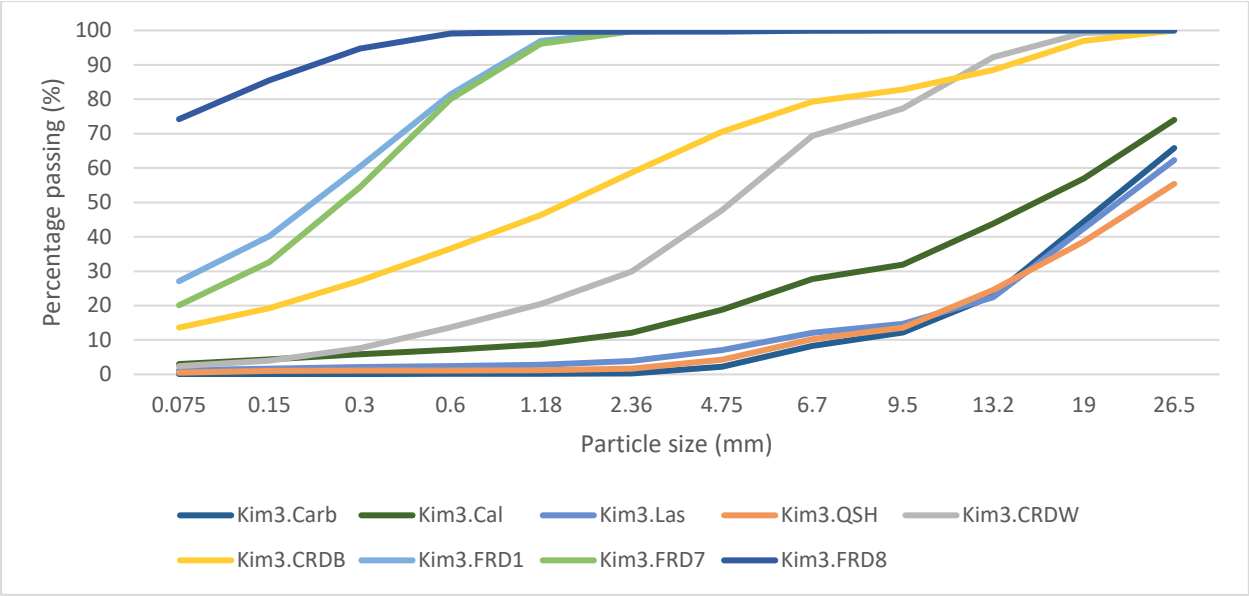


Figure 4-6: The grading of Kimberlite 3 mine waste.

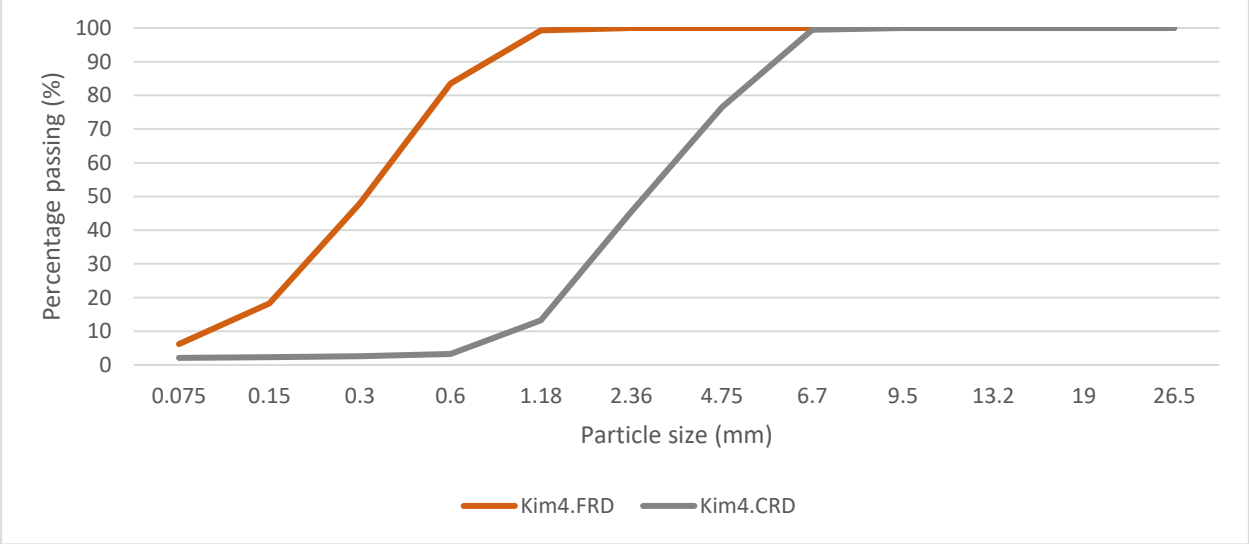


Figure 4-7: The grading of Kimberlite 4 mine waste.

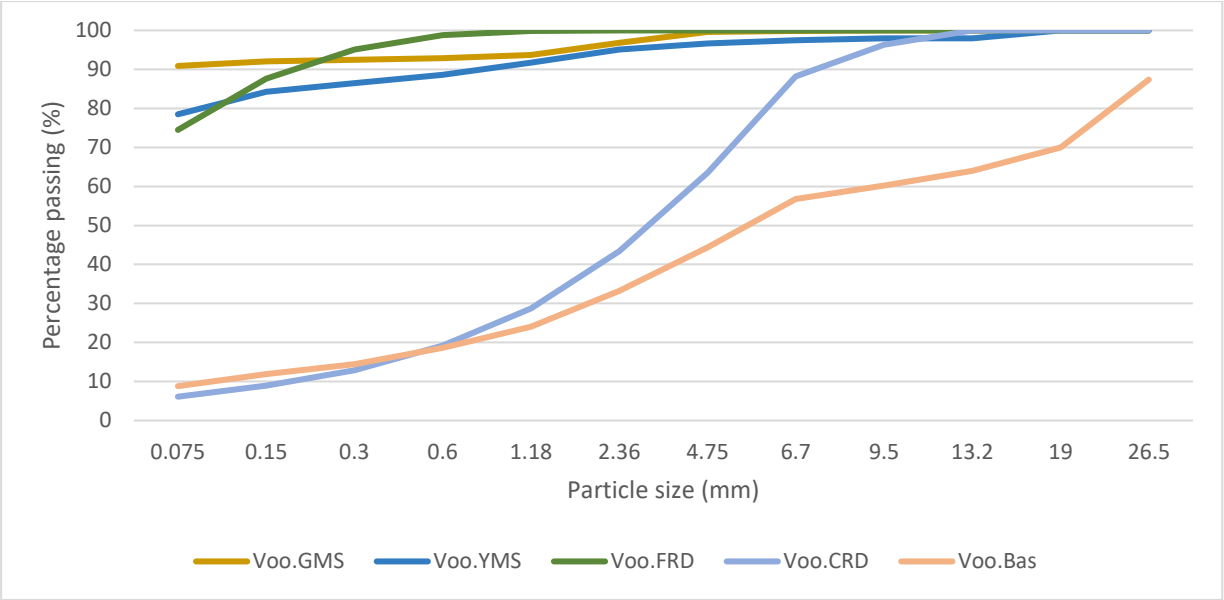


Figure 4-8: Grading of Voorspoed mine waste.

4.4 Fineness modulus

The fineness modulus, as calculated according to SANS 201, is a measure to help define the nature of the fine aggregate proportion (<4.75mm) of a concrete, and is illustrated in Figure 4-9 using the data in Annexure C. This figure shows the average value for the material tested, based on up to 5 replications per material type. The lowest fineness modulus values were achieved by the Kim3.FRD8, Voo.FRD, Voo.GMS and Voo.YMS, respectively. Some of the higher fineness modulus values included waste rocks and CRDs. This characteristic can be seen as another method to define the texture of a material: the lower the fineness modulus, the finer the texture.

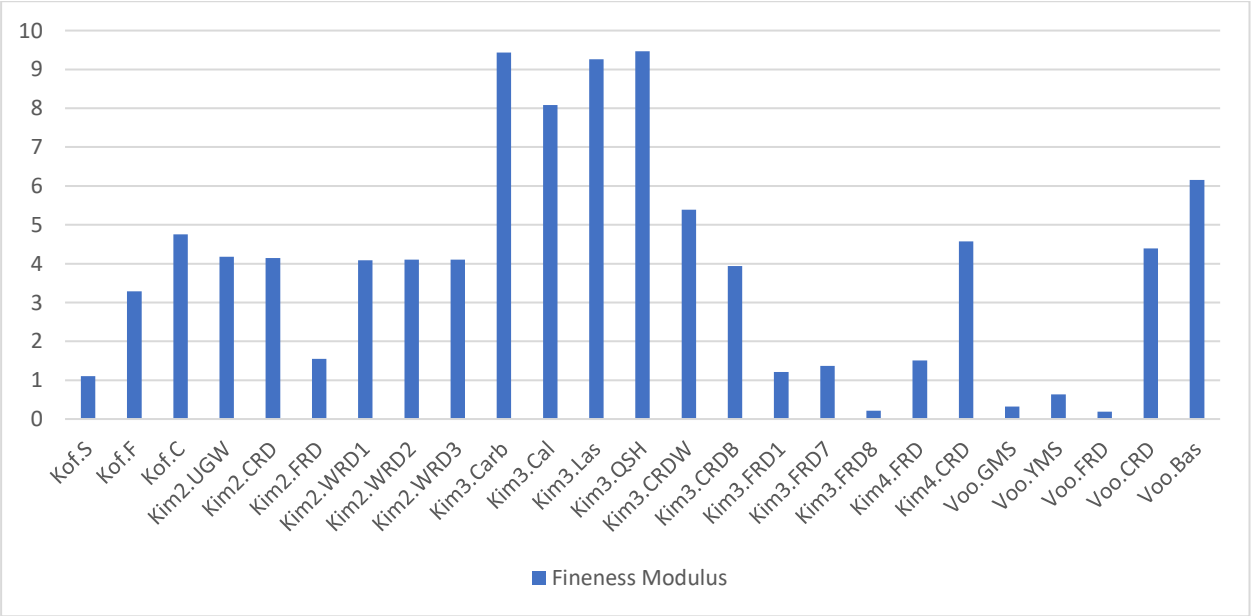


Figure 4-9: The fineness modulus of the studied material.

4.5 Dust content

The dust content, as calculated according to SANS 201, is a measure of the total amount of material passing the 75µm sieve and is illustrated in Figure 4-10 using the data in Annexure C. This figure shows the average value for the material tested, based on up to 5 replications per material type. The FRD8 of Kimberlite 3, the FRD of Voorspoed, and both Voorspoed mudstones had an extremely high proportion of material smaller than 75µm. As expected, the FRDs generally had more fines than the CRDs in most cases, with the relatively unweathered Kimberlite 4 samples indicating the lowest dust contents of the tailings materials tested. All four types of waste rocks from Kimberlite 2 and the basaltic material at Voorspoed had relatively high dust contents, with values similar to those of the CRD. The rest of the waste rocks, like those found at Kimberlite 3, had very low to almost negligible dust contents. The dust content results align with the PSD analysis findings and illustrate the distribution of very fine particles in the material.

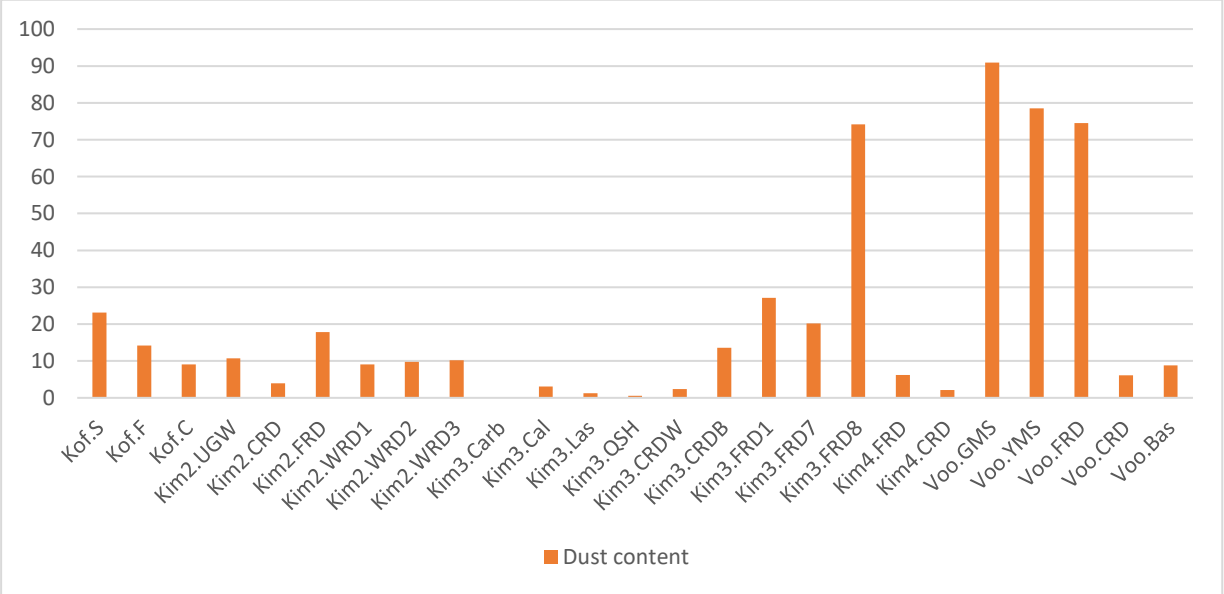


Figure 4-10: The dust content of the studied material.

4.6 AIV

The aggregate impact value (AIV), as calculated according to SANS 6239, is a measure to help define the resistance to breaking of a coarse aggregate to impacts and is illustrated in Figure 4-11, based on the data in Annexure D. This figure shows the average value of the material tested, with up to 2 replications per material type. The waste rocks of Kimberlite 3 and Voorspoed performed well and indicated low AIV's, meaning they resisted impact well. The waste rocks of Kimberlite 2 indicated quite high AIV's for a waste rock, compared to those of Kimberlite 3 and Voorspoed. The CRDB of Kimberlite 3 had the highest AIV of the materials tested. Some materials indicated changes in AIV, with some decreasing, others increasing, or remaining relatively uniform

across successive impact events. Generally, if impact events continue, changes between successive events will become smaller and eventually stabilise, as can be seen in the overall changes from a 3-impact event to a 6-impact event, compared to the 6-impact event to a 9-impact event, as shown in Figure 4-11.

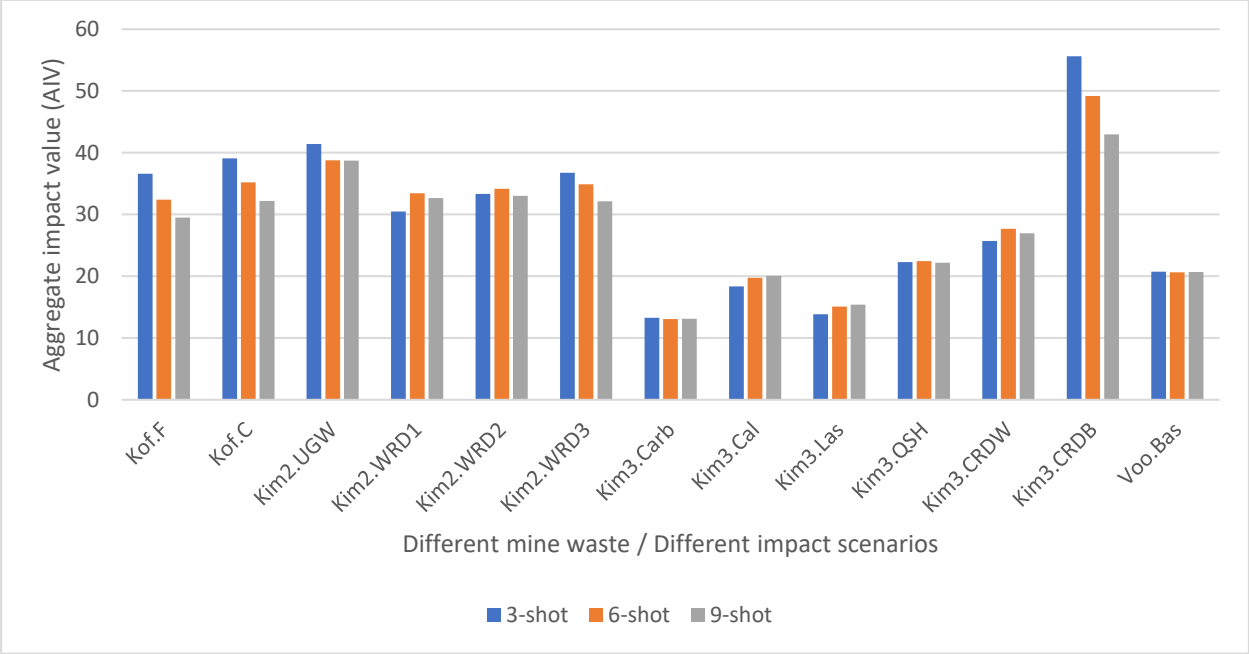


Figure 4-11: The AIV of the studied material.

4.7 Mineralogy

The mineralogy of the different samples was grouped into their general classification, similarly to Dawson, but using the groups' common names for simplicity (Dawson, 1980:65-108). The classifications also resemble the mineral classification in ASTM C 294-05 (ASTM, 2009:1-9; Neville, 2011:169). The mineralogy was determined by XRD and recalculated into their respective groups for analyses based on the data in annexures E and F. The phyllosilicate classification was split into the main groups of micas and clays for further clarity. Each mine's mineral diversity will be discussed separately in its appropriate section. A follow-up section will discuss the relationship between the primary and secondary minerals of the different materials. It should be noted that tailings are typically contaminated by waste rock from the mining process and may influence their mineralogy.

4.7.1 Koffiefontein

All three types of mine wastes from the Koffiefontein mine that were investigated were tailings-derived, which represent materials such as slimes, fines, and coarse. The mineralogy differs considerably between them, but some noteworthy observations can be made from Figure 4-12. Quartz is enriched in the coarser material, as it is most abundant in the Kof.C and in much less

quantities in the Kof.F and devoid in the Kof.S. The feldspars are high in the Kof.C and the Kof.F, with the latter having the highest concentration. The Kof.S also contains feldspar, but not nearly as much as Kof.F and Kof.C. The pyroxenes are high in the Kof.S and very low in the Kof.C and absent in the Kof.F material. The dominant primary minerals for Kof.C and Kof.F are the feldspars, whilst pyroxene is the dominant primary mineral for Kof.S. Biotite is present in all three materials, with an increasing trend towards the finer-type materials. Muscovite is only present in the Kof.F. All three materials have relatively high clay contents, where Kof.C is enriched in 2:1:1 clays, the Kof.F is enriched in 2:1 clays, and the Kof.S contains both 1:1 and 2:1 clays. The beryllium silicate was only present in the Kof.S material.

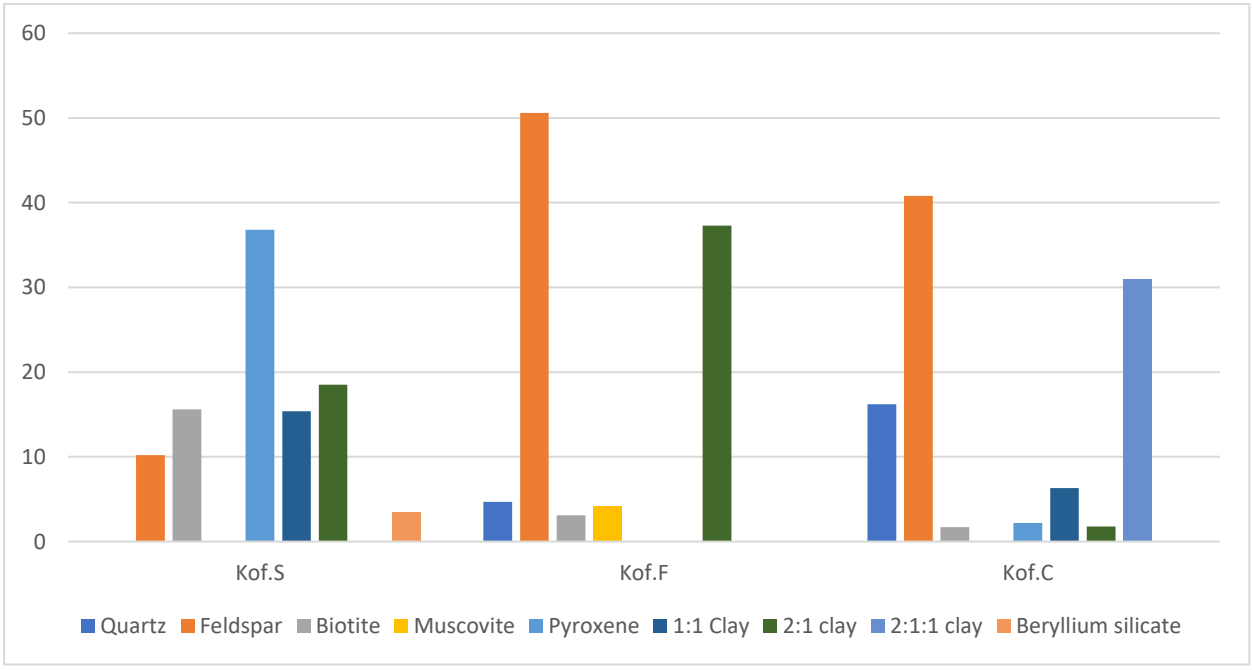


Figure 4-12: The mineralogy of Koffiefontein diamond mine.

4.7.2 Kimberlite 2

Two types of tailings and four types of waste rock were investigated for the Kimberlite 2 mine, and the results of their mineralogy are illustrated in Figure 4-13 the Kim2.CRD contains primary minerals such as feldspar, biotite, pyroxene, and amphibole, whilst the Kim2.FRD contains the primary minerals of quartz, biotite and cordierite. The Kim2.CRD is enriched in 2:1:1 clay, with almost negligible 2:1 clays. The Kim2.FRD contains high amounts of 2:1:1 clays (the dominant clay type), with 1:1 and 2:1 clays present in lesser amounts. The four waste rocks have some relationships among them, but they still show noticeable differences. The Kim2.UGW and Kim2.WRD2 has an almost identical mineralogy, with quartz, feldspar, biotite, and amphibole present in very similar ratios, but it differs in that the Kim2.UGW has an extremely high carbonate content. The Kim2.WRD3 material has some similarities to the previously mentioned material in

that quartz, feldspar, and biotite have similar ratios, but differs in that it has much lower carbonate levels than Kim2.WRD2, extreme levels of feldspar, is absent in amphibole, and contains cordierite. The Kim2.WRD1 differs from the other three waste rocks in that it has a much higher biotite content than the other felsic minerals, such as quartz and feldspar. The Kim2.WRD1 is absent in cordierite and amphibole, whereas it is the only waste rock to contain pyroxene.

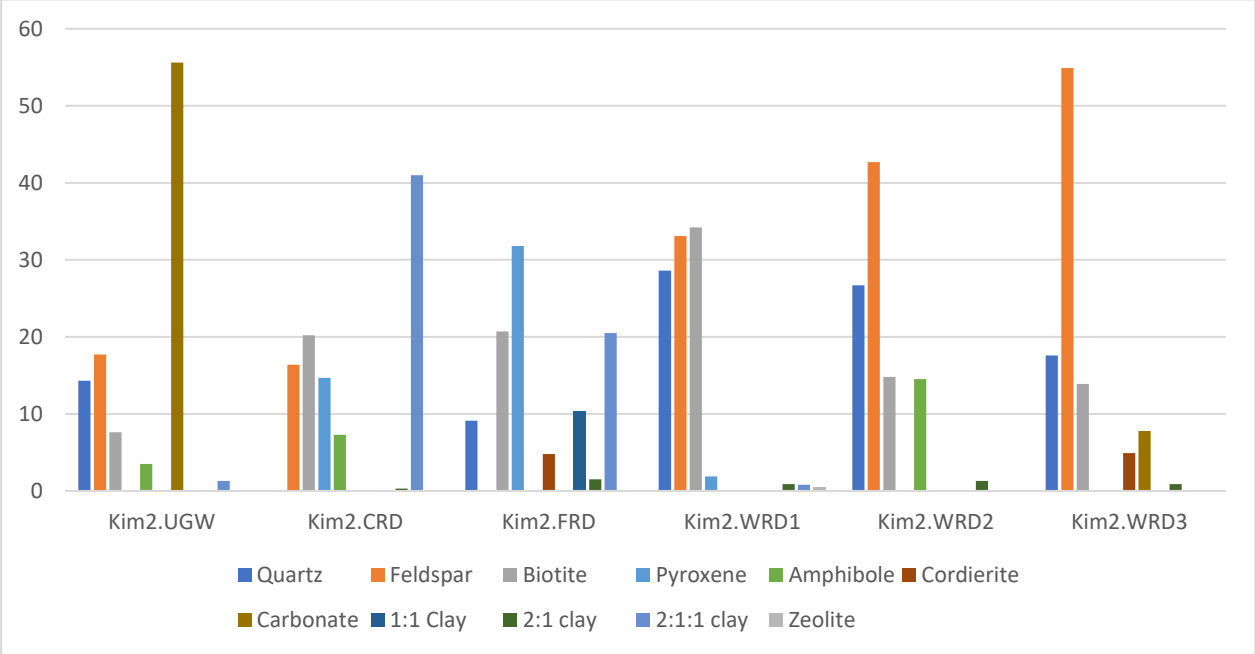


Figure 4-13: The mineralogy of Kimberlite 2 diamond mine.

4.7.3 Kimberlite 3

Five types of tailings and four types of waste rock were investigated for the Kimberlite 3 mine, and the results of their mineralogy are illustrated in Figure 4-14. The two CRDs differ considerably from each other, the Kim3.CRDW consist almost entirely of carbonate minerals, with quartz and pyroxene found in minor amounts, and some 2:1 clays are just measurable, whilst the Kim3.CRDB contains only phyllosilicates, with biotite as the only primary mineral, and the rest as clay minerals. The Kim3.CRDB consists of about three-quarters clay, with 1:1 clays dominant, 2:1 clays intermediate (about the same concentration as biotite), and 2:1:1 clays in minor amounts. The FRDs for comparison share much more similarities with each other than what the CRDs do with each other, but still have some noticeable differences. The Kim3.FRD1 contains pyroxene, quartz, and biotite as primary minerals, in that order of decreasing abundance. The Kim3.FRD1 contains considerable amounts of 2:1:1 clays and 2:1 clays, the former being slightly more abundant, and 1:1 clays and zeolites being present in minor amounts. The Kim3.FRD7 contains only quartz as a primary mineral, and consists mostly of 2:1 clays followed by carbonates and minor amounts of 1:1 clays. The Kim3.FRD8 contains only pyroxene as a primary mineral, and consists mostly of

1:1 clays that are closely followed by carbonates, 2:1 clays and zeolites. The Kim3.Carb, Kim3.Las and Kim3.QSH have very similar mineralogy and mineral ratios. They consist dominantly of quartz and 2:1:1 clays with lesser amounts of muscovite, followed by feldspars. Some differences do exist where Kim3.Carb is the only one with carbonates and without biotite, Kim3.Las is the only one with titanium oxide minerals and Kim3.QSH contains minute amounts of 2:1 clays. Other interesting trends include a positive correlation between quartz and muscovite, whilst the 2:1:1 clays show a negative relation to both quartz and muscovite, as can be seen in Figure 4-14. The Kim3.Cal differs considerably from the other waste rocks and is practically identical to the Kim3.CRDW, apart from the additional minor feldspar content.

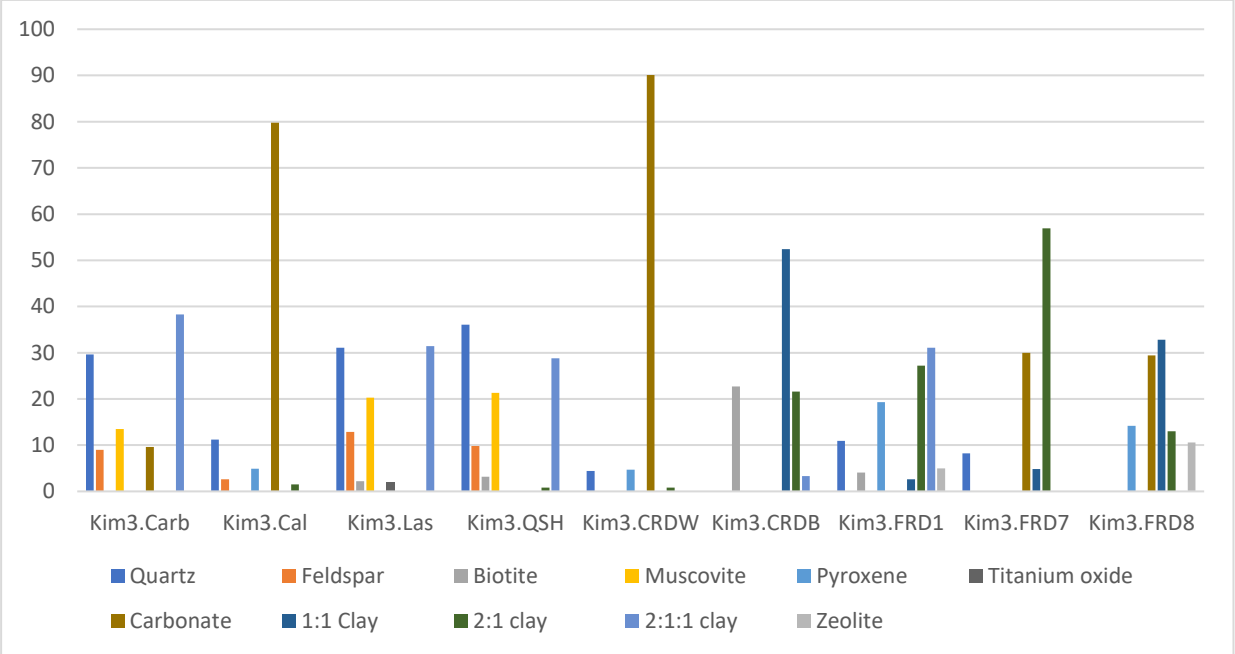


Figure 4-14: The mineralogy of Kimberlite 3 diamond mine.

4.7.4 Kimberlite 4

Two tailings were investigated for the Kimberlite 4 mine, and the results of their mineralogy are illustrated in Figure 4-15. The Kim4.FRD and Kim4.CRD both contain feldspar, biotite, and pyroxene, albeit at different concentrations. The Kim4.FRD has a higher biotite content but lower feldspar and pyroxene contents. Other differences are that the Kim4.FRD contains large amounts of 1:1 clays, followed by garnets and minor amphibole. The Kim4.CRD, on the other hand, contains similar concentrations of 2:1:1 clays as the 1:1 clays of the Kim4.FRD and some smaller amounts of quartz.

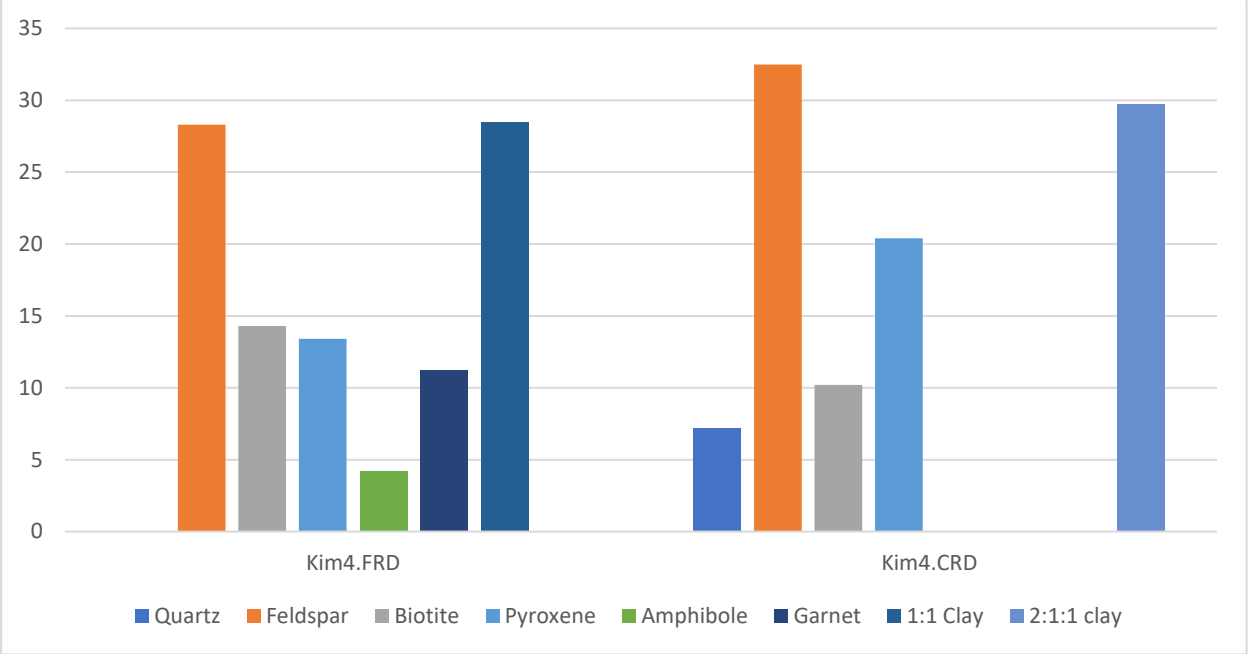


Figure 4-15: The mineralogy of Kimberlite 4 diamond mine.

4.7.5 Voorspoed

Two types of tailings and three types of waste rock were investigated for the Voorspoed mine, and the results of their major elements are illustrated in Figure 4-16. The Voo.CRD mostly contains feldspars with lesser amounts of pyroxene and only minor amounts of 2:1 clays. The Voo.FRD also contain large amounts of feldspars, but much more 2:1 clays than the Voo.CRD. The Voo.FRD also differs from the Voo.CRD in that it contains noteworthy amounts of muscovite and minor amounts of pyroxene. The Voo.Bas has a mineral diversity and concentration between Voo.CRD and Voo.FRD, with the only difference being the additional minor amounts of quartz. The Voo.GMS and the Voo.YMS both have similar mineralogy, with about one-third quartz, one-third feldspar, and one-third phyllosilicates. The phyllosilicate content of the Voo.GMS is dominantly 2:1 clays with almost negligible biotite and 2:1:1 clays, whilst the phyllosilicate content of the Voo.YMS is dominantly biotite with minor amounts of muscovite and 2:1 clays.

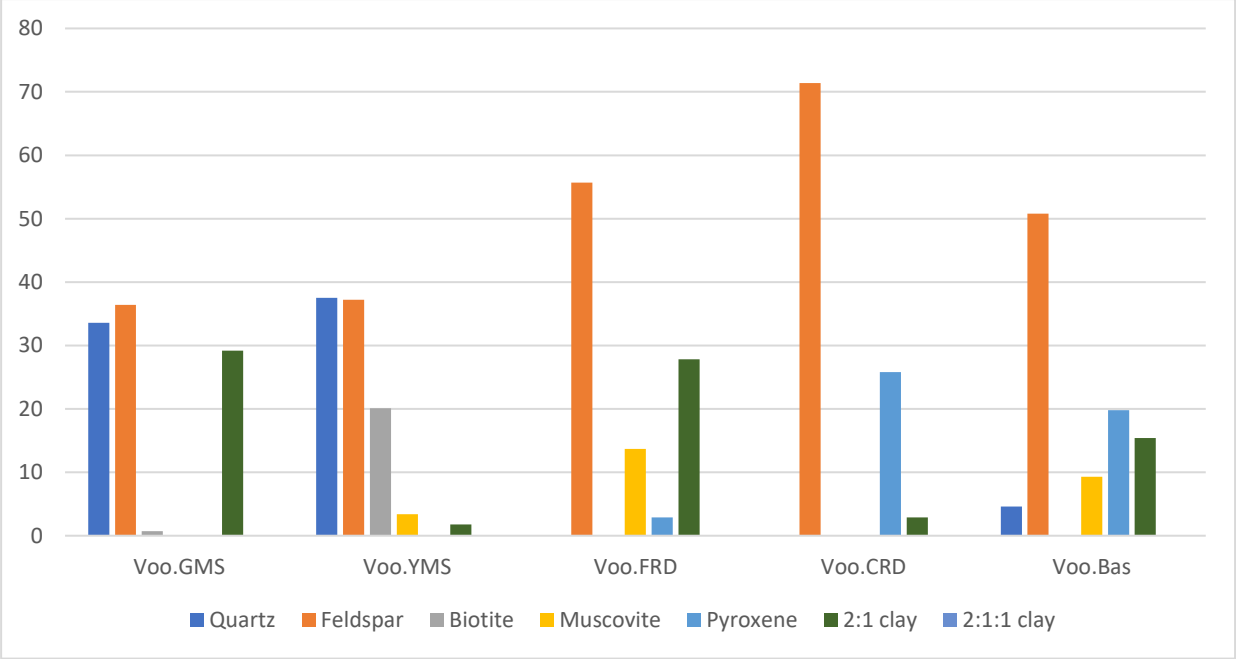


Figure 4-16: The mineralogy of Voorspoed diamond mine.

4.7.6 Primary versus secondary mineral relationship

The specific minerals, as identified by XRD, were interpreted as part of a primary or secondary mineral occurrence to help evaluate the state of the material tested. The results of these groupings are illustrated in Figure 4-17 using data from Annexure G, where primary minerals represent minerals formed during primary formation, whilst secondary minerals indicate formation during alteration or secondary formation sequences (Dawson, 1980:65-109; Mitchell, 1986:137-274; Klein & Dutrow, 2007:331-550). This is not a perfect representation as weathering and neoformation of minerals are extremely dynamic, which complicates the classification (Wagner, 1914:52-53; Millot, 1970:97; Dawson, 1980:65-109; Skinner & Clement, 1982:304; Mitchell, 1986:137-274; Allen & Hajek, 1989:240; Klein & Dutrow, 2007:331-550; Morkel, 2006:6; Strydom, 2015:12-14). The trends for both the tailings and the waste rocks can be confusing for this study, as there is no clear relationship that predicts the primary or secondary mineral content for these examples. It can be expected that the FRDs would have higher secondary mineral content, but this was not always the case. Most tailings had a higher primary mineral content than the secondary mineral content, apart from the Kimberlite 3 tailings. The known ROM tailings of Kimberlite 4 had the fewest secondary minerals, with Kimberlite 2 samples showing the second fewest, indicating the least weathering. Although the Kim3.CRD technically had the lowest amount of secondary minerals among the tailing types, it can be attributed to the very high amounts of minerals associated with the waste rock, which discredit it from being used as a monologue to normal tailings waste. This might be the same reason why Kimberlite 3 tailings have such high secondary mineral content. There are different types of waste rocks at the mine, and the

contamination of certain waste types might influence the primary versus secondary mineral relationship, as some are dominantly primary, whilst others are secondary mineral-dominated.

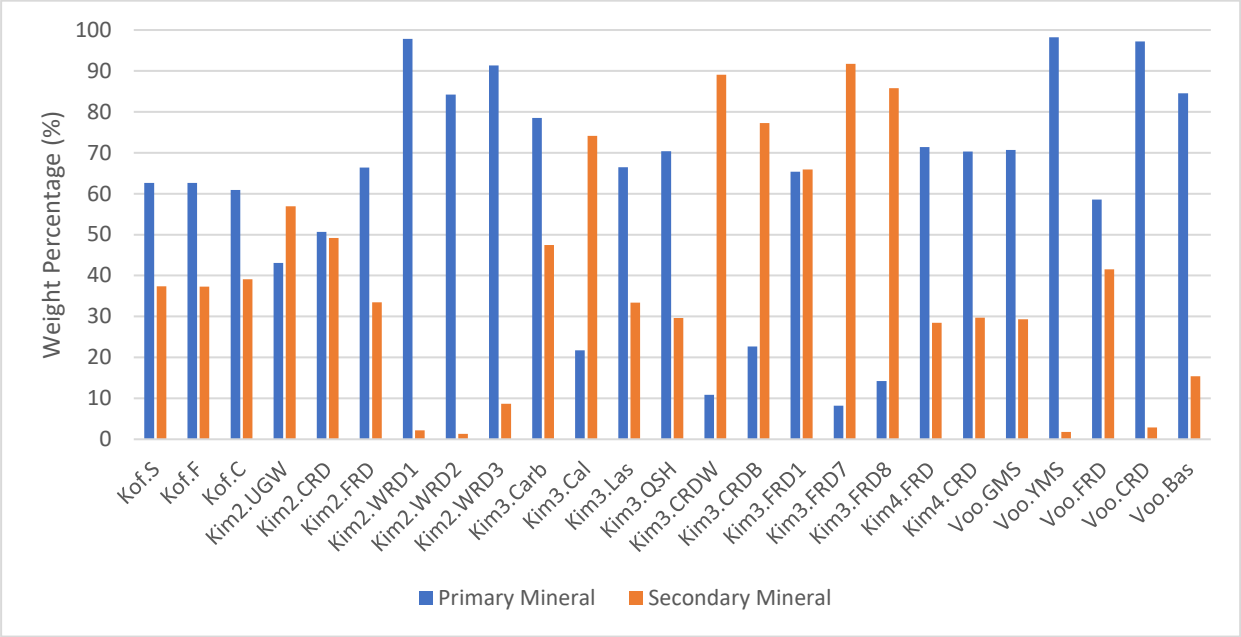


Figure 4-17: The relationship between primary and secondary minerals per material.

4.8 Chemical composition

The chemical properties were grouped into major, minor and trace elements based on the classification system proposed by Winter (2014:141-142). The samples were scanned using the P-XRF mentioned in the methods section and recalculated to their appropriate oxide form, where applicable, using the correction factors proposed by JCU (2025). The samples were appropriately sampled and mixed to produce large bulk samples for analysis. The full list of elements tested is represented in Annexure H.

4.8.1 Koffiefontein

Three types of mine wastes from the Koffiefontein mine that were investigated are tailings, which include slimes, fines, and coarse material. The major element in the tailings is SiO_2, with MgO, Fe_2O_3, Al_2O_3, CaO, and K_2O present in smaller amounts, as shown in Figure 4-18. The tailings have very similar compositions, with minor but notable differences among the different tailing types. There are strong decreasing trends in Al_2O_3 and increasing trends in MgO with increasing product fineness. The Kof.S and Kof.F have similar CaO and SiO_2 values compared to the Kof.C product. Fe_2O_3 and K_2O show no clear trend or change across the different tailing types. SiO_2 and Al_2O_3 have a negative relation to the CaO and MgO concentration of the tailings.

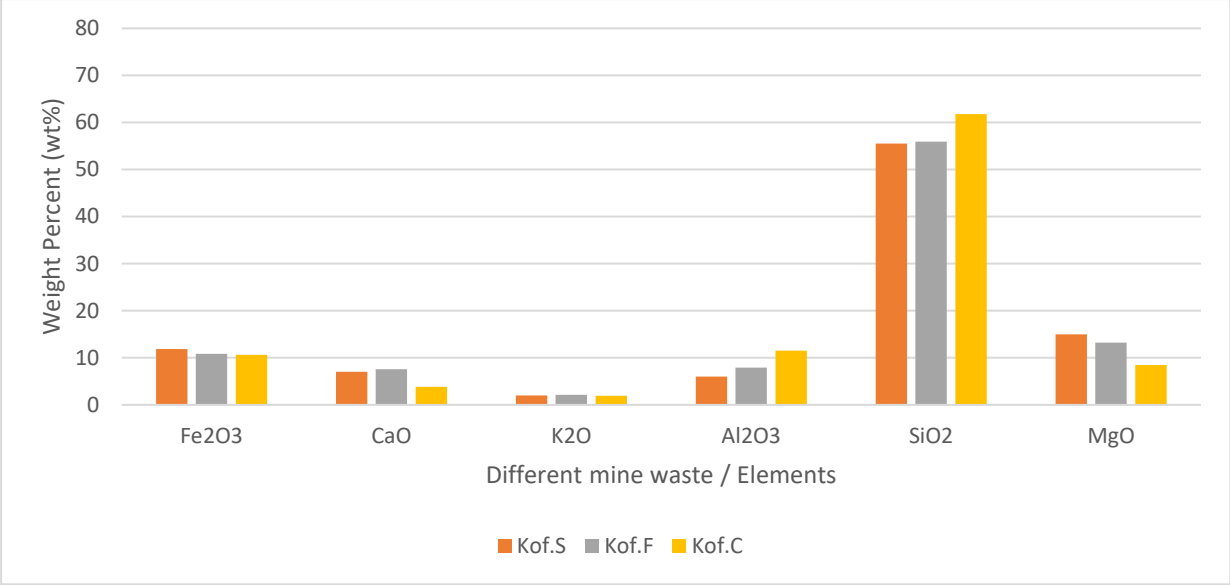


Figure 4-18: The major oxide composition of Koffiefontein.

The minor elements can be seen in Figure 4-19, which indicates that the tailings consist of TiO_2 and SO_3 as the dominant components, with P_2O_5 as supplementary, and NiO, MnO, Cr_2O_3, and BaO found in trace amounts. The elements of NiO, MnO, Cr_2O_3, TiO_2 and SO_3 indicate an increase in concentration with the finer textured tailings. The P_2O_5 and BaO concentrations are stable and constant throughout the tailings material products. There is, however, a slight enrichment in the Kof.F above that of the Kof.S and Kof.C material for P_2O_5 and a slight diminishment of BaO of Kof.F, indicating a possible negative relation between P_2O_5 and BaO.

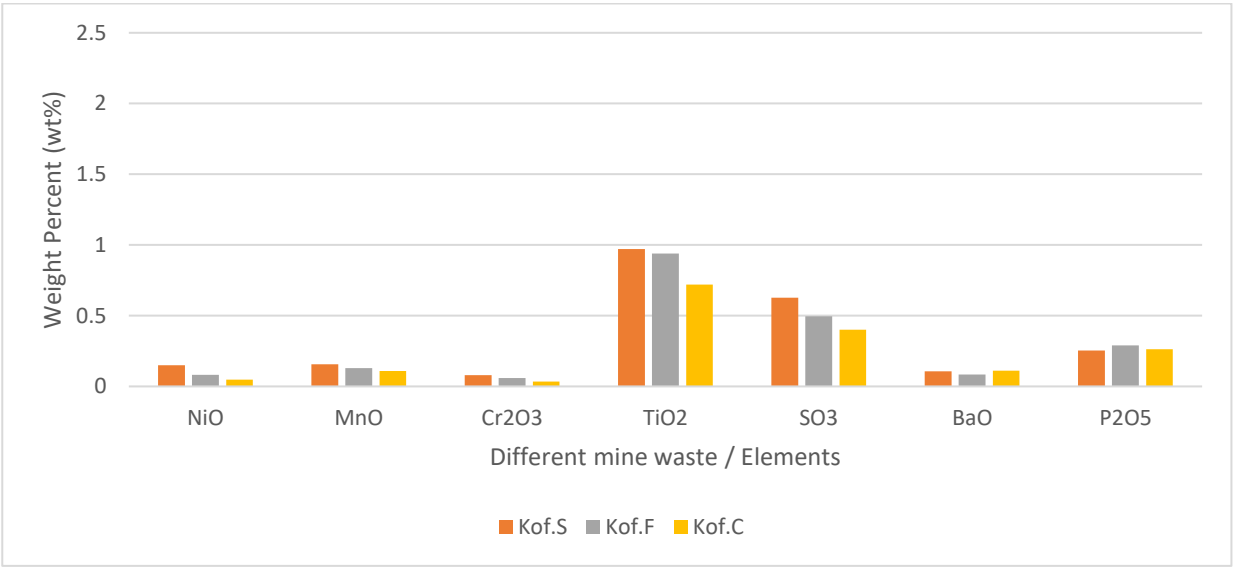


Figure 4-19: The minor oxide composition of Koffiefontein.

The trace elements are shown in Figure 4-20, where the elements indicated are of interest to this study. Zn, Cu, Co, and V are found in much higher concentrations than Pb and As. There is also no presence of Hg and Cd measured for the mine. Pb, Zn, and Cu show similar trends across the

different tailings types, whereas V shows the opposite trend. The As was higher in the coarser tailings (Kof.C) than in finer tailings (Kof.F). The Kof.F was the only sample that indicated the presence of Cd.

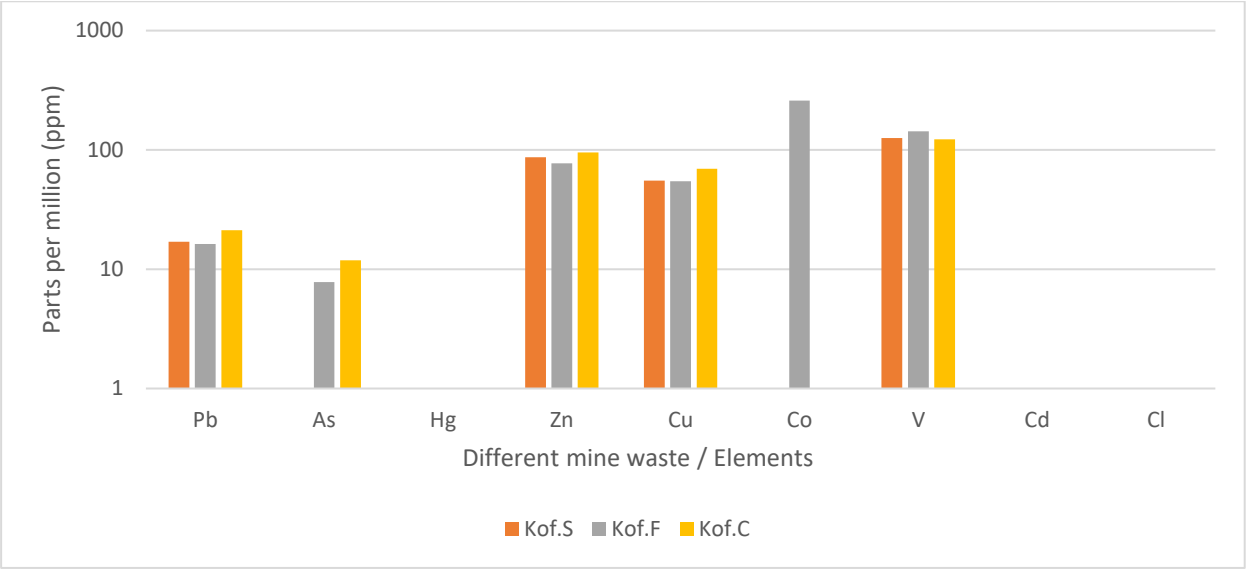


Figure 4-20: The trace elements of interest for Koffiefontein.

4.8.2 Kimberlite 2

Two types of tailings and four types of waste rock were investigated at the Kimberlite 2 mine, and the results for their major elements are illustrated in Figure 4-21. The major elements of the tailings and the waste rock consist of SiO_2 with MgO, Fe_2O_3, CaO, Al_2O_3 and K_2O forming lesser amounts of the composition. The difference between the FRD and the CRD tailings is only very slight, but some differences can still be identified. The CaO show enrichment for the FRD compared to the CRD. SiO_2, MgO, and Fe_2O_3 show enrichment in the CRD than in the FRD. The K_2O and Al_2O_3 is very similar for both the FRD and CRD. The waste rock of Kim2.WRD1, Kim2.WRD2 and Kim2.WRD3 show similar compositions. These three waste rocks show a positive relationship between Fe_2O_3 and Al_2O_3, and a negative relationship with CaO content. The SiO_2 and MgO also show a negative relationship with each other. The Kim2.UGW show drastically different compositions to the other waste rocks already mentioned, with much higher CaO content and relatively lower Fe_2O_3 and SiO_2 content. The recognisably higher MgO content of the tailings compared to the waste rocks helps to separate them.

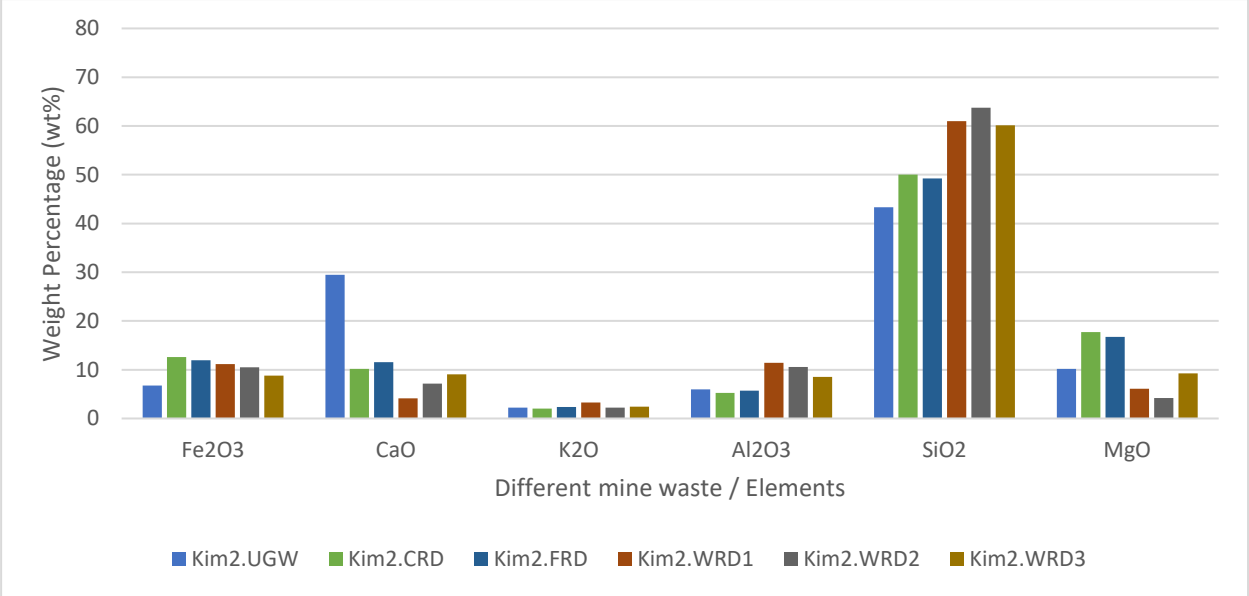


Figure 4-21: The major oxide composition of Kimberlite 2.

The minor elements can be seen in Figure 4-22, which indicates that the tailings and waste rocks consist of TiO_2 and SO_3 as the dominant components, with P_2O_5 (if present) and MnO as supplementary components, and NiO, Cr_2O_3, and BaO found in trace amounts. The elements of NiO, MnO, Cr_2O_3 and BaO indicate a decrease in concentration with the finer textured tailings. The TiO_2 content is relatively stable, with only SO_3 and P_2O_5 showing increases in the finer-textured tailings. The four waste rocks had similarly low NiO, Cr_2O_3, and BaO. Overall, the Kim2.WRD2 and Kim2.WRD3 have very similar compositions, except for the absence of P_2O_5 for the Kim2.WRD2 material. The Kim2.WRD1 differed from the other waste rocks in that it had much higher TiO_2 and SO_3 values. The Kim2.UGW differed from the other waste rocks in that it had much higher MnO content, an elevated SO_3 value, and a much lower TiO_2 value. The recognisably higher NiO, Cr_2O_3, and P_2O_5 content of the tailings compared to the waste rocks helps separate them.

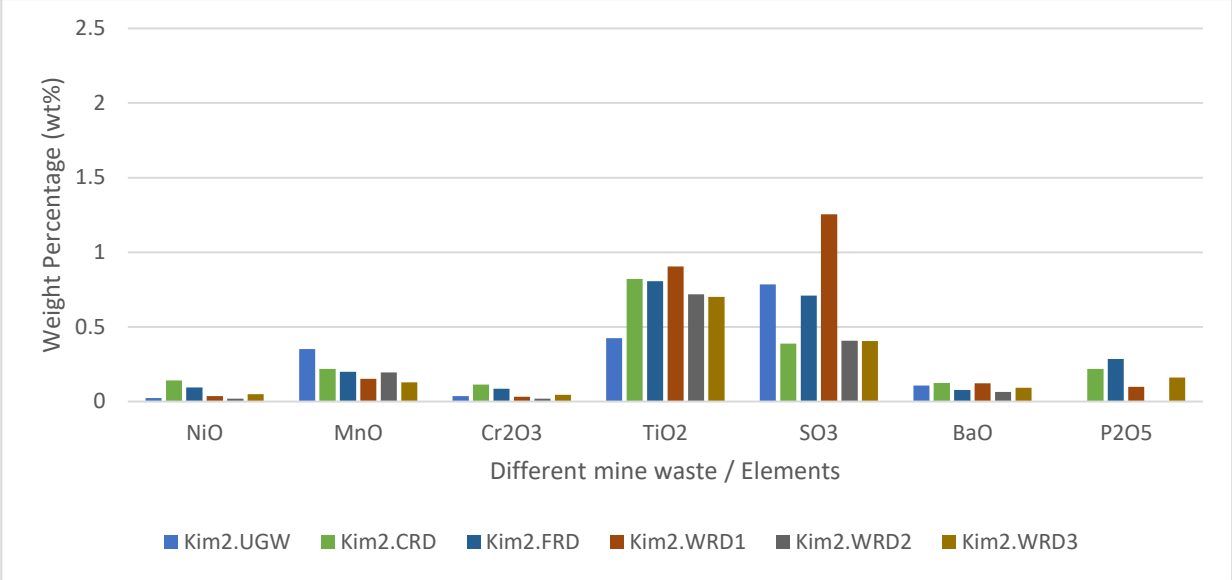


Figure 4-22: The minor oxide composition of Kimberlite 2.

The trace elements are shown in Figure 4-23; the elements indicated are of interest to this study. Co, V, Zn, and Cu are found in much higher concentrations than Pb, Hg, and As. There is also no Cd detected in the mine. In the tailings, Co, V, Zn, and Cu are present in relatively high concentrations, whereas As is present at lower concentrations. The Zn and Cu were higher in the finer tailings (Kim2.FRD) than in the coarser tailings (Kim2.CRD). The As and Co were higher in the coarser tailings (Kim2.CRD) than in finer tailings (Kim2.FRD). The V indicated no clear concentration between the different tailings, maybe a slight enrichment in the Kim2.FRD material. For most of the waste rocks, Co, V, Zn, and Cu are found in relatively high concentrations, whereas Pb, Hg, and As are found in lower concentrations. It should be noted that the Kim2.UGW and Kim2.WRD1 do not contain As, and the Kim2.WRD3 does not contain Co.

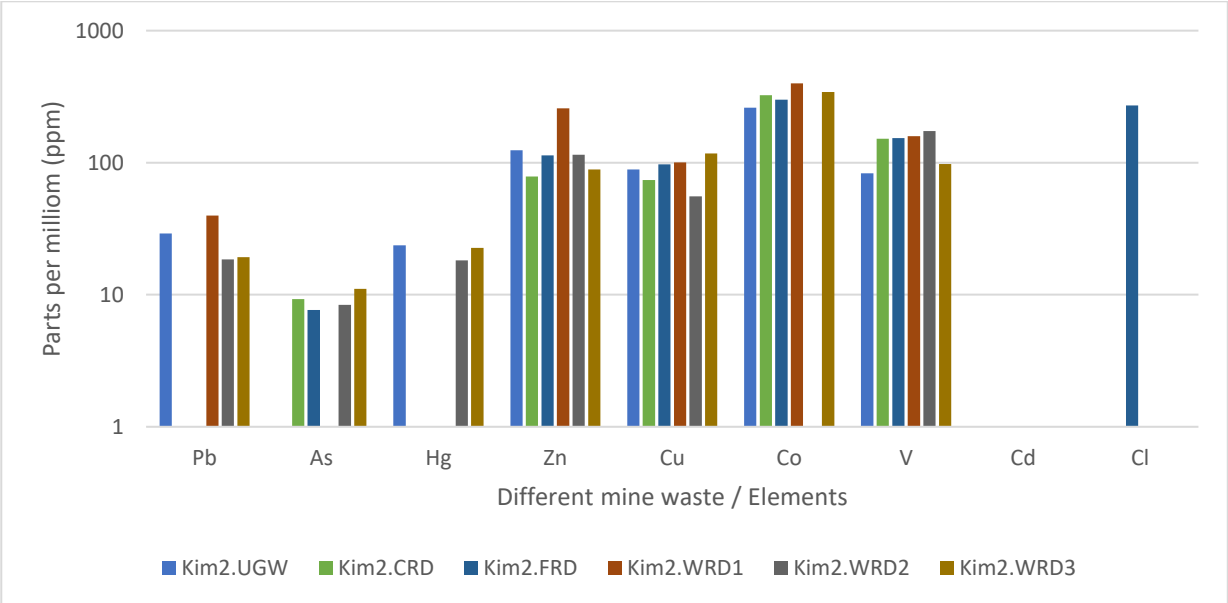


Figure 4-23: The trace elements of interest for Kimberlite 2.

4.8.3 Kimberlite 3

Five types of tailings and four types of waste rock were investigated at the Kimberlite 3 mine, and the results for their major elements are illustrated in Figure 4-24. The major elements of the tailings and the waste rock consist of SiO_2 with MgO, Fe_2O_3, CaO, Al_2O_3 and K_2O forming lesser amounts of the composition. There are two types of CRD tailings and three types of FRD/Slimes tailings. SiO_2 and MgO have a negative relationship in the tailings materials. When comparing the tailings material with each other, it becomes obvious that the Kim3.CRDW differs considerably from the other tailings materials with its very high CaO content and notably lower Fe_2O_3 and SiO_2 content. The other elements of K_2O, Al_2O_3 and MgO show no great difference between tailings and differ only when compared to the waste rocks. The recognisably higher MgO content of the tailings compared to the waste rocks helps to separate them. The Kim3.Cal differs from the other waste rocks by having much lower Fe_2O_3, Al_2O_3, and SiO_2 content and much higher CaO and MgO content. The other three waste rocks tend to have very similar compositions, except for Kim3.Carb has a slightly lower SiO_2 and slightly higher CaO content than the other two waste rocks.

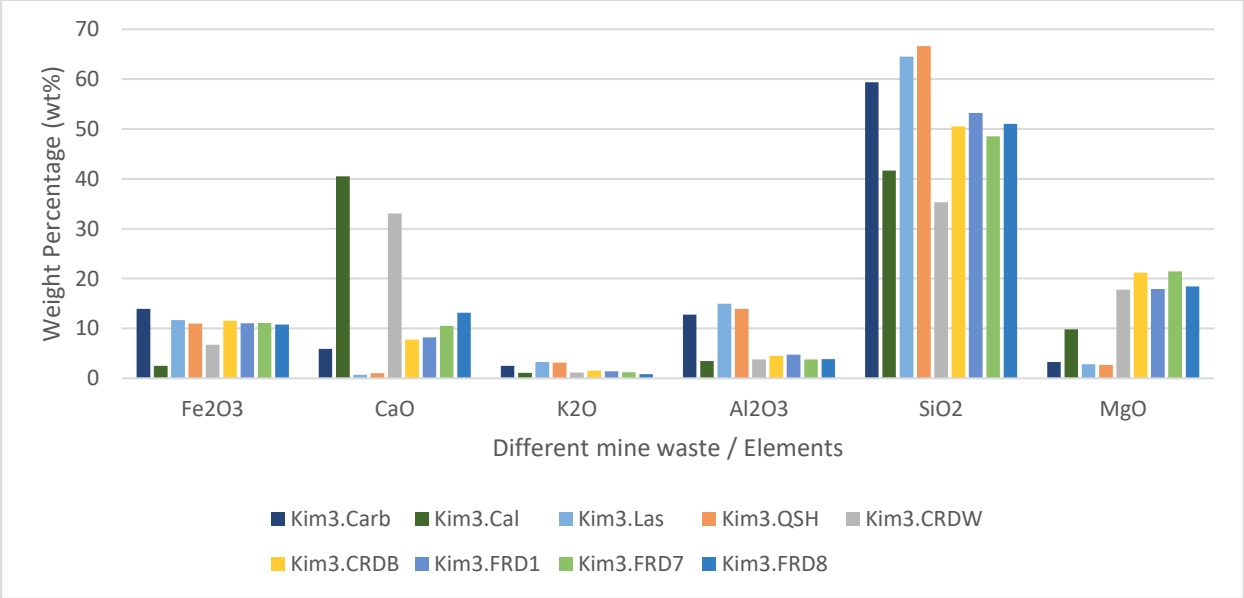


Figure 4-24: The major oxide composition of Kimberlite 3.

The minor elements can be seen in Figure 4-25, which indicates that the tailings and waste rocks consist of TiO_2 and SO_3 as the dominant components, with P_2O_5, MnO, NiO, Cr_2O_3, and BaO as supplementary components in almost trace amounts. The Kim3.CRDW has lower TiO_2, SO_3, NiO, and Cr_2O_3 contents and similar P_2O_5, MnO, and BaO contents to those of Kim3.CRDB. The different FRDs have compositions similar to Kim3.CRDB with NiO being almost the same. The different FRDs differ in the TiO_2, SO_3, Cr_2O_3, MnO, and BaO contents, but, when combined, will

give similar values to those of Kim3.CRDB. The P_2O_5 content of the FRDs is notably less than that of the CRDs. The relatively high NiO and Cr_2O_3 content of the tailings is what separates them from the waste rocks. The waste rocks have a great variety, and the only things they have in common are low NiO and Cr_2O_3. The Kim3.Cal has very low TiO_2 and no measurable P_2O_5 values, whilst the other three waste rocks have values similar to those of the tailings. The Kim3.Carb has notably higher MnO and SO_3 values than the other three waste rocks, even surpassing those of the tailings materials in some cases.

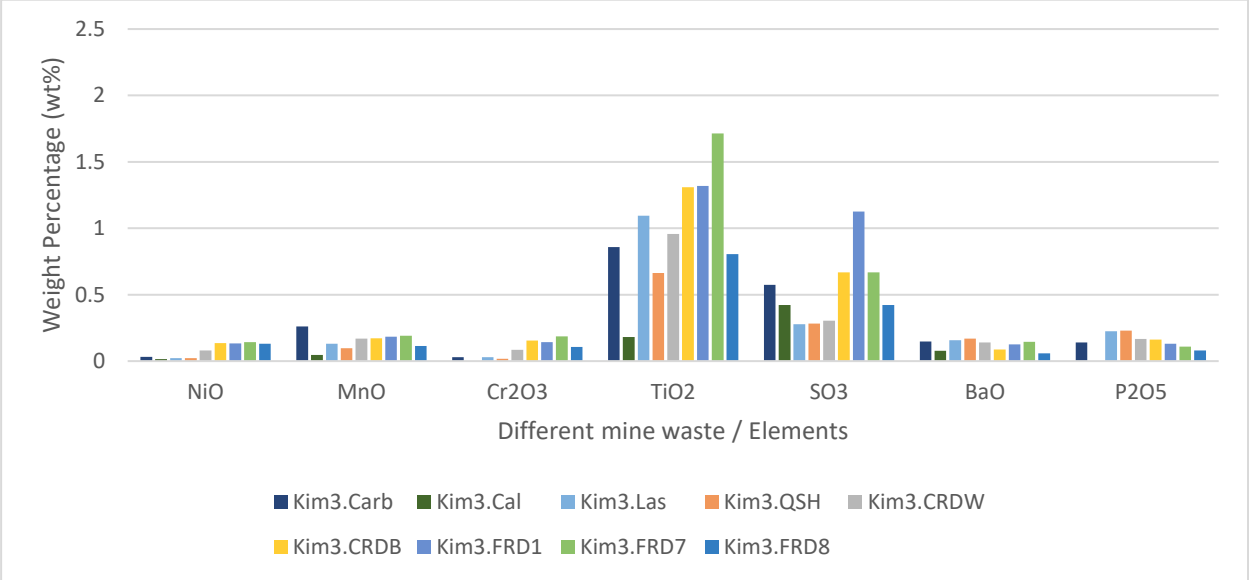


Figure 4-25: The minor oxide composition of Kimberlite 3.

The trace elements are shown in Figure 4-26; those indicated are of interest to this study. Co, V, Zn, and Cu are found in much higher concentrations than As, Pb, and Cd. There is also no Hg detected at the mine. For the tailings, Co and V are found in relatively high concentrations, Zn and Cu in intermediate concentrations, and Pb and As in lower concentrations. The Kim3.CRDW tends to have the lowest trace element concentrations in the tailings material. By comparing the different tailing types, a pattern emerges in which the highest trace element concentrations tend to be at Kim3.CRDB for the Pb element, the Kim3.FRD7 (the coarsest of the FRDs) for the As and Cu elements, and the bi-modal distribution of Zn, Co and V elements at Kim3.CRDB and Kim3.FRD1/Kim3.FRD8 material. For most of the waste rocks, Co, V, Zn, and Cu are found in relatively high concentrations, whereas As, Pb, and Cd are found in lower concentrations. The Kim3.Carb tends to have a very high Pb, As and Cu content compared to the other rocks tested. The Kim3.Cal and Kim3.CRDB does not have any As content. The Kim3.QSH does not contain Zn. The Kim3.Cal is the only waste rock containing Cd.

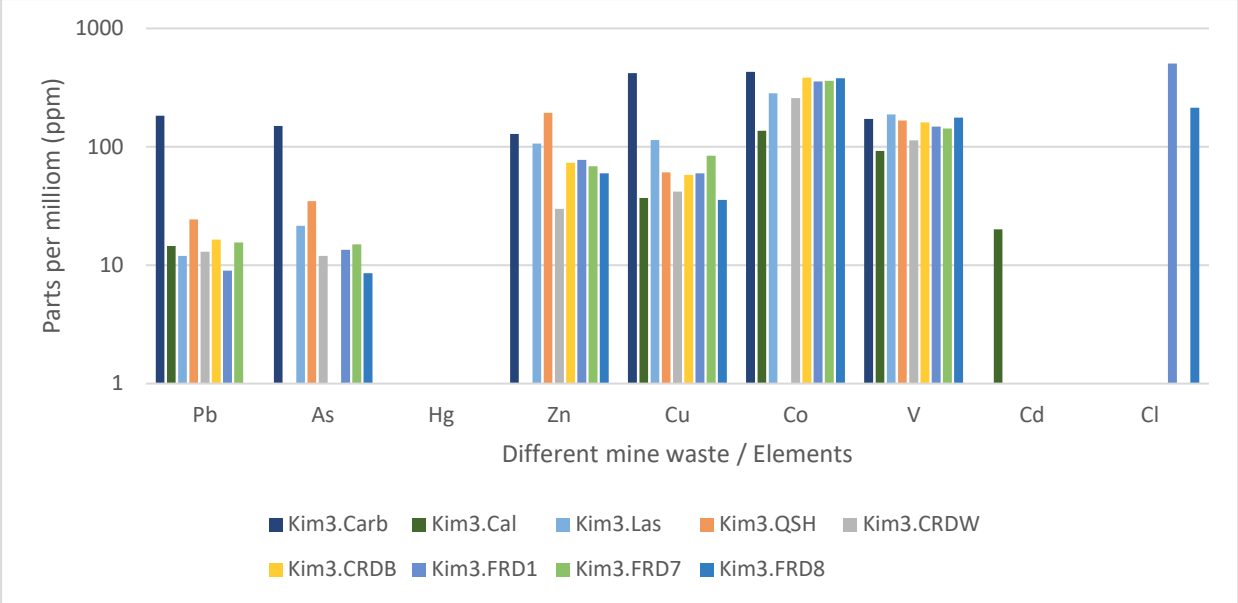


Figure 4-26: The trace elements of interest for Kimberlite 3.

4.8.4 Kimberlite 4

Two tailings were investigated for the Kimberlite 4 mine, and the results of their major elements are illustrated in Figure 4-27. The major elements of the tailings are SiO_2, with MgO, Fe_2O_3, CaO, Al_2O_3, and K_2O present in lesser amounts, respectively. The difference between the FRD and the CRD tailings is only very slight, but some differences can still be identified. MgO, Fe_2O_3, and CaO show enrichment in the FRD compared to the CRD. SiO_2 and Al_2O_3 show enrichment in the CRD relative to the FRD. The K_2O is very similar for both the FRD and CRD.

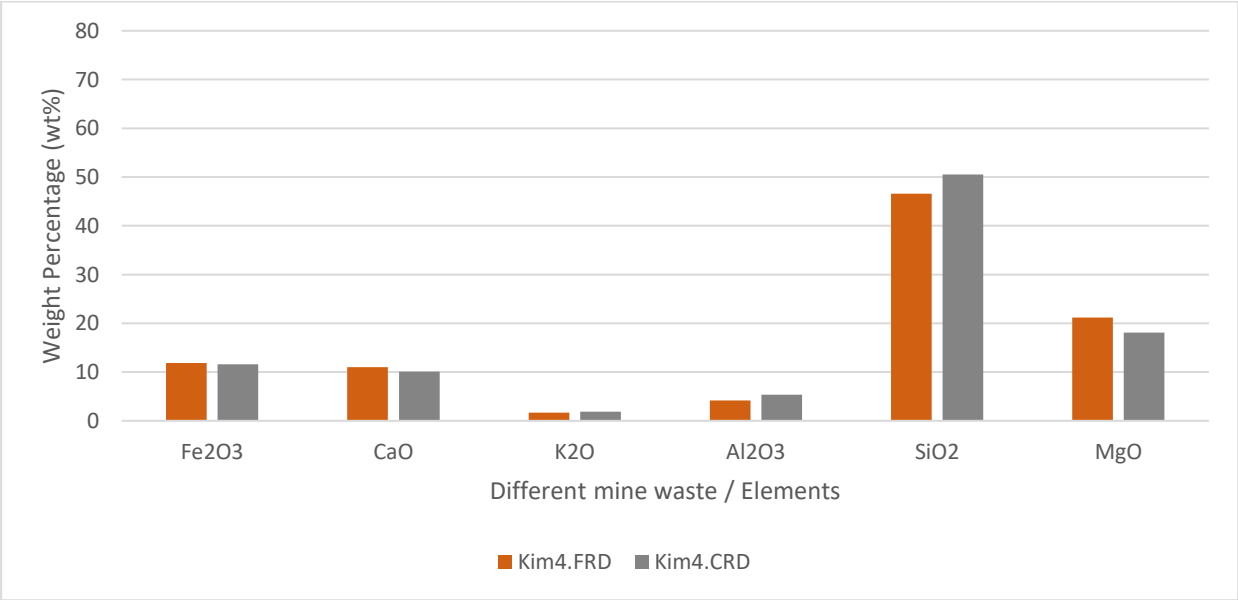


Figure 4-27: The major oxide composition of Kimberlite 4.

The minor elements are shown in Figure 4-29, which indicates that the tailings and waste rocks consist of TiO_2, with SO_3, P_2O_5, MnO, Cr_2O_3, NiO, and BaO present in trace amounts. The NiO, MnO, Cr_2O_3, BaO and TiO_2 show enrichment in the FRD compared to the CRD, with the latter being pronounced. SO_3 and P_2O_5 show very similar values, with minor enrichment in the CRD relative to the FRD.

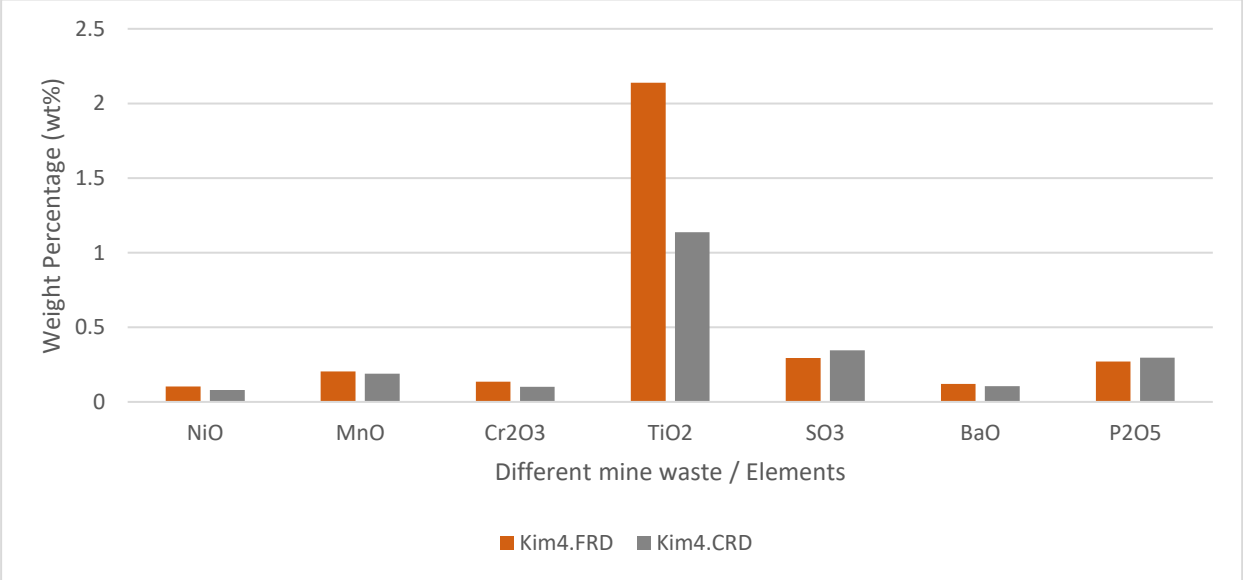


Figure 4-28: The minor oxide composition of Kimberlite 4.

The trace elements are shown in Figure 4-29; those indicated are of interest to this study. There are Co and V, found at relatively high concentrations; Zn and Cu, found at intermediate concentrations; and Pb, found at lower concentrations. There are no measurable As, Hg and Cd in the materials tested for Kimberlite 4. The Zn, Cu, Co and V were higher in the finer tailings (Kim4.FRD) than in the coarser tailings (Kim4.CRD). The Zn does, however, show this trend only slightly. The Pb was higher in the coarser tailings (Kim4.CRD) than in finer tailings (Kim4.FRD).

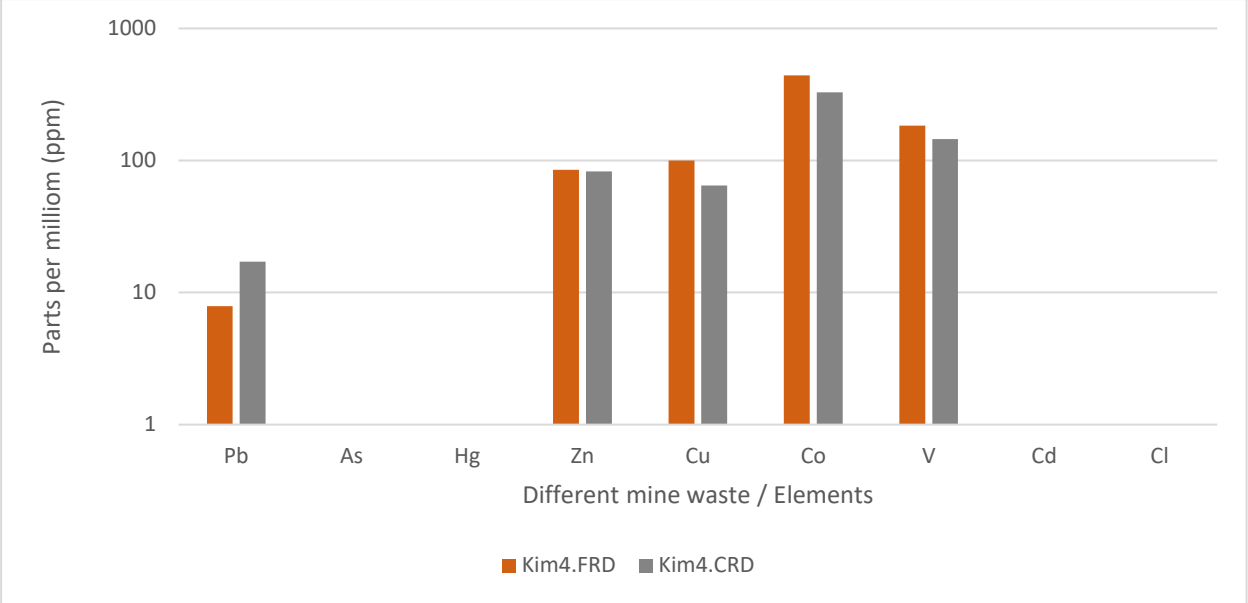


Figure 4-29: The trace elements of interest for Kimberlite 4.

4.8.5 Voorspoed

Two types of tailings and three types of waste rock were investigated for the Voorspoed mine, and the results of their major elements are illustrated in Figure 4-30. The major elements of the tailings and the waste rock consist of SiO_2 with Fe_2O_3, Al_2O_3, CaO, MgO and K_2O forming lesser amounts of the composition. MgO, K_2O, and CaO show enrichment in the FRD compared to the CRD. SiO_2 and Al_2O_3 show enrichment in the CRD relative to the FRD. Fe_2O_3 is very similar in both the FRD and CRD materials. The basaltic material (Voo.Bas) waste rock has very similar compositions to the tailings material, where only very slight differences like lower MgO, CaO and K_2O and higher Fe_2O_3 and SiO_2 distinguish it. The two different mudstones (Voo.GMS and Voo.YMS) differ considerably from the other materials. The mudstones have much higher SiO_2 contents and lower Fe_2O_3, CaO and MgO. The mudstones have a slightly higher K_2O and Al_2O_3 content than the other tailings and waste rock. The only differences between the Voo.GMS and the Voo.YMS has slightly higher Fe_2O_3 and K_2O contents and slightly lower CaO contents than the first-mentioned compared to the latter.

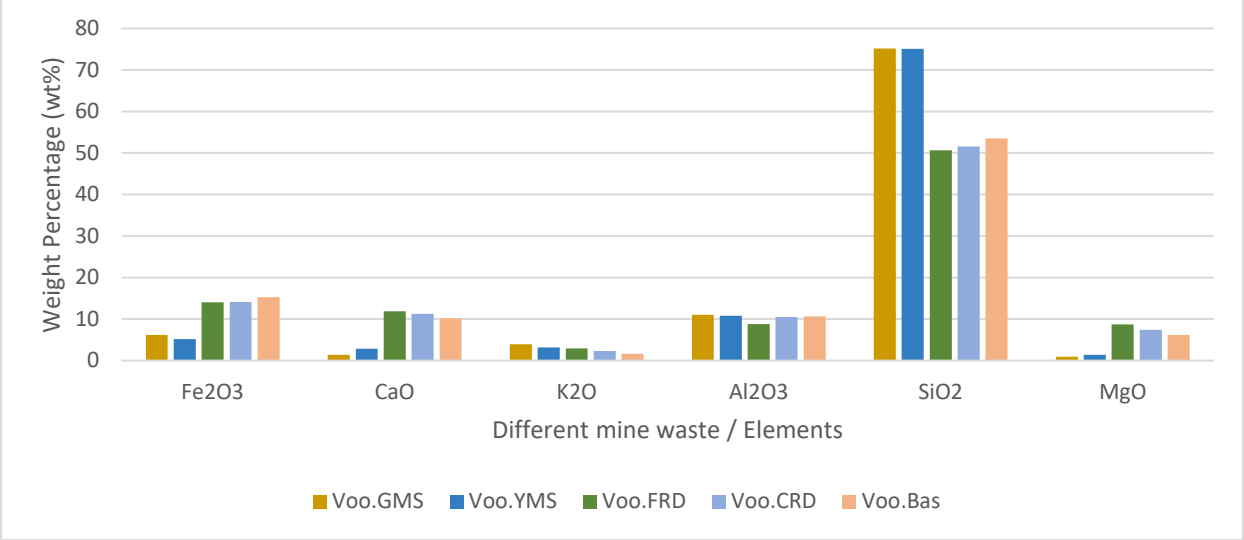


Figure 4-30: The major oxide composition of Voorspoed.

The minor elements are shown in Figure 4-31, which indicates that the tailings and waste rocks consist of TiO_2 and SO_3 as the dominant components, with P_2O_5, MnO, NiO, Cr_2O_3, and BaO present in trace amounts. NiO and Cr_2O_5 are present at minor concentrations and can be considered trace for this mine. NiO, Cr_2O_3, TiO, and P_2O_5 show enrichment in the FRD compared to the CRD. SO_3, MnO, and BaO show enrichment in the CRD relative to the FRD. All of the mentioned elements show only slight differences, except for P_2O_5, which is prominent. The Voo.Bas material has similar compositions to the tailings materials, with only consignable differences being lower SO_3, BaO, P_2O_5 and Cr_2O_5 values. The Voo.GMS and Voo.YMS mudstones differ considerably from the other materials. The mudstones tend to have lower concentrations of minor elements than the other tailings and waste rock. The Voo.GMS has a higher TiO_2, SO_3 and Cr_2O_3 content than the Voo.YMS material. The YMS has a higher MnO, BaO and P_2O_5 content than the Voo.GMS material. Both the mudstones are absent of NiO.

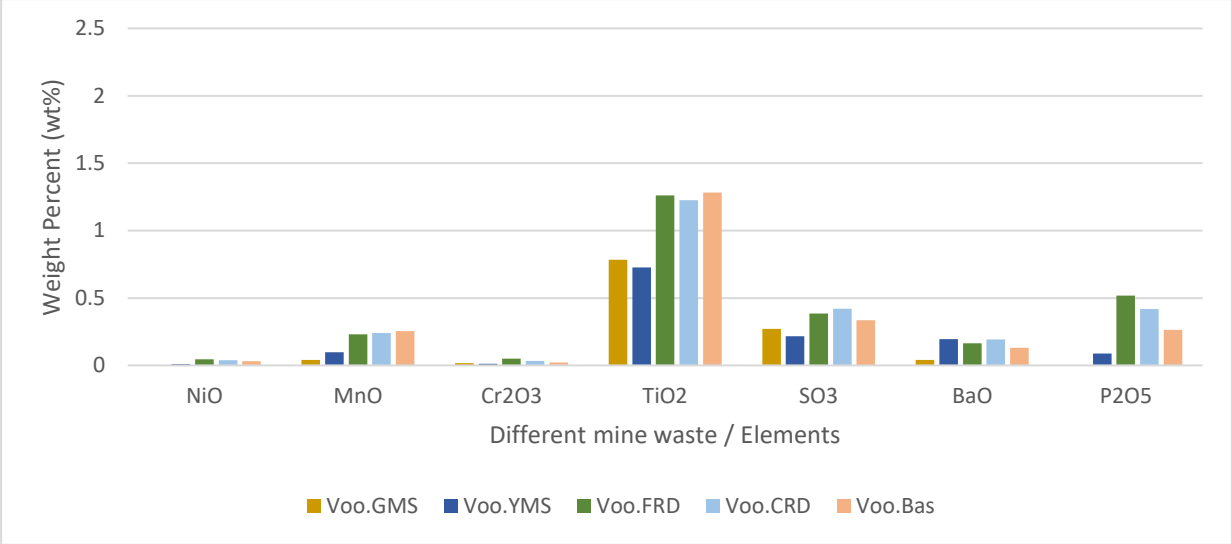


Figure 4-31: The minor oxide composition of Voorspoed.

The trace elements are shown in Figure 4-32; those indicated are of interest to this study. Co, V, Zn, and Cu are found in much higher concentrations than Pb and As. There is also no presence of Hg and Cd measured for the mine. In the tailings, Co and V are found at relatively high concentrations, Cu and Zn at intermediate concentrations, and Pb and As at lower concentrations. The Co and As were higher in the finer tailings (Voo.FRD) than in the coarser tailings (Voo.CRD), even though it is very slight. The Zn, Cu and V were higher in the coarser tailings (Voo.CRD) than in finer tailings (Voo.FRD). Only the Voo.FRD material had measurable As for the tailings material. The Voo. Bas has a very close relationship with tailings material, with similar As and Zn content but higher Cu and V content than tailings. It does, however, not contain any measurable Co. The other waste rocks, Voo.GMS and Voo.YMS are almost identical, except for small differences, such as higher Pb and V contents and lower Zn in Voo.YMS compared to the Voo.GMS material. Another noteworthy difference is the absence of As in the Voo.YMS material.

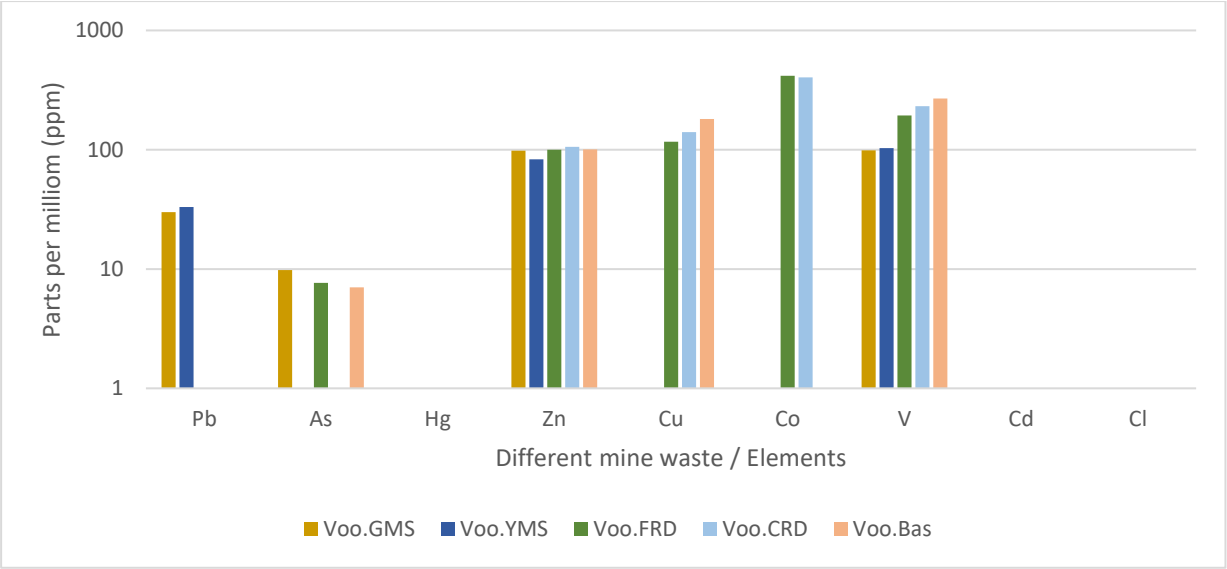


Figure 4-32: The trace elements of interest for Voorspoed.

Chapter 5: Discussion

The previous chapter focused on identifying trends in the data, whilst this chapter will explain these trends, their possible reasons for occurrence, and their potential for use. This chapter will discuss the properties of the individual sections and will be followed by a section focusing on the outcomes of each of the studied materials. The last-mentioned section that confines the findings will evaluate the properties of the different materials and determine their suitability for use, if any.

5.1 Densities

The apparent relative density and dry bulk density, according to SANS 5844 and SANS 5845, respectively, were calculated for all 25 mine rock waste types across five mine sites. The materials tested had an apparent relative density close to the generally accepted 2500-3000 kg/m3 range used by some industry professionals, but this is not a requirement (AfriSam, 2021b:42). Three materials had higher than range values, nine materials had in-range values, and 13 materials had below range apparent relative density values. All of the materials tested had a dry bulk density higher than 1000 kg/m^3. None of the materials, therefore, has the appropriate dry bulk density to be classed as a light aggregate under SANS 794 (SANS, 2009b:4).

Considering that the SANS 794 document only focuses on materials below the 1000 kg/m^3 threshold, the documents of further interest were those of SANS 1083 and SANS 1090 (SANS, 2009b:4). The SANS 1083 and SANS 1090 do not specify a preferred or required density (SANS, 2013a; SANS, 2009a). The calculation of the different density types helped to establish other aggregate properties (like voids content as an example) and to define density of the final concrete as required in some special projects (SANS, 2006j:4; AfriSam, 2021b:42). The required density of an aggregate will depend on the project as some require the use of high-density aggregate (above 3000 kg/m^3) for example radiation shielding or in the use of foundations, whilst others require a lower-density aggregate (below 2000 kg/m^3) to decrease the overall weight of the concrete in some multi story buildings (AfriSam, 2021b:42; UltraTech Cement, 2021).

5.2 Voids content

The void content, according to SANS 5845, was tested for all 25 different materials across the five mines. By comparing Figures 4-1 and 4-2 from the previous chapter, it is noted that the difference between the apparent relative density and the dry bulk density determines the void content. Both the tailings and the waste rocks indicated a wide distribution of void contents. They range from 27.85% to 50.75% for the different materials. This is likely due to the material's packing characteristics. Rock material with a well-sorted, loose packing tends to have more pore/void space than a well-graded rock material, which tends to pack tightly and reduce available pore/void

space (Weil & Brady, 2017:182). This explains why fine materials like the FRDs and mudstones can have similar void contents to possibly well-sorted coarse-grained waste rock, as seen with the Kimberlite 3 waste rocks.

The SABS does not have a SANS document that specifies an acceptable void content of an aggregate for use in concrete. There is however a minimum requirement of 40% void content required for ballast stone (Spoornet, 1998:2). The ASTM D3398 does specify an acceptable voids content as being between 35% and 50% for concrete, but is based on the ASTM method (ASTM, 2006; Rahman *et al*., 2019:13). This method has been withdrawn since 2014 however (Rahman *et al*., 2019:13). The voids content of an aggregate is usually calculated for a blend developed by a specialist for an intended purpose (AfriSam, 2021b:46). It is mostly used to establish deviation between batches, and more importantly the water requirements (SANS, 2006g:2; SANS, 2006j:4). Lower voids content tends to give the concrete a smoother finish, but might increase overall cement requirement, whilst higher voids content can lead to the cement and water to concentrate in the pores which decreases concrete strength and increases porosity when dried (AfriSam, 2021a:6; AfriSam, 2021b:46). This being said, this is only a measure and the actual grading should receive preference (AfriSam, 2021a:6; AfriSam, 2021b:46).

5.3 Grading

The particle size distribution (PSD) assessment using the SANS 201 procedures was conducted to determine the grading of all 25 mine rock waste types across five mine sites. Samples can be group into: 1) ‘slimes’, 2) ‘fines’, 3) ‘coarse’, and 4) ‘waste rock’ based on their grading characteristics. This groupings is also illustrated in the hierarchical clustering analyses presented in Figure 5-1, which used Ward’s method with Euclidean distance to best categorise the samples. The weathered mudstones of Voorspoed, which have close textural similarities to the Kim3.FRD8 and Voo.FRD exhibits slime characteristics due to their very fine nature. Textures ranging from well-sorted to well-graded are found in the tailings materials. This observation can be attributed to comparing the generally unweathered kimberlite tailings from recent processing with the intensively weathered, possibly mixed slimes, FRD, and CRD in a common deposition environment in the TSF. The sharp cutoff at near 1mm particle size between the FRD and the CRD is a result of the 1mm sieve used during processing where fines are washed off from the coarser material that can be processed for diamond extraction (Morkel, 2006:1; Aslam, 2021:5; Motsau & van Wyk, 2022:3). The Kimberlite 4 FRD and CRD indicated the best representation of run of mine (ROM) as it was collected directly in the processing plant from the conveyer, whilst the rest of the examples were mostly collected from the TSF’s where they were allowed to mix and weather for a period of time before collection. The Kimberlite 2 FRD and CRD, however, show similar patterns to Kimberlite 4 tailings and might indicate that it too is from ROM or a less

weathered or mixed sample. The Kimberlite 2 tailings do, however, contain a higher proportion of fines than Kimberlite 4, but still notably less than the other tested tailings materials, as shown in Figure 5-1. Kimberlites and lamproites weather very easily and, coupled with mechanical processing, might lead to extensive alteration (Rai & Kittrick, 1989:180; Weil & Brady, 2017:54-60). The hierarchical clustering analyses in Figure 5.1 interestingly also indicate that waste rocks can be further divided into 'slimes' (as already mentioned for the Voo.GMS and Voo.YMS), processed waste rock (as can be seen grouped between the unweathered CRD and weathered CRD), and unprocessed waste rock (between 'slimes' and 'FRD').

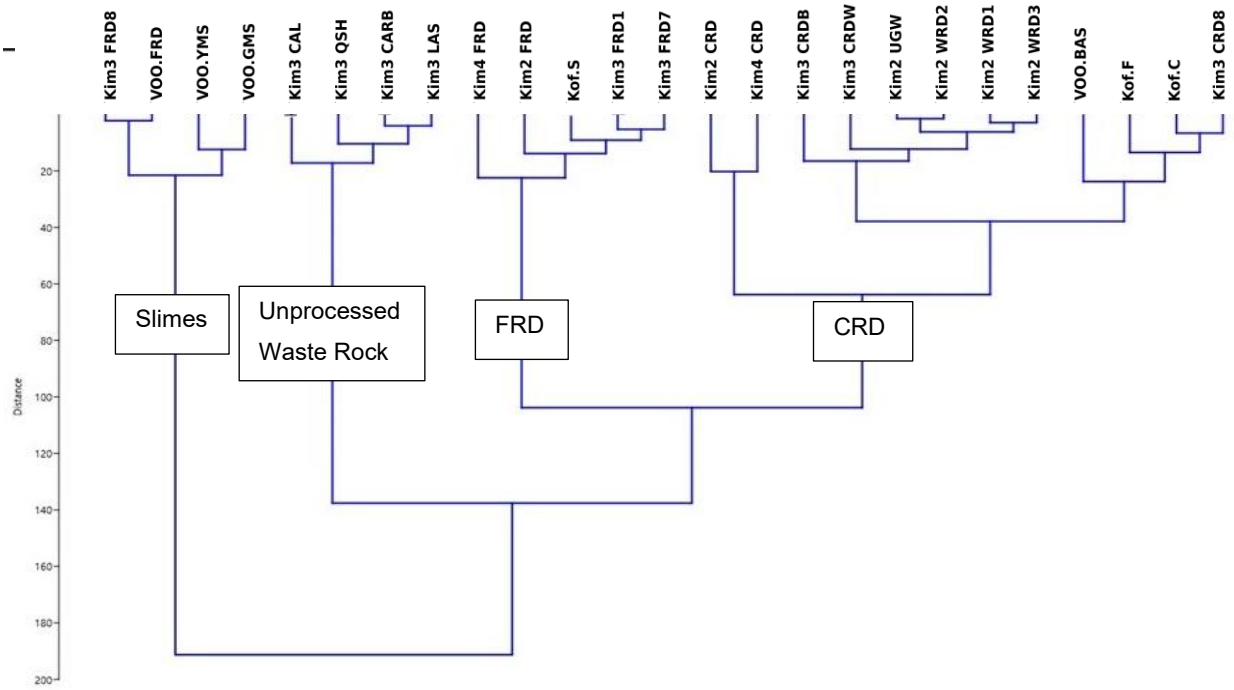


Figure 5-1: Hierarchical clustering analyses of grading characteristics.

The SABS acknowledges numerous types of aggregate that can be used in the construction industry, with each sector having its own appropriate set of specifications. As already mentioned, SANS 1083 and SANS 1090 are used for aggregates in concrete, and examples of permissible gradings are illustrated in Figure 5-2. Here, the figure illustrates the upper and lower limits allowed for the grading of an aggregate, where they are illustrated in the same colour for the same class. Both the plaster and mortar aggregates, as described in SANS 1090, share the same lower limits of coarseness. The coarse aggregate component that is complementary to the mortar-like fine aggregates in concrete is also illustrated, as defined by SANS 1083. The fine aggregate component only specifies between 90% and 100% passing 4.75 mm and between 5% and 25% passing 150µm. The fine and coarse aggregates are commonly measured separately and mixed by the appropriate specialist to form a well graded texture for a specific project (SANS, 2008b:13-

14; AfriSam, 2021a:4). An example of how this mixture would look like is illustrated by the COLTO Coarse Slurry 2, which is one of the many types used in the construction of roads, and indicates how an “all-in” concrete mix would look like (AfriSam, 2021b:45).

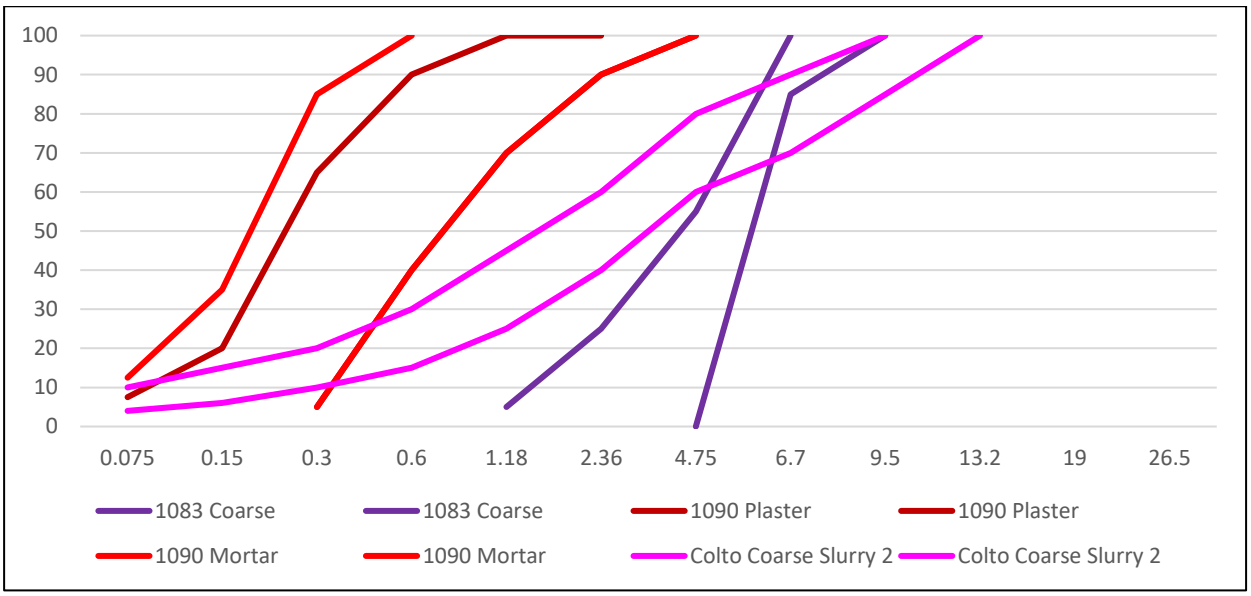


Figure 5-2: Examples of permissible grading criteria for SANS 1083, SANS 1090 and COLTO.

5.3.1 Koffiefontein

The Kof.S has textures similar to the mortar and plaster specifications mentioned in SANS 1090, but has significantly more fines than allowable, especially in the smallest fractions. The Kof.F and Kof.C are much more similar to each other than to the Kof.S. The Kof.F and Kof.C have similarities to the COLTO Coarse Slurry 2, which is the coarsest aggregate mixture type under COLTO specifications. The Kof.F has a finer texture than recommended by this specification, with much higher-than-allowable fines in the smaller grain fractions. The Kof.C is very similar to the COLTO Coarse Slurry 2, apart from a slightly coarser texture at the larger fractions.

5.3.2 Kimberlite 2

The Kim2.FRD fits almost perfectly into the grading of SANS 1090 aggregates, where it meets both the mortar and plaster requirements, but has issues with a too high <75µm concentration, which makes it unsuitable. The Kim2.CRD is texturally similar to SANS 1083 coarse aggregate in its well-sorted nature, but differs in that it is finer-grained. The four waste rocks, namely Kim2.UGW, Kim2.WRD1, Kim2.WRD2 and Kim2.WRD3 have almost identical textures, which all fit perfectly into the COLTO Coarse Slurry 2 specification.

5.3.3 Kimberlite 3

The grading of Kim3.FRD8 is not even close to any of the specifications covered, as it is too finely textured and cannot be used. The Kim3.FRD1 and Kim3.FRD7 has very similar textures, with the latter being a little coarser. These two FRDs fit almost perfectly into the grading of SANS 1090 aggregates, meeting both the mortar and plaster requirements, but have issues with a too-high <75µm concentration, which makes them unsuitable. The Kim3.CRDB and Kim3.CRDW is similar to the COLTO Coarse Slurry 2 specification, except for some minor differences. The Kim3.CRDB is slightly more well graded than the specification and has a higher than allowable <75µm concentration. The Kim3.CRDW is texturally similar to the specification, apart from being a bit coarser. The Kim3.Cal, Kim3.Carb, Kim3.Las and Kim3.QSH waste rocks have most of their material concentrated in the coarser fractions at a relatively well-sorted texture. The Kim3.Cal has a notably finer texture compared to the other three, which have almost identical textures to each other. None of the four waste rocks has a satisfactory texture for use apart from being used as 26mm class rock if properly sieved to reduce finer rocks (SANS, 2013a:6).

5.3.4 Kimberlite 4

The grading of Kim4.FRD fits perfectly into the grading of the SANS 1090 aggregates, where it fits both the mortar and plaster specifications. The Kim4.CRD has a very well-sorted texture that closely resembles the SANS 1083 coarse aggregate specification, with the only exception that it is only slightly more finely textured.

5.3.5 Voorspoed

The grading of Voo.FRD, Voo.GMS and Voo.YMS are not even close to any of the specifications covered, as it is too finely textured and cannot be used. The Voo.CRD fits perfectly into the COLTO Coarse Slurry 2 specification. The Voo.Bas fits well into the COLTO Coarse Slurry 2 specification, except for the higher than >2.36mm rock particles that makes the Voo.Bas too coarsely textured.

5.4 Fineness modulus

The fineness modulus as calculated according to SANS 201 is a measure to help define the nature of the fine aggregate proportion (<4.75mm) of a concrete. As mentioned in the results section, the materials tested had a wide range of fineness modulus values with some ranging from low to high. The highly weathered and processed materials illustrated the lowest fineness modulus value, whilst the less processed and more resistant materials had the highest fineness modulus value.

The SANS 1083 specifies a fineness modulus value between 1.2 and 3.5, whilst the SANS 1090 does not specify a specific value (SANS, 2013a:7; SANS, 2009a:5). The SANS 1083 and SANS 1090 also specifies that the ideal fineness modulus value is based on the recommendation of the specialist involved and that it should not deviate by more than 0.2 from the agreed upon value (SANS, 2013a:6; SANS, 2009a:5). The Kim3.FRD8, Voo.FRD, Voo.GMS and Voo.YMS had a fineness modulus value far lower than permissible, whilst the Kof.S had a fineness modulus value just below the bottom extent of the allowable range. The Kim2.CRD, Kim3.Carb, Kim3.Cal, Kim3.Las, Kim3.QSH, Kim3.CRDW, Kim4.CRD and Voo.CRD had a fineness modulus value exceeding the top extent of the allowable range. The remaining materials had acceptable fineness modulus values, as per SANS 1083. Within this acceptable fineness modulus range, however, some failed because the deviation exceeded 0.2 from the median, including Kim2.UGW, Kim2.FRD, Kim2.WRD1 and Kim2.WRD2. The only materials with an acceptable fineness modulus and a low deviation between samples were Kof.F, Kof.C, Kim3.CRDB, Kim3.FRD1, Kim3.FRD7, Kim4.FRD, and Voo.Bas.

5.5 Dust content

The dust content, as calculated according to SANS 201, is a measure of the total amount of material passing the 75µm sieve. As mentioned in the results section, the dust content was extremely high for FRD8 of Kimberlite 3, the FRD of Voorspoed, and both mudstones of Voorspoed. The FRDs had higher dust content than the CRDs, which further increased as the product became more weathered. The waste rocks from Kimberlite 2 and the basalt waste rock from Voorspoed had relatively high dust content, which was comparable to the CRDs. The waste rocks from Kimberlite 3 had very low dust contents.

The SANS 1083 specifies that a fine aggregate should have a dust content below 5% and 10%, depending on its source where it be from natural disintegration (or blends thereof) and through mechanical crushing, respectively (SANS, 2013a:7). The SANS 1090 specifies that a fine aggregate for use in plaster or mortar should have a dust content below 7.5% and 12.5%, respectively (SANS, 2009a:5). This being said, materials that exceed these limits can be tested using the SANS 6243 (Methylene blue adsorption) and SANS 6244 (Clay content) procedures to bump up these dust content limits to 10%, 20%, 12.5% and 17.5%, respectively (SANS, 2013a:5; SANS, 2009a:5). This is only on the condition if the materials pass these procedures, if not, the material has to be rejected. Additionally, coarse aggregates, as described in SANS 1083, must have a dust content below 2% (SANS, 2013a:9).

Based on their different natures, the tailings will have to be classified as a natural disintegration aggregate, due to their quick weathering nature, whilst the waste rocks (except for the mudstones

of Voorspoed) should be classified as a mechanically crushed aggregate. Based on the mentioned criteria, the only compliant tailings are: the Kof.C with mortar and the Kim4.FRD and Voo.CRD with the former and plaster, and the Kim2.CRD, Kim3.CRDW and Kim4.CRD with the previous two mentioned and the fine aggregate specifications. The waste rocks like Kim2.UGW complies with the mortar specification, whilst the Kim2.WRD1, Kim2.WRD2, Kim2.WRD3 and Voo.Bas complies with the former and fine aggregate under SANS 1083 for concrete. The waste rocks of Kimberlite 3 have very low dust contents that comply with coarse aggregate under SANS 1083, except for Kim3.Cal, which had 3% dust content instead of the mandatory 2%.

5.6 AIV

The AIV, as calculated according to SANS 6239, is a measure to help define the resistance to impact breakage of a coarse aggregate. As mentioned in the results section, the waste rocks performed better than the tailings materials as determined by the low AIV. Some trends were also noted between successive impact events. The decrease in AIV trends with increasing numbers of impact events at Kof.F, Kof.C, and Kim3.CRDB could be explained by weathered kimberlite content, which initially produces a high AIV as the weathered kimberlite is easily broken and then decreases as remaining country rock and smaller kimberlite fragments influence further fragmentation due to compaction. Some of the waste rocks also showed this trend, likely due to kimberlite content. Other waste rocks indicated no change or only a slight increase with successive hits in AIV and are likely due to the material's resistance.

There is no specific SABS document that specifies an acceptable AIV for coarse aggregate in concrete. The SANS 6239 was developed from the BS 812-112 document which are practically identical apart from the BS 812-112 requiring calculation on impact event 15 whilst the SANS 6239 require repeats that aim for the defined fines to be between 5% and 20% (BSI, 1990; SANS, 2012b:3). The British Standards Institution (BSI) developed the BS 882 document, which specifies the requirements of a natural aggregate for use in concrete and is comparable to the SANS 1083 used in South Africa (BSI, 1992:3; SANS, 2013a: ii). Both have their advantages, but it does make it difficult to directly compare their thresholds, as the methods differ slightly. The BS 882 requires an aggregate to have a <25 AIV for heavy duty concrete, a <30 AIV for pavement wearing surfaces and a <45 AIV for any other types of concrete (BSI, 1992:3). Another useful property is that the BS 882 states that the BS 812-112 can substitute the BS 812-111 test (10% fines test), which in theory means that the SANS 6239 can potentially be used to substitute the SANS 5842 (as this is the equivalent procedure to the BS 812-111) (BSI, 1992:3). The SANS 6239 is currently only used as an on-site rapid and repeatable test for aggregates that typically have AIV’s smaller than 30 for quality control and batch monitoring purposes (SANS, 2012b:3).

If the values stated in BS 882 are deemed acceptable criteria, likely due to the decreasing changes between successive impact events, then the AIV limiting values of BS 882 can be used for SANS 6239. It should be noted that all materials complied with the requirements of SANS 6239 by the 6th impact event, but the 9th impact event will be used, as it is closer to the 15 required impacts of BS 812-112 and still had most materials comply with SANS 6239 requirements. Based on these assumptions, the Kim3.QSH, Voo.Bas, Kim3.Cal, Kim3.Las and Kim3.Carb comply with the heavy-duty concrete class, the Kof.F and Kim3.CRDW complies with the pavement wearing surface class and the Kim3.CRDB, Kim2.UGW, Kim2.WRD1, Kim2.WRD2, Kim2.WRD3 and Kof.C comply with other concrete classes. It should be remembered that the other materials that form part of this study, but were not included in the AIV assessment, are due to the lack of, or total absence of, large enough aggregates to conduct the tests, as this test is dependent on aggregates of a certain size.

5.7 Mineralogy

The general mineralogy of the different mines was briefly mentioned in the previous chapter, along with some observable trends. The general mineralogy as well as the full list of minerals in Annexture E and F help to shed more light on the characteristics. Here the importance of understanding the mineralogical diversity comes in to help interpret the results. The influence of mineral contamination for both the tailings and the waste rocks should be considered as mining and processing of ore causes the inevitable mixture of materials.

The SABS has no document that directly states a list of suitable, or unsuitable, minerals that can be used in the making of concrete. The SABS does however give clear instruction for in-depth testing of aggregates before use which include determining physical and chemical properties that impact applicability (SANS, 2013a:4; SANS, 2009a:4). The SANS 1083 and SANS 1090 recommend consulting the Annex C of the respective documents if a material is suspected to contain minerals that could have negative impacts on the performance of the concrete (SANS, 2013a:4; SANS, 2009a:4). The Annex C of SANS 1083 and SANS 1090 basically explain how an aggregate should be investigated if it is considered for use and what additional tests are required to assess the aggregates qualities (SANS, 2013a:14-15; SANS, 2009a:9-10). The ASTM C294 does however give a comprehensive list of common rock types, their minerals and their possible issues when used in construction (ASTM, 2005:1-9; Neville, 2011:210).

5.7.1 Koffiefontein

The primary minerals like quartz, feldspar, pyroxene (specifically enstatite), muscovite and biotite are found at various concentrations in the tailings. This is most likely due to the mineral's hardness, where quartz is the most resistant at 7 Mohs, feldspars having 6 to 6.5 Mohs of

hardness, enstatite having a hardness of 5 to 6 Mohs, muscovite having a hardness of 2.5 to 4 Mohs, and biotite having a hardness of 2.5 to 3 Mohs (Cairncross & McCarthy, 2015:251-291). These differences can be the most likely reason why quartz content peaks in the Kof.C, the feldspar and muscovite content peaks at Kof.F, and the enstatite and biotite content peaks at Kof.S. The different clay minerals also show interesting trends based on the dominant clay type. The chlorite dominated 2:1:1 clay of the Kof.C, the vermiculite dominated 2:1 clay of the Kof.F, and the montmorillonite (2:1 clay) / antigorite (1:1 clay) dominated clays of the Kof.S fits perfectly into the proposed alteration sequence of typical kimberlite minerals (Dawson, 1980:106).

5.7.2 Kimberlite 2

The primary minerals like cordierite, quartz, feldspar, amphibole (specifically actinolite), pyroxene (specifically diopside), and biotite are found at various concentrations in the tailings. This is most likely due to the mineral's hardness, where quartz is the most resistant at 7 Mohs, feldspars having 6 to 6.5 Mohs of hardness, actinolite having 5 to 6 Mohs of hardness, diopside having a hardness of 5.5 to 6.5 Mohs, and biotite having a hardness of 2.5 to 3 Mohs (Cairncross & McCarthy, 2015:251-291). The higher cordierite and quartz however cannot be explained by this logic. The deposition or collection of samples could possibly attribute to this. The mineralogical differences of the tailings can be attributed to different waste rock contamination during periods of processing and disposal. The different clay minerals also show interesting trends based on the dominant clay type. The chlorite dominated 2:1:1 clay of the Kim2.CRD, and the chlorite dominated (2:1:1 clay) with antigorite (1:1clay) and sepiolite (2:1 clay) fits perfectly into the proposed alteration sequence of typical kimberlite minerals (Dawson, 1980:106).

The four waste rocks have some relationships between each other, but still noticeable differences. All four waste rocks have components that most likely coincide with gneissic rocks (Field *et al*., 2008). The Kim2.UGW is the only one with considerable carbonates, indicating that a large component of it also contains the metasedimentary rocks which is characterized by dolomitic marble and limestone (Field *et al*., 2008).

5.7.3 Kimberlite 3

The primary minerals like quartz, pyroxene and biotite along with the secondary mineral dolomite are found at various concentrations in the tailings. This is most likely due to the mineral's hardness, where quartz is the most resistant at 7 Mohs, pyroxenes having a hardness of 5 to 6.5 Mohs (slight differences between types), dolomite having a hardness of 3.5 to 4 Mohs, and biotite having a hardness of 2.5 to 3 Mohs (Cairncross & McCarthy, 2015:176-291). The two CRDs differ considerably from each other. The Kim3.CRDW is composed almost entirely of dolomite, with quartz and pyroxene forming very minor components. This is in stark contrast to the Kim3.CRDB

which is composed entirely out of phyllosilicates where antigorite (1:1 clay) is dominant at over 50% of the mineral composition. The rest is split about equally between biotite (specifically phlogopite) and the 2:1 clay group minerals like talc, vermiculite and montmorillonite. Some 2:1:1 clays like chlorite is also present, but is at very low concentrations. The Kim3.CRDW has low to almost negligible characteristic kimberlite mineral content, whilst the Kim3.CRDB likely only contains kimberlite derived material based on the mineral contents. The difference might be derived from processing techniques that separate minerals for extraction. Alternatively, it is also very likely that the Kim3.CRDW is derived from the more country rock rich kimberlite facies and that the Kim3.CRDB is derived from the relatively purer kimberlite facies (Field *et al*., 2008:50; Dunn *et al*., 2022:111).

The three types of FRD also have distinguishing features. The Kim3.FRD1 and Kim3.FRD7 contains quartz, whilst Kim3.FRD8 does not. The Kim3.FRD1 and Kim3.FRD8 contain different types of pyroxenes, which are diopside and clinoenstatite respectively. The Kim3.FRD1 is the only one of the FRDs to contain biotite. The Kim3.FRD7 and Kim3.FRD8 contain moderate amounts of dolomite, which can technically have formed from the weathering sequence of Dawson (1980:106) but is most likely from other sources like host rock. The clay mineralogy is even more impressing where Kim3.FRD1 contains about 60% clays, the Kim3.FRD.7 contains about 60% clays and the Kim3.FRD8 contains about 45% clays. The Kim3.FRD1 is dominated by 2:1:1 clays (specifically chamosite) and 2:1 clays like vermiculite and montmorillonite, with minor amounts of antigorite (1:1 clay). The Kim3.FRD7 is dominated by 2:1 clays like vermiculite and talc, with minor amounts of illite (2:1 clay), antigorite (1:1 clay) and nepouite (1:1 clay). The Kim3.FRD8 is dominated by 1:1 clays like antigorite, with lessor amounts of 2:1 clays like vermiculite and montmorillonite. The Kim3.FRD1 and Kim3.FRD8 also contain zeolites, where the latter has the highest concentration. The natrolite species was identified for Kim3.FRD1 and the Zeolite-L for the Kim3.FRD8. Based on the mineral diversity of the clay, it seems as if Kim3.FRD1 and Kim3.FRD8 are closer related to each other than the Kim3.FRD7. The mineral diversities of the tailings fit perfectly into the proposed alteration sequence of typical kimberlite minerals (Dawson, 1980:106).

There are three quartzitic and one carbonaceous waste rock. The Kim3.Las and Kim3.QSH have very similar mineral diversities, with the only major differences being that the former has more feldspar and the latter has more quartz—the Kim3.Carb differs from the Kim3.Las and Kim3.QSH, where it is absent in biotite (specifically phlogopite), lower in muscovite, contains minor carbonates (specifically calcite) and has chamosite-type chlorite (2:1:1 clay) instead of normal chlorite—the Kim3.Cal, in contrast, is dominantly dolomite with some calcite and ankerite (all carbonates). In addition to this, the Kim3.Cal has about a third of the quartz and feldspar of the

other waste rocks and also contains some minor pyroxene (specifically clinoenstatite), which the others do not.

5.7.4 Kimberlite 4

The mineralogy of the Kimberlite 4 mine represents the best analogy of what happens to minerals during processing, as this is freshly sampled ROM that underwent minimal weathering and possible co-disposal with other rock wastes. The primary minerals, such as quartz, garnet (specifically andradite), feldspar, pyroxene, amphibole (specifically tremolite), and biotite, are found at varying concentrations in the tailings. This is most likely due to the mineral's hardness, where quartz is the most resistant at 7 Mohs, andradite having 6 to 7 Mohs of hardness, feldspars having 6 to 6.5 Mohs of hardness, diopside having a hardness of 5.5 to 6.5 Mohs, tremolite having 5 to 6 Mohs of hardness, and biotite having a hardness of 2.5 to 3 Mohs (Cairncross & McCarthy, 2015:251-291). The distribution of mineralogy for Kim4.FRD is exactly what is expected, as it contains less primary minerals than the Kim4.CRD due to increased weathering and increased content of softer minerals due to processing. The Kim4.FRD and Kim4.CRD are distinguished by their different types of pyroxenes and biotites, where the former is characterised by diopside and phlogopite (with little normal biotite), whilst the latter is characterised by augite and biotite. Another important difference that distinguishes the Kim4.FRD and Kim4.CRD is that the former is characterised by antigorite (1:1 clay) and the latter by chlorite (2:1:1 clay). The differences in mineral properties between types might seem small, but can have significant impacts (Cairncross & McCarthy, 2015:255-275). The quartz most likely originated from contamination by sandstone or quartzite, whilst the feldspars most likely originated from contamination by plutonic intrusions (Kent, 1980; Field *et al*., 2008; de Wit *et al*., 2016).

5.7.5 Voorspoed

The primary minerals, such as feldspar, pyroxene, and muscovite, are present at varying concentrations in the tailings. This is most likely due to the mineral's hardness, where feldspar is the most resistant at 6 to 6.5 Mohs, followed by pyroxenes (specifically diopside) having a hardness of 5.5 to 6.5 Mohs, and muscovite (specifically phengite) having a hardness of 2 to 2.5 Mohs (Cairncross & McCarthy, 2015:176-291). The mineralogy distribution is exactly as expected, given the Voo. Lower amounts of primary minerals with higher hardness values characterise FRD. The Voo.CRD is composed almost entirely of feldspar and pyroxenes with only minor amounts of vermiculite (2:1) clay. The Voo.FRD, on the other hand, contains lower feldspar and diopside than the Voo.CRD is characterised by phengite content and much higher vermiculite (2:1) clay content.

The Voo.Bas has very close mineral diversity and ratios to the tailings, especially the Voo.FRD. The Voo.Bas only differs from the Voo.FRD in that it contains quartz and has a pyroxene content

closer to Voo.CRD. Likely, the intricate nature of the basalt reef in the orangeite pipe is responsible for the severe contamination of basalt material in the tailings dams and orangeite material in the basalt waste dumps. The intricate nature has been a downside to the mine's economic viability for many years (Wagner, 1914:5-7; Kent, 1970:540; McCarthy & Rubidge, 2013:210)—the Voo.CRD sample could be a closer representation of the actual basalt material than the Voo.Basalt sample due to the processing methods that effectively separate the relatively soft orangeite rock from the harder basaltic rock. Other waste rocks are the Karoo supergroup shales known as “Grey mudstone” and “Yellow mudstone” at the mine. The Voo.GMS and Voo.YMS have some similarities, such as being composed of about one-third quartz, one-third feldspar, and one-third phyllosilicates. They differ in that the Voo.GMS has dominantly anorthite feldspar with minor albite feldspar, whilst the Voo.YMS has dominantly albite feldspar with minor anorthite feldspar. Both Voo.GMS and Voo.YMS contain minor amounts of hyalophane feldspar, which is also present in some of the tailings, indicating possible contamination from these sources as well. The phyllosilicates also differ in that the Voo.GMS is almost entirely of illite (2:1) clay, whilst the phyllosilicates of Voo.YMS is dominantly biotite with very minor amounts of muscovite.

5.7.6 Inter-mine mineralogy

A hierarchical clustering analysis was performed to illustrate inter-mine relationships in mineralogy, using Ward’s method with Euclidean distance to categorise the bulk samples most effectively. The hierarchical clustering analysis of the primary and secondary minerals of all sites are presented in Figure 5-3. The hierarchical clustering analysis divides the mineralogy of different mine waste materials in two groups, namely, between carbonate-rich and silicate-rich materials. The carbonate-rich grouping is dominated by dolomite as the main mineral constituent and include Kim2.UGW, Kim3.Cal and Kim3.CRDW. The silicate-rich materials, however, have many branches to accommodate the greater diversity and the best possible grouping. These are extremely diverse but can be grouped into six main groups, as shown in Figure 5.3. The silicate-rich groups are therefore (from left): the feldspar-quartz-biotite-rich group, the feldspar-2:1 clay group, the 2:1:1 clay-feldspar-quartz group, the quartz-2:1:1 clay-muscovite-feldspar group, the 2:1 clay-pyroxene group, and the 1:1 clay group. The Kim2.WRD1, Kim2.WRD2 and Kim2.WRD3 has very similar mineralogy (silicate rich), which indicate that they most likely came from a similar source lithology or unit, whilst the Kim2.UGW is mostly derived from a completely different lithology (dolomite rich). The Voo.GMS and Voo.YMS, though both being shales/mudstones from the same locality, did not group due to differences in dominant phyllosilicate type. There are two 2:1 clay groups because one represents material with high feldspar content (due to high waste-rock contamination), whilst the other represents high pyroxene content (due to low to no waste-rock contamination). Similarly, there are two types of 2:1:1 clay groups. However, one is composed of different tailings, being dominantly 2:1:1 clay with lesser amounts of feldspar and/or

quartz from contamination sources, whilst the other is composed of waste rocks that are dominantly quartz with lesser amounts of 2:1:1 clay that do not share the same origins. The last group comprises tailings characterised by a predominantly 1:1 clay. In some instances, the waste rock can dominate the tailings if contamination is severe enough, much like how Kim3.Cal and Kim3.CRDWs are closely similar to each other, much like the Voo.Bas and Voo.CRD. The different FRDs are mostly grouped by similarly high phyllosilicate content, although in some cases, they are vastly different in type.

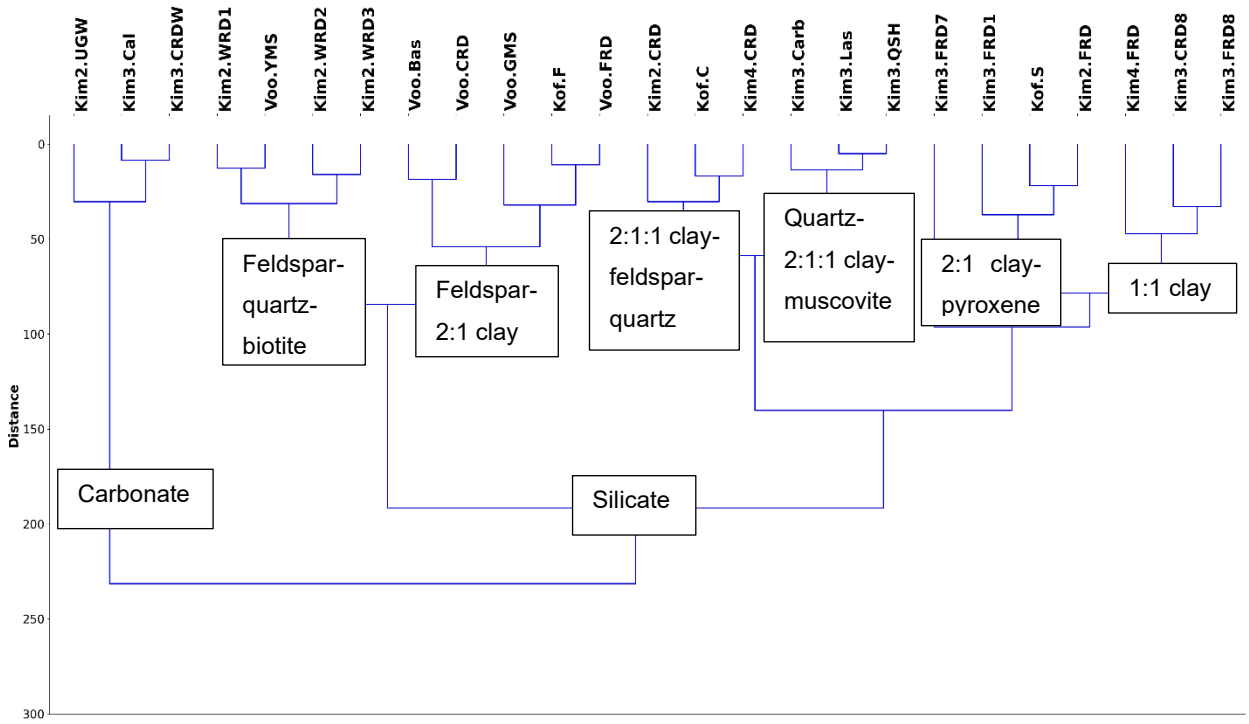


Figure 5-3: Hierarchical clustering analyses of mineralogical characteristics.

5.8 Chemical composition

The general composition of the different mine wastes has already been discussed in the previous chapter, as have some observable trends. The general composition, as well as the full elemental composition is presented in Annexure H. The influence of contamination on both the tailings and the waste rocks should be considered, as ore mining and processing inevitably mix materials.

The SABS has no document that directly specifies an ideal or recommended bulk chemical composition of an aggregate for use in the production of concrete. The SABS does, however, give clear instructions for in-depth testing of aggregates before use, which include determining physical and chemical properties that impact applicability (SANS, 2013a:4; SANS, 2009a:4). These tests have already been mentioned in the methodology section in Table 2.1, which outlines the most important chemical properties to consider when assessing an aggregate for use. These methods are more complex but are very useful because they focus on chemical reactivity rather

than inherent chemical composition, unlike XRF. XRF remains a valuable tool that can provide large amounts of information with relatively little effort (ASTM, 2005:3).

5.8.1 SiO_2 (Silica)

SiO_2 is a prominent component of most minerals, where pure varieties like quartz are very stable, and rocks containing high amounts, such as sandstone or granite, are commonly used as aggregate in concrete (Kosmatka *et al*., 2016:111-112; AfriSam, 2021b:119). Alkali-silica reaction (ASR) is the main chemical issue related to SiO_2 content, where reactions with alkali metals like Na_2O and K_2O in the cement lead to the formation of a gel-like substance that later causes cracking and deterioration of the concrete (Mindess *et al*., 2003:154; Neville, 2011:217-219; Kosmatka *et al*., 2016:113). As the amount of amorphous, or poorly crystalline, SiO_2 content increases, so too does the risk for ASR (Mindess *et al*., 2003:154; Neville, 2011:217; Kosmatka *et al*., 2016:113).

5.8.2 CaO (Calcium Oxide)

The CaO forms a prominent component in some common minerals, such as sound dolomite and calcite-containing rocks, like dolostone and limestone, which can be used as aggregate in concrete (Neville, 2011:222; Kosmatka *et al*., 2016:111-112; AfriSam, 2021b:119). Chemical instability is the main chemical issue related to CaO content, with carbonate-rich rocks in Weinert N<5 areas being highly susceptible and capable of causing deterioration of the concrete (Weinert, 1984:465). The climate of the area is important to assess how susceptible the rocks are to weathering, as well as the impurities such as swelling clay and organic matter (Mindess *et al*., 2003:154; Neville, 2011:222; Kosmatka *et al*., 2016:113). Other issues, such as alkali-carbonate reaction (ACR), can be detrimental to concrete stability, but are relatively rare because rocks susceptible to this tend to fail other criteria, such as strength (Mindess *et al*., 2003:154; Kosmatka *et al*., 2016:113). Dolomites are, in most cases, very stable and can be used successfully, but if an aggregate is suspected of having detrimental characteristics, further testing is required (Neville, 2011:222).

5.8.3 Al_2O_3 (Alumina)

Al_2O_3 is a prominent component of phyllosilicates and feldspars, the latter of which are found in rocks such as granites, which are commonly used as aggregate in concrete (Kosmatka *et al*., 2016:111-112; AfriSam, 2021b:119). On the other hand, phyllosilicates, such as micas and clay, can physically and chemically impact concrete in detrimental ways (Neville, 2011:210). Decreased aggregate-cement bonding is the main chemical issue related to Al_2O_3 content, where reactions between water and cement impact the bonding strength potential of the cement, thereby

decreasing workability and strength of the concrete (Neville, 2011:210; Kosmatka *et al*., 2016:81). Another issue is where Al_2O_3 reacts with alkali metals that form gases that increase voids (Neville, 2011:332). The Al_2O_3 content, however, helps reduce the effects of sulphate attack (Kosmatka *et al*., 2016:81).

5.8.4 MgO (Magnesium Oxide)

MgO is a prominent component of minerals such as olivine, pyroxene, and dolomite, and rocks such as dolostone can be used as aggregate in concrete (Kosmatka *et al*., 2016:111-112). Decreased aggregate-cement bonding, similar to Al_2O_3, is the main chemical issue related to MgO content, where reactions between water and cement affect the cement's bonding potential through the ACR process, thereby decreasing workability and strength of the concrete (Kosmatka *et al*., 2016:212). In most cases, the MgO is very stable, but excessive free MgO can lead to brucite [$Mg(OH)_2$] formation, leading to detrimental effects (Kosmatka *et al*., 2016:212). As the amount of amorphous, or reactive, forms of MgO content increases, so too does the risk for concrete deterioration (Kosmatka *et al*., 2016:212). Dolomites are, in most cases, very stable and can be used successfully, but if an aggregate is suspected of having detrimental characteristics, further testing is required (Neville, 2011:222).

5.8.5 Fe_2O_3 (Iron Oxide)

Fe_2O_3 can form part of some minerals found in rocks commonly used as aggregate in concrete (Neville, 2011:169; Kosmatka *et al*., 2016:111-112). The Fe_2O_3 is inert in most cases, but can become problematic in sulphide form (Mindess *et al*., 2003:142; Neville, 2011:211). Aesthetic staining is the main chemical issue related to reactive Fe_2O_3 content, but can also indicate possibly the presence of sulphide minerals that can lead to deterioration of the concrete (Mindess *et al*., 2003:142; Neville, 2011:205; Kosmatka *et al*., 2016:111). According to SANS 794, the Fe_2O_3 shall not exceed 7.5mg/kg by weight using the method described in the document (SANS, 2009b:6).

5.8.6 SO_3 (Sulphur Trioxide)

SO_3 is a prominent component of some common minerals, such as gypsum ($CaSO_3$) and pyrite (Fe_2S) (Mindess *et al*., 2003:142; Neville, 2011:211; Kosmatka *et al*., 2016:111-112). Sulphate attack is the main chemical issue related to SO_3 content, where reactions with the cement's calcium hydroxide consume it to form other types of expanding hydroxides, which can lead to cracking and deterioration of the concrete (Mindess *et al*., 2003:142; Neville, 2011:211; Kosmatka *et al*., 2016:219). According to SANS 794, the SO_3 shall not exceed 1% by weight using the method described in the document (SANS, 2009b:6).

5.8.7 Na_2O and K_2O (Sodium and Potassium Oxides)

The alkali metals, such as Na_2O and K_2O, are prominent components of many minerals, including phyllosilicates and feldspars, and the latter is commonly found in rocks used as aggregate in concrete (Kosmatka *et al*., 2016:111-112; AfriSam, 2021b:119). ASR is the main chemical issue related to Na_2O and K_2O content, where reactions with amorphous or reactive SiO_2 can exacerbate its effects (Mindess *et al*., 2003:154; Neville, 2011:217-219; Kosmatka *et al*., 2016:113). Alkali metals can also cause ACR where it replaces CaO from some cement bonds to increase early strength in concrete, but severely impacts long term strength and durability (Neville, 2011:68). As the amount of amorphous, or poorly crystalline, alkali metals content increases, so too does the risk for ASR (Mindess *et al*., 2003:154; Neville, 2011:217; Kosmatka *et al*., 2016:113).

5.8.8 Cl (Chloride)

The Cl is typically associated with minerals from evaporate environments, where halite (NaCl) is well known (Kosmatka *et al*., 2016:111-112). Chloride attack, or corrosion, is the main chemical issue related to Cl content, where reactions can corrode steel in reinforced concrete and cause cracking and deterioration of the concrete (Neville, 2011:208; Kosmatka *et al*., 2016:204). Apart from this, if salt content is high, the susceptibility to physical disintegration through hydration-dehydration also becomes apparent (Neville, 2011:209; Kosmatka *et al*., 2016:220). According to SANS 1083, the Cl shall not exceed 0.03% (300 ppm) by weight for reinforced and non-reinforced concrete, and 0.01% (100 ppm) by weight for prestressed concrete, using the method described in SANS 202 (SANS, 2013a:7).

5.8.9 Contamination elements

Although some elements do not necessarily affect the quality of concrete or its soundness, they can sometimes impact the environment and the health of organisms in contact with it. The Department of Water and Sanitation has outlined the acceptable soil screening values for a range of land uses for the elements of concern (Department of Water and Sanitation, 2012:8-9). The land uses of interest will be that of standard residential and the commercial/industrial categories, where the metal and metalloid elements that the PXRF detected are of interest (Department of Water and Sanitation, 2012:8-9).

5.8.10 Inter-mine chemical composition

A hierarchical clustering analysis was performed to illustrate the inter-mine relationships of chemical composition, using the UPGMA method with Euclidean distance to best categorise the bulk samples. From Figure 5-4, the chemical compositions of different mine waste materials can be compared with those of similar materials from different mines. The main split, based on

chemical composition, is between carbonate-rich materials and silicate-rich materials. The carbonate-rich materials mostly contain CaO as their dominant chemical constituent and are the Kim2.UGW, Kim3.Cal and Kim3.CRDW. The silicate-rich materials, however, have many branches to accommodate the greater diversity and to achieve the best possible grouping. These are extremely diverse and difficult to constrain due to the large number of variables that influence their categorisation, and have already been discussed previously in detail. It is therefore more efficient to explain that the silicate branch of Figure 5-4 can be split into a MgO-CaO-Fe_2O_3 and a SiO_2-Al_2O_3-K2O-dominant branch, where the leftmost branches represent material more concentrated in MgO-CaO-Fe_2O_3, whilst the rightmost branches represent material more concentrated in SiO_2-Al_2O_3-K_2O. The materials in the middle have chemical compositions intermediate between these end-member branches.

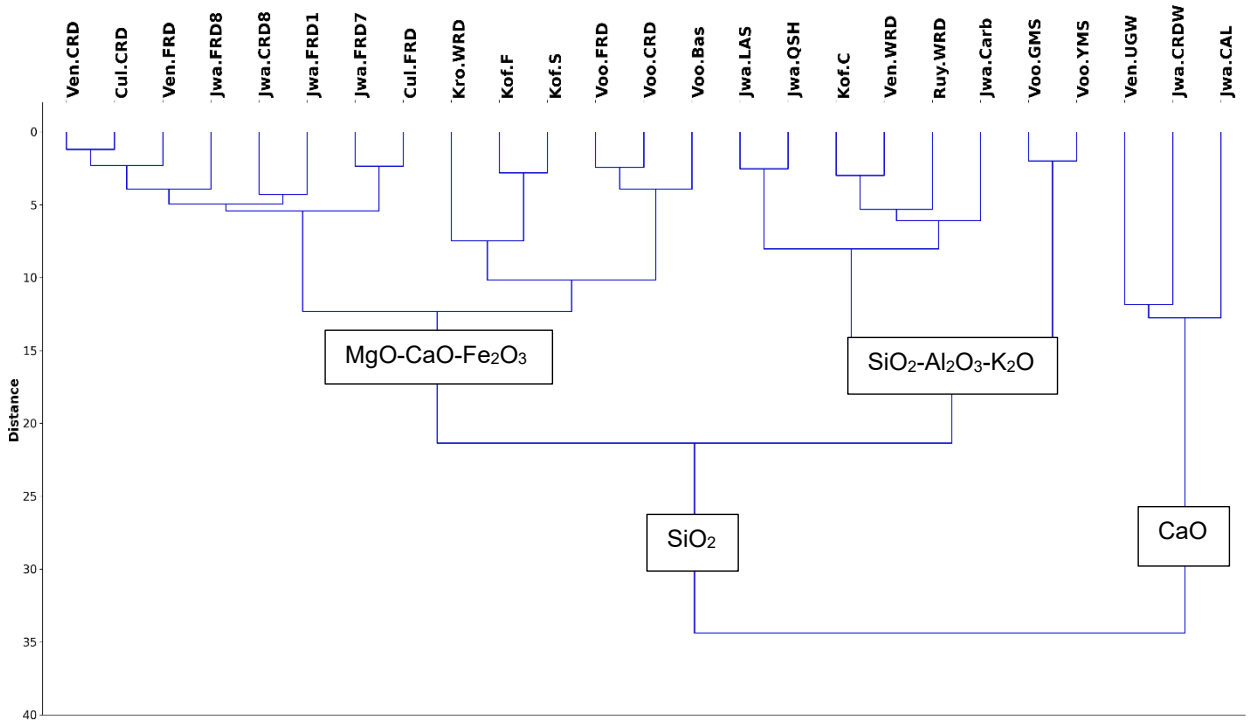


Figure 5-4: Hierarchical clustering analyses of compositional characteristics.

5.9 Suitability for use

5.9.1 Koffiefontein

The Kof.S has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of both plaster and mortar aggregate, as according to SANS 1090, but the excessive amounts of fines would not make it useable in its

current form (SANS, 2009a:5-6). The fineness modulus was just below acceptable specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content was above acceptable specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to very high phyllosilicate content comprising of biotite and an assortment of clays with some minor zeolites (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The NiO and MnO concentrations were above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate the sound feldspar and pyroxene minerals from the predominantly phyllosilicate minerals, the former can be used successfully in conventional concrete (if the pyroxene is not too weathered or part of phyllosilicate particles) whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4).

The Kof.F has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of COLTO Coarse Slurry 2 aggregate, as according to COLTO specifications, but the excessive amounts of fines would not make it useable in its current form (AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content was above acceptable specifications (SANS, 2013a:5; SANS, 2009a:5). The AIV indicated that the material complied with ‘pavement wearing’ class and ‘other concrete’ class (BS, 1992:3; SANS, 2012b). The mineralogy suggests that it would be unsuited for use in concrete due to a very high phyllosilicate content, comprising micas such as biotite and muscovite, and an assortment of clay, minerals with vermiculite as the dominant clay mineral (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). If it is possible to separate the sound quartz and feldspar minerals from the predominantly phyllosilicate minerals, the former can be used successfully in conventional concrete, whilst the latter can potentially be beneficiated into other products, such as light aggregate, under SANS 794 (ASTM, 2005:9; SANS, 2009b:4).

The Kof.C has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It has just below acceptable void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of COLTO Coarse Slurry 2 aggregate, as according to COLTO specifications, apart from having a coarser grading (AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content had acceptable values for mortar specification (SANS, 2013a:5; SANS, 2009a:5). The AIV indicated that the material complied with 'other concrete' class (BS, 1992:3; SANS, 2012b). The mineralogy suggests that it would be unsuited for use in concrete due to its very high phyllosilicate content, comprising micas such as biotite and an assortment of clays, predominantly 2:1:1 clays such as chlorite (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). If it is possible to separate the sound quartz and feldspar minerals from the predominantly phyllosilicate minerals, the former can be used successfully in conventional concrete, whilst the latter can potentially be beneficiated into other products, such as light aggregate, under SANS 794 (ASTM, 2005:9; SANS, 2009b:4).

5.9.2 Kimberlite 2

The Kim2.UGW has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It has a lower than acceptable void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture exactly to requirements of COLTO Coarse Slurry 2 aggregate, as according to COLTO specifications (AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications, but issues related to deviation might imply heterogeneity of sample (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for mortar specifications (SANS, 2013a:5; SANS, 2009a:5). The AIV indicated that the material complied with 'other concrete' class (BS, 1992:3; SANS, 2012b). The mineralogy suggests that it could be used in concrete, given the dominantly dolomite mineralogy, with some minor biotite as the only mineralogical issues (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO and Hg concentrations were double and 24 times, respectively, the allowable levels for the standard

residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). The mine is situated in a favourable area for dolomite stability, but should still be further assessed before use (Weinert, 1984:465-466; ASTM, 2005:9; Kosmatka *et al*., 2016:111-112).

The Kim2.CRD has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of coarse aggregate, as according to SANS 1083 specifications, where it is graded in much the same manner apart from being a little bit finer grained (SANS, 2013a:7; AfriSam, 2021b:45). The fineness modulus is higher than recommended by the specifications, meaning it might give the concrete a grainy instead of smooth appearance (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for mortar, plaster and fine aggregate in concrete specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to very high phyllosilicate content comprising of micas like biotite and of the 2:1:1 clay clinochlore chlorite (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). If it is possible to separate the sound feldspar and pyroxene minerals from the predominantly phyllosilicate minerals, the former can be used successfully in conventional concrete (if the pyroxene is not too weathered or part of phyllosilicate particles) whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4). This does still seem unlikely as the waste rock which contaminates this sample is probably gneissic, which is known to be deleterious and especially prone to cause ASR (ASTM, 2005:7; Field *et al*., 2008:52).

The Kim2.FRD has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of mortar and plaster aggregate, as according to SANS 1090 specifications, where only issue is related with too much fines (SANS, 2013a:7; AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications, but issues related to deviation might imply heterogeneity of sample (SANS, 2013a:7; SANS, 2009a:5). The dust content was above acceptable specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to very high phyllosilicate content comprising of micas like biotite and of an assortment of clay that is dominantly clinochlore chlorite (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210;

Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 levels were acceptable, Cl levels were elevated and may cause issues (Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). Other issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO concentration was above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate the sound minerals like quartz and pyroxene from the predominantly phyllosilicate minerals, the former can be used successfully in conventional concrete (if the pyroxene is not too weathered or part of phyllosilicate particles) whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4). This does still seem unlikely as the waste rock which contaminates this sample is probably gneissic, which is known to be deleterious and especially prone to cause ASR (ASTM, 2005:7; Field *et al*., 2008).

The Kim2.WRD1 has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It has a lower than acceptable void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture exactly to requirements of COLTO Coarse Slurry 2 aggregate, as according to COLTO specifications (AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications, but issues related to deviation might imply heterogeneity of sample (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for mortar and plaster under SANS 1090 and fine aggregate in concrete under SANS 1803 specifications (SANS, 2013a:5; SANS, 2009a:5). The AIV indicated that the material complied with ‘other concrete’ class (BS, 1992:3; SANS, 2012b). The mineralogy suggests that it may be unsuitable for use in concrete due to a very high phyllosilicate content, comprising micas such as biotite (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although Cl levels were acceptable, SO_3 levels were elevated and may cause issues (Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). Other issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO concentration was above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate the sound minerals like quartz and feldspar from the deleterious phyllosilicate minerals like biotite, the former group can be used successfully in conventional concrete whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4). This does still

seem unlikely as this waste rock is probably gneissic, which is known to be deleterious and especially prone to cause ASR (ASTM, 2005:7; Field *et al*., 2008).

The Kim2.WRD2 has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It has a lower than acceptable void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture exactly to requirements of COLTO Coarse Slurry 2 aggregate, as according to COLTO specifications (AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications, but issues related to deviation might imply heterogeneity of sample (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for mortar and plaster under SANS 1090 and fine aggregate in concrete under SANS 1803 specifications (SANS, 2013a:5; SANS, 2009a:5). The AIV indicated that the material complied with 'other concrete' class (BS, 1992:3; SANS, 2012b). The mineralogy suggests that it may be unsuitable for use in concrete due to a very high phyllosilicate content, comprising micas such as biotite (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO and Hg concentrations were just above and 18 times, respectively, the allowable levels for the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate the sound minerals like quartz and feldspar from the deleterious phyllosilicate minerals like biotite, the former can be used successfully in conventional concrete whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4). This does still seem unlikely as this waste rock is probably gneissic, which is known to be deleterious and especially prone to cause ASR (ASTM, 2005:7; Field *et al*., 2008).

The Kim2.WRD3 has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It has a lower than acceptable void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture exactly to requirements of COLTO Coarse Slurry 2 aggregate, as according to COLTO specifications (AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications, but issues related to deviation might imply heterogeneity of sample (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for mortar and plaster under SANS 1090 and fine aggregate in concrete under SANS 1803 specifications (SANS, 2013a:5; SANS, 2009a:5). The AIV indicated that the material complied with 'other concrete' class (BS, 1992:3; SANS, 2012b). The mineralogy suggests that it may be unsuitable for use in concrete due to a very high phyllosilicate content, comprising micas such as biotite (Weinert,

1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The Hg concentration was 23 times the allowable levels for the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate the sound minerals like quartz and feldspar from the deleterious phyllosilicate minerals like biotite, the former can be used successfully in conventional concrete whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4). This does still seem unlikely as this waste rock is probably gneissic, which is known to be deleterious and especially prone to cause ASR (ASTM, 2005:7; Field *et al*., 2008). Kimberlite 3

5.9.3 Kimberlite 3

The Kim3.Carb has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of nominal 26.5mm coarse aggregate, as according to SANS 1083 specifications (SANS, 2013a:9; AfriSam, 2021b:45). The fineness modulus is higher than recommended by the specifications, which are good for nominal aggregates (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for coarse aggregate in concrete specifications (SANS, 2013a:9; SANS, 2009a:5). The AIV indicated that the material complied with ‘heavy duty concrete’ class, ‘pavement wearing’ class and ‘other concrete’ class (BS, 1992:3; SANS, 2012b). The mineralogy suggests that it would be unsuited for use in concrete due to a very high phyllosilicate content, comprising micas such as muscovite and the 2:1:1 clay chlorite (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO and As concentrations were double and three times, respectively, above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). This waste rock is homogenous, making any beneficiation attempts difficult or separation of deleterious material impossible (ASTM, 2005:7; Field *et al*., 2008).

The Kim3.Cal has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies

with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of nominal 26.5mm coarse aggregate, as according to SANS 1083 specifications (SANS, 2013a:9; AfriSam, 2021b:45). The fineness modulus is higher than recommended by the specifications, which are good for nominal aggregates (SANS, 2013a:7; SANS, 2009a:5). The dust content was just above acceptable for coarse aggregate in concrete specifications (SANS, 2013a:9; SANS, 2009a:5). The AIV indicated that the material complied with 'heavy duty concrete' class, 'pavement wearing' class and 'other concrete' class (BS, 1992:3; SANS, 2012b). The mineralogy suggests it could be used in concrete, given the dominantly dolomite composition, with only concerns arising from said mineral (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The mine is situated in a favourable area for dolomite stability, but should still be further assessed before use (Weinert, 1984:465-466; ASTM, 2005:9; Kosmatka *et al*., 2016:111-112).

The Kim3.Las has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of nominal 26.5mm coarse aggregate, as according to SANS 1083 specifications (SANS, 2013a:9; AfriSam, 2021b:45). The fineness modulus is higher than recommended by the specifications, which are good for nominal aggregates (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for coarse aggregate in concrete specifications (SANS, 2013a:9; SANS, 2009a:5). The AIV indicated that the material complied with 'heavy duty concrete' class, 'pavement wearing' class and 'other concrete' class (BS, 1992:3; SANS, 2012b). The mineralogy suggests that it would be unsuited for use in concrete due to a very high phyllosilicate content, comprising micas such as muscovite and the 2:1:1 clay chlorite (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). This waste rock is homogenous, making any beneficiation attempts difficult or the separation of deleterious material impossible (ASTM, 2005:7; Field *et al*., 2008).

The Kim3.QSH has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies

with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of nominal 26.5mm coarse aggregate, as according to SANS 1083 specifications (SANS, 2013a:9; AfriSam, 2021b:45). The fineness modulus is higher than recommended by the specifications, which are good for nominal aggregates (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for coarse aggregate in concrete specifications (SANS, 2013a:9; SANS, 2009a:5). The AIV indicated that the material complied with 'heavy duty concrete' class, 'pavement wearing' class and 'other concrete' class (BS, 1992:3; SANS, 2012b). The mineralogy suggests that it would be unsuited for use in concrete due to a very high phyllosilicate content, comprising micas such as muscovite and the 2:1:1 clay chlorite (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). This waste rock is homogenous, making any beneficiation attempts difficult or the separation of deleterious material impossible (ASTM, 2005:7; Field *et al*., 2008).

The Kim3.CRDW has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of COLTO Coarse Slurry 2 aggregate, as according to COLTO specifications, apart from having a coarser grading (AfriSam, 2021b:45). The fineness modulus is higher than recommended by the specifications, meaning it might give the concrete a grainy instead of smooth appearance (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for mortar, plaster and fine aggregate in concrete specifications (SANS, 2013a:5; SANS, 2009a:5). The AIV indicated that the material complied with 'pavement wearing' class and 'other concrete' class (BS, 1992:3; SANS, 2012b). The mineralogy suggests it could be used in concrete, given the dominantly dolomite composition, with only concerns arising from said mineral (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO concentration was above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). The mine is situated in a favourable area for dolomite stability, but should still be further assessed before use (Weinert, 1984:465-466; ASTM, 2005:9; Kosmatka *et al*., 2016:111-112).

The Kim3.CRDB has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It has a lower than acceptable void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of COLTO Coarse Slurry 2 aggregate, as according to COLTO specifications, apart from having a finer grading (AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications, but issues related to deviation might imply heterogeneity of sample (SANS, 2013a:7; SANS, 2009a:5). The dust content was above acceptable for coarse aggregate in concrete specifications (SANS, 2013a:9; SANS, 2009a:5). The AIV indicated that the material complied with 'other concrete' class (BS, 1992:3; SANS, 2012b). The mineralogy suggests that it would be unsuited for use in concrete due to the almost pure phyllosilicate content of the material, where it comprises micas like biotite and dominantly of an assortment of clay from the 1:1 clay and 2:1 clay groups (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The NiO and MnO concentrations were above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). This material is not suited for concrete in its natural form. However, due to its high phyllosilicate content, it may be beneficiated into other products, such as light aggregate, under SANS 794 (ASTM, 2005:9; SANS, 2009b:4).

The Kim3.FRD1 has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It has a lower than acceptable void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of mortar and plaster aggregate, as according to SANS 1090 specifications, where only issue is related with too much fines (SANS, 2013a:7; AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content was above acceptable specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to high phyllosilicate content comprising of an assortment of clays from the 2:1 clay and 2:1:1 clay groups with some minor zeolites (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that SO_3 and Cl might cause detrimental effects, along with other possible chemical reactions related to its mineralogy and should therefore first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The NiO and MnO concentrations were above

the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate the sound minerals like quartz and pyroxene from the predominantly phyllosilicate minerals, the former can be used successfully in conventional concrete (if the pyroxene is not too weathered or part of phyllosilicate particles) whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4).

The Kim3.FRD7 has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to the requirements of mortar and plaster aggregate, as according to SANS 1090 specifications, where only issue is related with too much fines (SANS, 2013a:7; AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content was above acceptable specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to high phyllosilicate content comprising dominantly of 2:1 clay, which is known for swelling (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The NiO and MnO concentrations were above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate sound minerals such as quartz and dolomite from predominantly phyllosilicate minerals, the former can be used successfully in conventional mortar or plaster, whilst the latter can potentially be beneficiated into other products, such as light aggregate, under SANS 794 (ASTM, 2005:9; SANS, 2009b:4).

The Kim3.FRD8 has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture that is far too fine to be used as an aggregate for any specification (SANS, 2013a:7; AfriSam, 2021b:45). The fineness modulus was far lower than specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content was far above acceptable specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to high phyllosilicate content comprising of an assortment of clays from the 2:1 clay and 2:1:1 clay groups with some minor zeolites (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 levels were acceptable, the Cl might, however, cause detrimental

effects, along with other possible chemical reactions related to its mineralogy and should therefore first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The NiO concentration was above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). This material will only have potential if beneficiated, like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4). This being said, the extremely fine nature makes it more suitable for beneficiation to products like clay bricks (Rashad, 2016:55; Chanturiya *et al*., 2018:13; Pashkevich & Alekseenko, 2020:8; Muheise-Araalia & Pavia, 2021:2; Singh, 2022:5).

5.9.4 Kimberlite 4

The Kim4.FRD has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It is just above the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture that perfectly fits the requirements of mortar and plaster aggregate, as according to SANS 1090 specifications (SANS, 2013a:7; AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for mortar and plaster in concrete specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to very high phyllosilicate content comprising of micas like biotite and clay from the 1:1 clay group (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that SO_3 and Cl levels were acceptable (Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). Other issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO concentration was above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate the sound minerals like feldspar and pyroxene from the predominantly phyllosilicate minerals, the former can be used successfully in conventional concrete (if the pyroxene is not too weathered or part of phyllosilicate particles) whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4).

The Kim4.CRD has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture fitting the requirements of coarse aggregate, as according to SANS 1083 specifications, where it is graded in much the same manner apart from being a little

bit finer grained (SANS, 2013a:7; AfriSam, 2021b:45). The fineness modulus is higher than recommended by the specifications, meaning it might give the concrete a grainy instead of smooth appearance (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for mortar, plaster and fine aggregate in concrete specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to very high phyllosilicate content comprising of micas like biotite and clay from the 2:1:1 clay (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO concentration was above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate the sound minerals like quartz, feldspar and pyroxene from the predominantly phyllosilicate minerals, the former can be used successfully in conventional concrete (if the pyroxene is not too weathered or part of phyllosilicate particles) whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4).

5.9.5 Voorspoed

The Voo.GMS has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture that is far too fine to be used as an aggregate for any specification (SANS, 2013a:7; AfriSam, 2021b:45). The fineness modulus was far lower than specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content was far above acceptable specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to relatively high phyllosilicate content comprising of clays from the 2:1 clay group, namely illite (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). This material will only have potential if beneficiated to other products, like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4). This being said, the extremely fine nature makes it more suitable for beneficiation to products like clay bricks (Rashad, 2016:55; Chanturiya *et al*., 2018:13; Pashkevich & Alekseenko, 2020:8; Muheise-Araalia & Pavia, 2021:2; Singh, 2022:5).

The Voo.YMS has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture that is far too fine to be used as an aggregate for any specification (SANS, 2013a:7; AfriSam, 2021b:45). The fineness modulus was far lower than specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content was far above acceptable specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to relatively high phyllosilicate content comprising of micas like biotite, which is dominant, and some minor muscovite and clay from the 2:1 clay group (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). This material will only have potential if beneficiated to other products, like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4). This being said, the extremely fine nature makes it more suitable for beneficiation to products like clay bricks (Rashad, 2016:55; Chanturiya *et al*., 2018:13; Pashkevich & Alekseenko, 2020:8; Muheise-Araalia & Pavia, 2021:2; Singh, 2022:5).

The Voo.FRD has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It also complies with the void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture that is far too fine to be used as an aggregate for any specification (SANS, 2013a:7; AfriSam, 2021b:45). The fineness modulus was far lower than specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content was far above acceptable specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it would be unsuited for use in concrete due to high phyllosilicate content comprising of micas like the phengite variety of muscovite, and vermiculite clay from the 2:1 clay group (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to its unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO concentration was above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). This material will only have potential if beneficiated into other products, such as light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4).

The Voo.CRD has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It has just lower than acceptable void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture exactly to requirements of COLTO Coarse Slurry 2 aggregate, as according to COLTO specifications (AfriSam, 2021b:45). The fineness modulus is higher than recommended by the specifications, meaning it might give the concrete a grainy instead of smooth appearance (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable for mortar and plaster for the SANS 1090 specifications (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it could be used for concrete and similar application due to high feldspar and pyroxene content (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to some minor unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO concentration was above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate the sound feldspar and pyroxene minerals from the minor phyllosilicate minerals, the former can be used successfully in conventional concrete and similar applications (if the pyroxene is not too weathered or part of phyllosilicate particles) whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4). It is likely that the majority of the sound minerals come from the basalt waste rock or in combination with the dolerite which is also found in the pipe's vicinity (Phillips *et al*., 1998:301; Field *et al*., 2008:52; Stiefenhofer, 2013:6). Precautions should still be adhered to as the basalt is known to contain amygdales, which can contain silica reactive or zeolite minerals that can severely impact cement bonding strengths through ASR (Phillips *et al*., 1998:301; ASTM, 2005:4-5; Field *et al*., 2008:52; Stiefenhofer, 2013:6).

The Voo. Bas has acceptable apparent relative density and dry bulk density to comply with both SANS 1083 and SANS 1090 specifications (SANS, 2013a:7; SANS, 2009a:5). It has just lower than acceptable void content of the now retracted ASTM D3398 recommendation (ASTM, 2006; Rahman *et al*., 2019:13). It has a texture close to requirements of COLTO Coarse Slurry 2 aggregate, as according to COLTO specifications, apart from being a bit coarser grained (AfriSam, 2021b:45). The fineness modulus is acceptable towards specifications (SANS, 2013a:7; SANS, 2009a:5). The dust content was acceptable plaster for the SANS 1090 specifications and fine aggregate for SANS 1083 (SANS, 2013a:5; SANS, 2009a:5). The mineralogy suggests that it could be used for concrete and similar application due to high feldspar and pyroxene content, if the deleterious phyllosilicates content comprising of micas like

muscovite, and vermiculite clay from the 2:1 clay group can be separated (Weinert, 1984:465-466; ASTM, 2005:1-9; Neville, 2011:210; Kosmatka *et al*., 2016:111-112). The chemical composition suggests that although SO_3 and Cl levels were acceptable, issues arising from other chemical reactions related to the unfavourable mineralogy should first be thoroughly investigated before possible use (Weinert, 1984:465-466; ASTM, 2005:1-9; SANS, 2009b:6; Neville, 2011:210; SANS, 2013a:7; Kosmatka *et al*., 2016:111-112). The MnO concentration was above the standard residential permissible contamination values (Department of Water and Sanitation, 2012:8-9). If it is possible to separate the sound feldspar and pyroxene minerals from the phyllosilicate minerals, the former can be used successfully in conventional concrete and similar applications (if the pyroxene isn't too weathered or part of phyllosilicate particles) whilst the latter can potentially be beneficiated to other products like light aggregate under SANS 794 (ASTM, 2005:9; SANS, 2009b:4). It is likely that the majority of the sound minerals come from the basalt waste rock or in combination with the dolerite which is also found in the pipe's vicinity (Phillips *et al*., 1998:301; Field *et al*., 2008:52; Stiefenhofer, 2013:6). Precautions should still be adhered to as the basalt is known to contain amygdales, which can contain silica reactive or zeolite minerals that can severely impact cement bonding strengths through ASR (Phillips *et al*., 1998:301; ASTM, 2005:4-5; Field *et al*., 2008:52; Stiefenhofer, 2013:6). The high phyllosilicate content of this sample suggests that large amounts of kimberlitic/lamproitic material was lost with the process of trying to remove the intricate basalt reef from the pipe, as this sample contains more kimberlitic/lamproitic material than the studied CRD (Voo.CRD) from the mine (Phillips *et al*., 1998:301; Field *et al*., 2008:52; Stiefenhofer, 2013:6).

5.9.6 Compliance summary table

Table 5-1: Physical and textural compliance

*'Compliant' = meets the relevant specification limit stated; 'Marginal' = borderline / just outside the acceptable limit; 'Non-compliant' = fails the relevant limit; 'Not tested' = insufficient coarse fraction was available for the test (SANS 6239). 'Conditional' (mineralogy) = usable subject to further assessment. * = value falls within the acceptable range but the deviation between replicate samples exceeds the ±0.2 tolerance recommended by SANS 1083/1090, suggesting sample heterogeneity.*

Material	Density (SANS 1083/1090)	Void Content (ASTM D3398†)	Grading / Best-fit Classification	Fineness Modulus (SANS 1083)	Dust Content	AIV Class (BS 882)
Kof.S	Compliant	Compliant	Non-compliant (SANS 1090 M/P envelope met, excess fines)	Marginal (just below range)	Non-compliant (above limit)	Not tested
Kof.F	Compliant	Compliant	Non-compliant (COLTO CS2 envelope met, excess fines)	Compliant	Non-compliant (above limit)	Pavement wearing
Kof.C	Compliant	Marginal (just below range)	Compliant (COLTO CS2, coarser)	Compliant	Compliant (mortar)	Other concrete
Kim2.UGW	Compliant	Non-compliant (below range)	Compliant (COLTO CS2, exact fit)	Compliant*	Compliant (mortar)	Other concrete
Kim2.CRD	Compliant	Compliant	Compliant (SANS 1083 coarse, finer)	Non-compliant (above range)	Compliant (mortar/plaster/fine agg.)	Not tested
Kim2.FRD	Compliant	Compliant	Non-compliant (SANS 1090 M/P envelope met, excess fines)	Compliant*	Non-compliant (above limit)	Not tested
Kim2.WRD1	Compliant	Non-compliant (below range)	Compliant (COLTO CS2, exact fit)	Compliant*	Compliant (mortar/plaster/fine agg.)	Other concrete
Kim2.WRD2	Compliant	Non-compliant (below range)	Compliant (COLTO CS2, exact fit)	Compliant*	Compliant (mortar/plaster/fine agg.)	Other concrete
Kim2.WRD3	Compliant	Non-compliant (below range)	Compliant (COLTO CS2, exact fit)	Compliant*	Compliant (mortar/plaster/fine agg.)	Other concrete
Kim3.Carb	Compliant	Compliant	Compliant (SANS 1083, 26.5mm nominal)	Non-compliant (above range; ok for nominal)	Compliant (coarse agg.)	Heavy-duty
Kim3.Cal	Compliant	Compliant	Compliant (SANS 1083, 26.5mm nominal)	Non-compliant (above range; ok for nominal)	Marginal (3% vs 2% limit)	Heavy-duty

Material	Density (SANS 1083/1090)	Void Content (ASTM D3398†)	Grading / Best-fit Classification	Fineness Modulus (SANS 1083)	Dust Content	AIV Class (BS 882)
Kim3.Las	Compliant	Compliant	Compliant (SANS 1083, 26.5mm nominal)	Non-compliant (above range; ok for nominal)	Compliant (coarse agg.)	Heavy-duty
Kim3.QSH	Compliant	Compliant	Compliant (SANS 1083, 26.5mm nominal)	Non-compliant (above range; ok for nominal)	Compliant (coarse agg.)	Heavy-duty
Kim3.CRDW	Compliant	Compliant	Compliant (COLTO CS2, coarser)	Non-compliant (above range)	Compliant (mortar/plaster/fine agg.)	Pavement wearing
Kim3.CRDB	Compliant	Non-compliant (below range)	Compliant (COLTO CS2, finer)	Compliant*	Non-compliant (above limit)	Other concrete
Kim3.FRD1	Compliant	Non-compliant (below range)	Non-compliant (SANS 1090 M/P envelope met, excess fines)	Compliant	Non-compliant (above limit)	Not tested
Kim3.FRD7	Compliant	Compliant	Non-compliant (SANS 1090 M/P envelope met, excess fines)	Compliant	Non-compliant (above limit)	Not tested
Kim3.FRD8	Compliant	Compliant	Non-compliant (too fine for any spec.)	Non-compliant (far below range)	Non-compliant (far above limit)	Not tested
Kim4.FRD	Compliant	Marginal (just above range)	Compliant (SANS 1090 M/P, exact fit)	Compliant	Compliant (mortar/plaster/fine agg.)	Not tested
Kim4.CRD	Compliant	Compliant	Compliant (SANS 1083 coarse, finer)	Non-compliant (above range)	Compliant (mortar/plaster/fine agg.)	Not tested
Voo.GMS	Compliant	Compliant	Non-compliant (too fine for any spec.)	Non-compliant (far below range)	Non-compliant (far above limit)	Not tested
Voo.YMS	Compliant	Compliant	Non-compliant (too fine for any spec.)	Non-compliant (far below range)	Non-compliant (far above limit)	Not tested
Voo.FRD	Compliant	Compliant	Non-compliant (too fine for any spec.)	Non-compliant (far below range)	Non-compliant (far above limit)	Not tested
Voo.CRD	Compliant	Marginal (just below range)	Compliant (COLTO CS2, exact fit)	Non-compliant (above range)	Compliant (mortar/plaster)	Not tested
Voo.Bas	Compliant	Marginal (just below range)	Compliant (COLTO CS2, coarser)	Compliant	Compliant (plaster/fine agg.)	Heavy-duty

† ASTM D3398 (Index of Aggregate Particle Shape and Texture) was formally withdrawn/retracted by ASTM but is retained here for reference, following Rahman et al. (2019), as no direct SANS replacement void-content benchmark exists.

Table 5-2: Chemical, mineralogical and overall compliance

*'Compliant' = meets the relevant specification limit stated; 'Marginal' = borderline / just outside the acceptable limit; 'Non-compliant' = fails the relevant limit; 'Not tested' = insufficient coarse fraction was available for the test (SANS 6239). 'Conditional' (mineralogy) = usable subject to further assessment. * = value falls within the acceptable range but the deviation between replicate samples exceeds the ±0.2 tolerance recommended by SANS 1083/1090, suggesting sample heterogeneity.*

Material	SO_3 & Cl (SANS 1083/794)	Trace-element Contamination‡	Mineralogical Suitability	Overall Recommendation
Kof.S	Compliant	NiO, MnO	Unsuitable (biotite, mixed clays, minor zeolites)	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kof.F	Compliant	None reported	Unsuitable (biotite, muscovite, vermiculite)	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kof.C	Compliant	None reported	Unsuitable (biotite, chlorite)	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kim2.UGW	Compliant	MnO (2x), Hg (24x)	Conditional (dolomite-dominant; minor biotite)	Potentially usable; requires further durability/stability assessment
Kim2.CRD	Compliant	None reported	Unsuitable (biotite, clinochlore chlorite); gneissic/ASR risk	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kim2.FRD	Cl elevated	MnO	Unsuitable (biotite, clinochlore chlorite); gneissic/ASR risk	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kim2.WRD1	SO_3 elevated	MnO	Unsuitable (biotite); gneissic/ASR risk	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kim2.WRD2	Compliant	MnO, Hg (18x)	Unsuitable (biotite); gneissic/ASR risk	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kim2.WRD3	Compliant	Hg (23x)	Unsuitable (biotite); gneissic/ASR risk	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kim3.Carb	Compliant	MnO (2x), As (3x)	Unsuitable (muscovite, chlorite); homogenous	Not suitable; beneficiation difficult (homogenous material)
Kim3.Cal	Compliant	None reported	Conditional (dolomite-dominant)	Potentially usable; requires further durability/stability assessment
Kim3.Las	Compliant	None reported	Unsuitable (muscovite, chlorite); homogenous	Not suitable; beneficiation difficult (homogenous material)

Material	SO_3 & Cl (SANS 1083/794)	Trace-element Contamination‡	Mineralogical Suitability	Overall Recommendation
Kim3.QSH	Compliant	None reported	Unsuitable (muscovite, chlorite); homogenous	Not suitable; beneficiation difficult (homogenous material)
Kim3.CRDW	Compliant	MnO	Conditional (dolomite-dominant)	Potentially usable; requires further durability/stability assessment
Kim3.CRDB	Compliant	NiO, MnO	Unsuitable (near-pure phyllosilicate/clay)	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kim3.FRD1	SO_3 & Cl flagged	NiO, MnO	Unsuitable (2:1/2:1:1 clays, minor zeolites)	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kim3.FRD7	Compliant	NiO, MnO	Unsuitable (2:1 clay - swelling risk)	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kim3.FRD8	Cl flagged	NiO	Unsuitable (2:1/2:1:1 clays, minor zeolites)	Not suitable as-is; potential light-aggregate / clay-brick beneficiation (extremely fine)
Kim4.FRD	Compliant	MnO	Unsuitable (biotite, 1:1 clay)	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Kim4.CRD	Compliant	MnO	Unsuitable (biotite, 2:1:1 clay)	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Voo.GMS	Compliant	None reported	Unsuitable (illite)	Not suitable as-is; potential light-aggregate / clay-brick beneficiation (extremely fine)
Voo.YMS	Compliant	None reported	Unsuitable (biotite, muscovite)	Not suitable as-is; potential light-aggregate / clay-brick beneficiation (extremely fine)
Voo.FRD	Compliant	MnO	Unsuitable (muscovite/phengite, vermiculite)	Not suitable as-is; potential SANS 794 light-aggregate beneficiation if sound minerals separated
Voo.CRD	Compliant	MnO	Conditional (feldspar/pyroxene-rich; ASR risk)	Potentially usable; ASR precautions required before use
Voo.Bas	Compliant	MnO	Conditional (feldspar/pyroxene if separated; ASR risk)	Potentially usable; ASR precautions required before use

‡ Trace-element concentrations (e.g. NiO, MnO, Hg, As) are compared against the Department of Water and Sanitation (2012) standard residential permissible contamination values, which are a soil/environmental screening guideline rather than a construction-material standard; they are included here as a screening flag only, not as a SANS/ASTM compliance criterion.

Chapter 6: Conclusion

In this study, 25 samples from five diamond mining operations were analysed to determine whether any of them could be utilised in the building industry, with particular focus on concrete. Numerous studies have proposed solutions for the sustainable and responsible use of mine-derived wastes, yet rehabilitation still remains as the most common practice being followed. Studies focusing on kimberlite tailings have made advances in this field, where a wide range of products can potentially be manufactured from the materials. This study primarily used SABS methods and a wide range of materials from different mines to evaluate how effectively these mine wastes can be used in concrete, as some have previously proven effective. From the results gathered, it was evident that, in some cases, kimberlite-derived wastes, such as tailings, exhibited satisfactory characteristics that might merit their use in concrete and similar products. However, issues related to chemical and physical properties strongly controlled by mineralogy make them unsuitable for long-term stability. There were major differences between the different types of tailings found on a mine site, like between different CRDs compared to different FRDs, and between different mines. From the tests, it was sometimes possible to infer how contaminated a tailings sample was with waste rock derived from the country rock, or even to distinguish how altered or weathered the tailings material is. The tailings tend to be too disintegrated to use when weathered, and issues related to the weathering of freshly processed kimberlite and lamproite material make it a very risky material to work with, even though it shows some good initial characteristics. This might explain why some other researchers obtained satisfactory results by using freshly harvested tailings, thus before any major weathering occurred, and by testing before the effects of weathering could be fully assessed. The building industry strives to uphold safety, and a material that could degrade and increase the risk of structural failure, endangering life, would most likely not be approved for use. That said, the material still has some use, as it has greater potential to be beneficiated into other products used in the building industry, such as light aggregates or clay bricks. As discussed, many other products can also be investigated. Other waste rocks indicated some potential for use in concrete, with some showing good potential, whilst others can be considered borderline aggregate and require further study before a decision is made. Mineralogy was a major influencing factor in the material's properties, as it defined its physical and chemical characteristics and, therefore, the prospects for utilising mine wastes in the future.

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ANNEXURE A: Relative density, dry bulk density and voids content.

	Relative density (kg/m^3)	Oven Dry Bulk Density (kg/m^3)	Void content (%)
Kof.C	2783.28	1850	33.55
Kof.F	2334.47	1460	37.45
Kof.S	2360.63	1340	43.25
Kim2.UGW	2564.76	1850	27.85
Kim2.CRD	2594.53	1460	43.75
Kim2.FRD	2180.73	1170	46.35
Kim2.WRD1	2499.66	1660	33.6
Kim2.WRD2	2433.63	1680	30.95
Kim2.WRD3	2335.16	1650	29.35
KIM3.CARB	3516.3	1790	49.1
KIM3.CAL	2896.64	1660	42.7
KIM3.LAS	3483.16	1840	47.15
KIM3.QSH	3654.62	1830	49.95
KIM3.CRDW	2611.32	1610	38.35
KIM3.CRDB	2368.72	1590	32.9
KIM3.FRD1	2079.05	1260	39.4
KIM3.FRD7	2013.61	1420	29.5
KIM3.FRD8	2136.12	1210	43.35
KIM4.FRD	2394.83	1180	50.75
KIM4.CRD	2807.47	1540	45.15
VOO.GMS	2202.92	1150	47.8
VOO.YMS	2035.45	1130	44.5
VOO.FRD	2053.37	1220	40.6
VOO.CRD	2552.63	1700	33.4
VOO.BAS	2650.44	1790	32.45

ANNEXURE B: Textural grading (mass retained in grams, on millimetre diameter sieve)

	Mud	Pan	0.075	0.15	0.3	0.6	1.18	2.36	4.75	6.7	9.5	13.2	19	26.5
Kof.S	45.4	17.1	42.7	67.7	65.8	27	3.6	0.3	0.2	0	0	0	0	0
Kof.F	35.4	6.3	17.5	25.1	31.5	38.3	58.5	27	17.2	8.5	21.9	6	0	0
Kof.C	26.6	5.3	16.7	26.9	30	26.4	32.3	39.2	41.9	16.1	29.9	35.4	4.5	18.8
Kim2.UGW	31	8.1	18.4	24.4	27.3	26.2	36.9	51.4	71.8	27	41.7	1.5	0	0
Kim2.CRD	9.9	1.1	3.3	4.5	6.4	20.8	92.7	138.2	3.6	0	0	0	0	0
Kim2.FRD	33.2	7.9	25.7	43.4	56.9	55.6	6.7	0.2	0.1	0.1	0.5	0	0	0
Kim2.WRD1	23.4	6.3	15.9	22.3	25	27.4	49.6	50.5	60	12.1	30.6	5.2	0	0
Kim2.WRD2	26.7	5.9	17.8	26.1	28.8	24.8	34.8	45.5	64.4	22.8	35.6	2.4	0	0
Kim2.WRD3	27.9	5.6	15.3	21.6	24.3	25.5	41	54.7	60.3	19.6	31.2	2	0	0
Kim3.Carb	0.4	0	0.1	0	0	0	0.4	6.8	22.1	13.7	38.2	77	76.3	122.4
Kim3.Cal	8.7	1.5	4.6	5	4.1	5.3	11.2	22.7	29.7	14.1	39.8	43.7	57.2	87.1
Kim3.Las	4.1	0.5	1.6	1.5	1.2	1.6	3.9	12	18.4	9.8	28.2	74.1	73.4	139.6
Kim3.QSH	1.8	0.2	1.9	0.2	0.2	0.3	1.8	9.4	22.1	12.5	40.5	51.2	62.1	164
Kim3.CRDW	6.7	1	5.1	11.9	19.7	22.2	30.7	57.9	70.1	26.3	48.3	23.1	2.4	0
Kim3.CRDB	37.8	5.4	18.1	25.6	29.5	30.8	39.1	38	27.9	11.1	18.1	27.2	9.4	0
Kim3.FRD1	57.3	11.5	33.3	51.3	53.2	39.8	7	0.4	0.3	0	0	0	0	0
Kim3.FRD7	48.7	8.3	35.4	61.5	72.5	45.6	10.4	0.5	0.1	0	0	0	0	0
Kim3.FRD8	168.7	10.4	27.3	22.2	10.7	1.2	0.1	0.2	0.5	0.1	0	0	0	0
Kim4.FRD	10.4	4.3	28.5	70.1	83.8	37.3	1.7	0	0	0	0	0	0	0
Kim4.CRD	6.1	0.4	0.6	0.9	2.1	30.5	99.7	95.8	71.1	1.6	0	0	0	0
Voo.GMS	203.4	3	2.8	0.8	0.9	1.9	6.9	6.5	0.6	0.2	0	0	0	0
Voo.YMS	163.2	11.2	12.7	5	4.5	7	7.5	3.7	1.8	1.1	0	4.4	0	0
Voo.FRD	166.6	14	31.7	18.3	8.9	2.6	0.2	0	0	0	0	0	0	0
Voo.CRD	19.3	1.4	9.5	13.5	21.4	32.1	50	67.9	83.6	27.4	12.7	0	0	0
Voo.Bas	28.5	2.6	11	8.7	14.8	19.3	32.5	39.4	43.9	11.9	13.5	21.2	61.4	44.6

ANNEXURE C: Fineness modulus and dust content

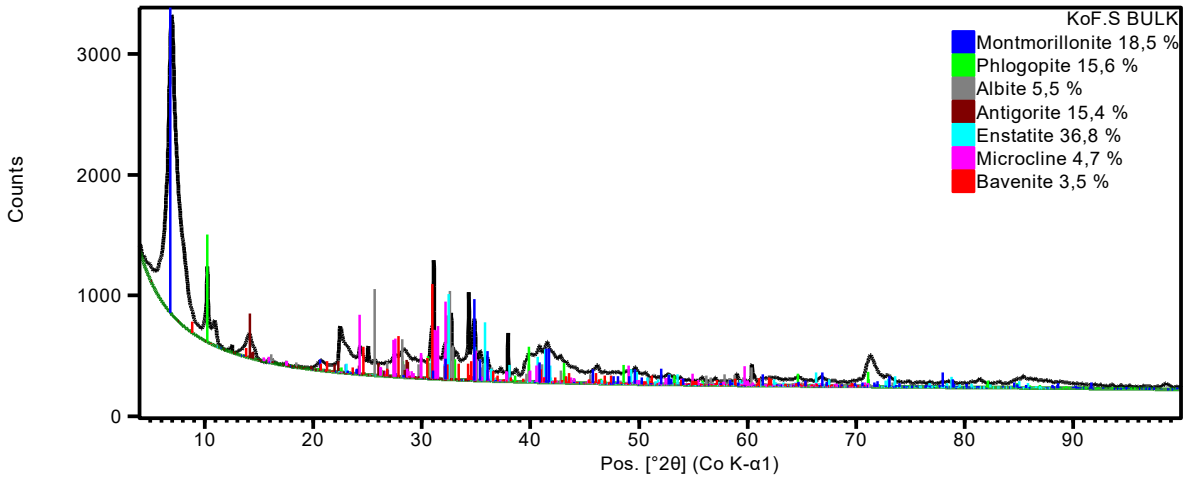
	Fineness Modulus	Dust content
Kof.S	1.1	23.2
Kof.F	3.3	14.2
Kof.C	4.8	9.1
Kim2.UGW	4.2	10.7
Kim2.CRD	4.1	3.9
Kim2.FRD	1.6	17.8
Kim2.WRD1	4.1	9
Kim2.WRD2	4.1	9.7
Kim2.WRD3	4.1	10.2
Kim3.Carb	9.4	0.1
Kim3.Cal	8.1	3
Kim3.Las	9.3	1.2
Kim3.QSH	9.5	0.5
Kim3.CRDW	5.4	2.4
Kim3.CRDB	3.9	13.6
Kim3.FRD1	1.2	27.1
Kim3.FRD7	1.4	20.1
Kim3.FRD8	0.2	74.2
Kim4.FRD	1.5	6.2
Kim4.CRD	4.6	2.1
Voo.GMS	0.3	90.9
Voo.YMS	0.6	78.5
Voo.FRD	0.2	74.5
Voo.CRD	4.4	6.1
Voo.Bas	6.2	8.8

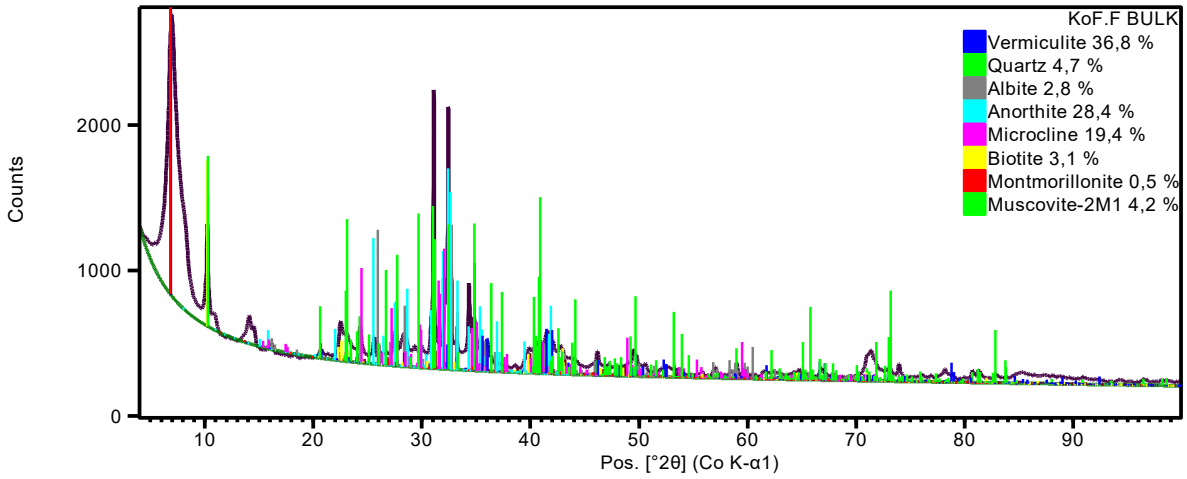
ANNEXURE D: Aggregate Impact Value (AIV)

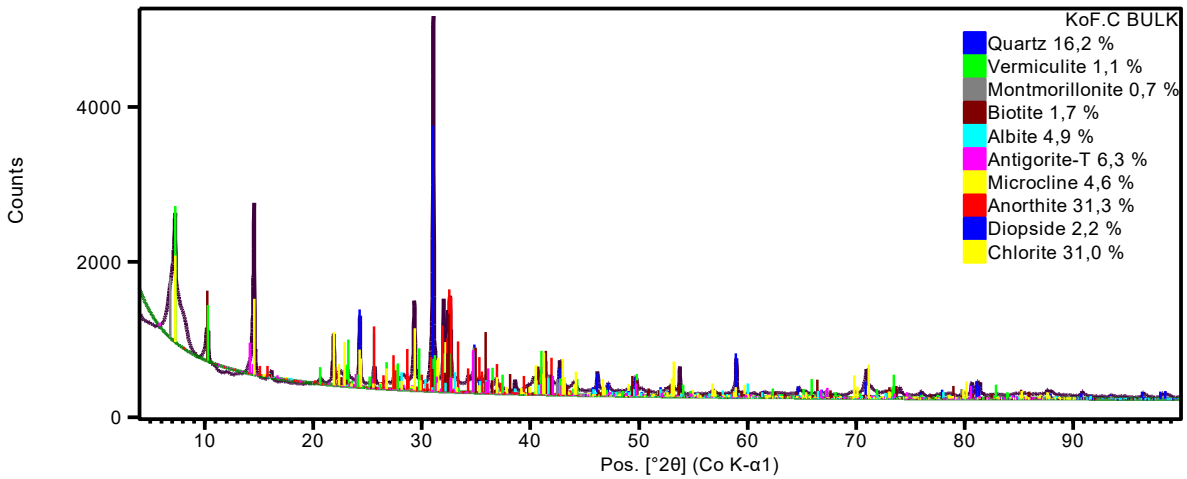
	3-shot	6-shot	9-shot
Kof.F	36.6	32.4	29.5
Kof.C	39.1	35.2	32.2
Kim2.UGW	41.4	38.8	38.75
Kim2.WRD1	30.5	33.45	32.65
Kim2.WRD2	33.35	34.15	33.05
Kim2.WRD3	36.75	34.9	32.15
Kim3.Carb	13.3	13.05	13.15
Kim3.Cal	18.35	19.75	20.05
Kim3.Las	13.85	15.1	15.4
Kim3.QSH	22.3	22.45	22.2
Kim3.CRDW	25.7	27.7	26.95
Kim3.CRDB	55.6	49.2	43
Voo.Bas	20.75	20.65	20.7

ANNEXURE E: Mineralogy - Diffractograms

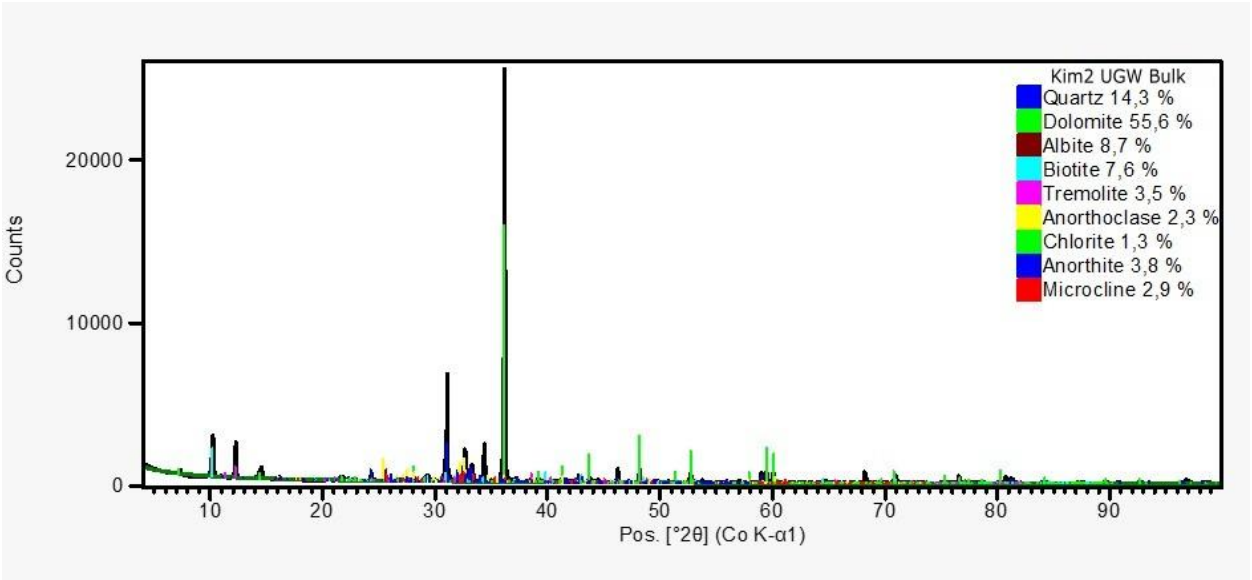
Koffiefontein

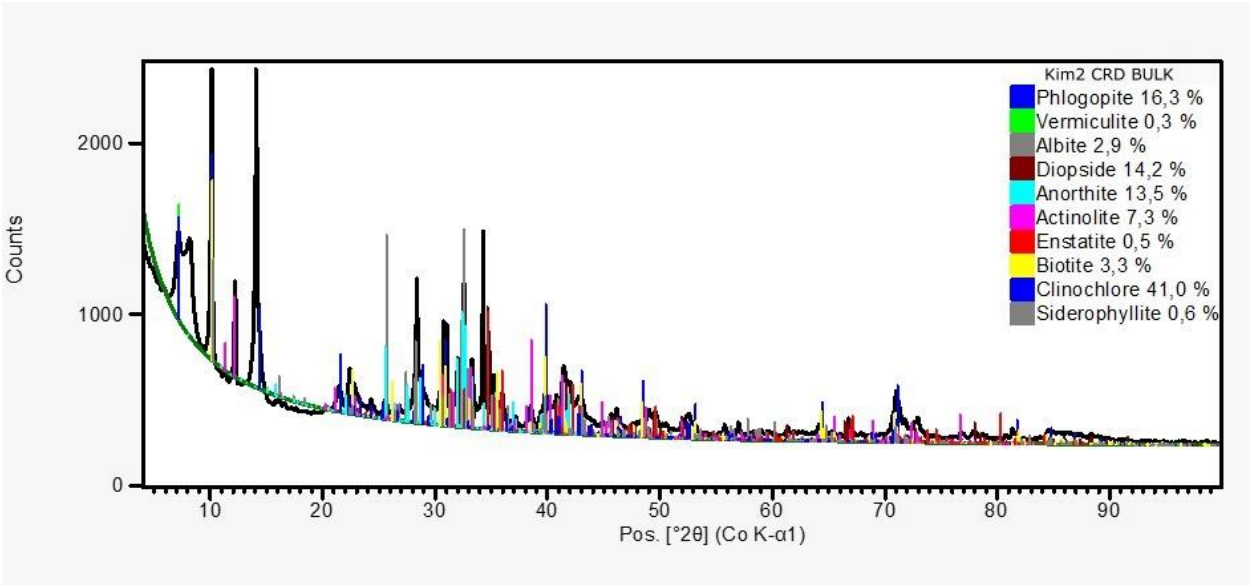


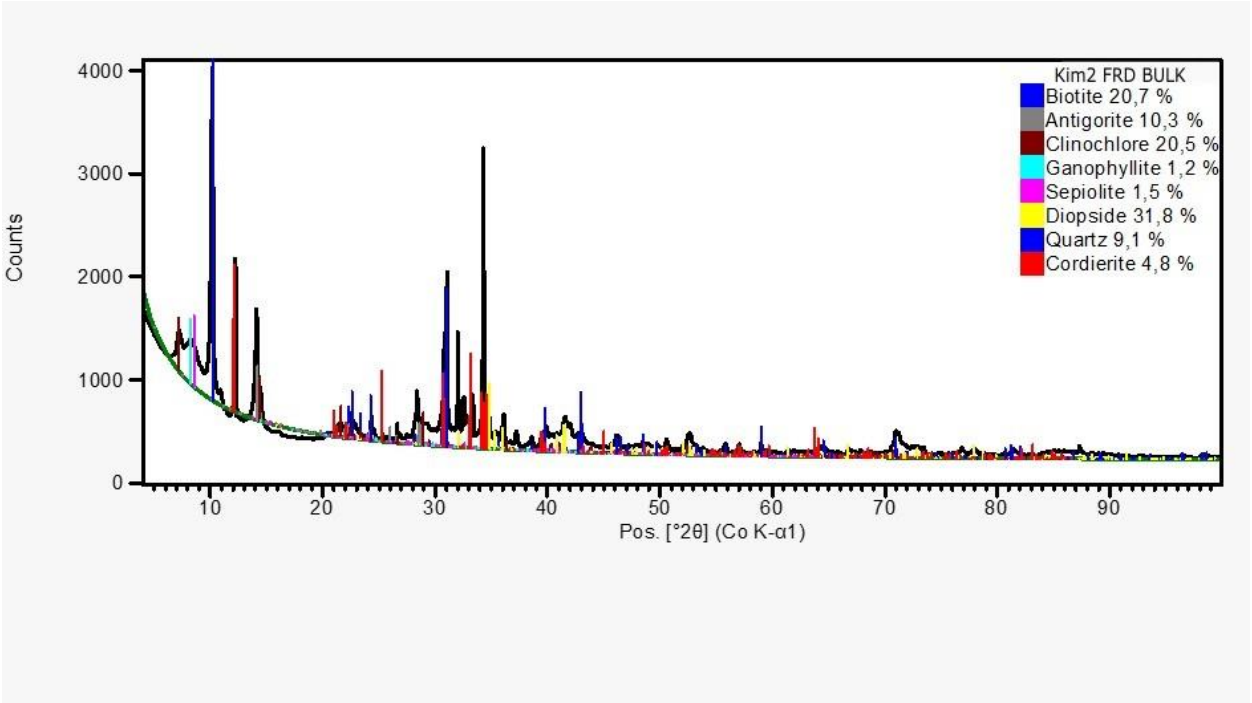


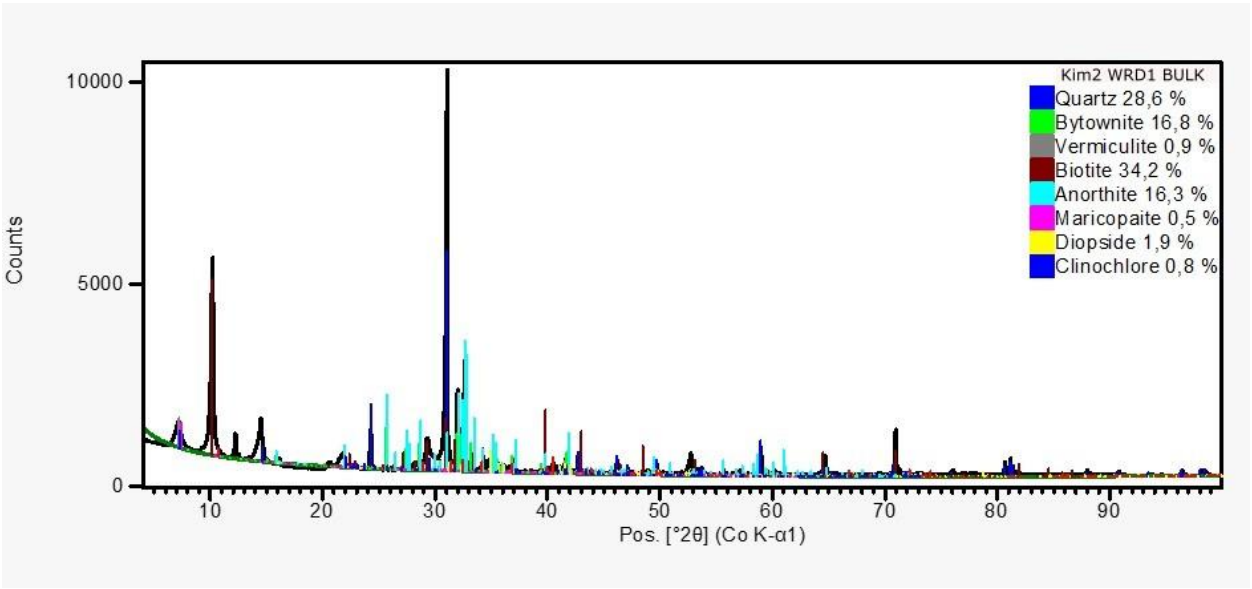


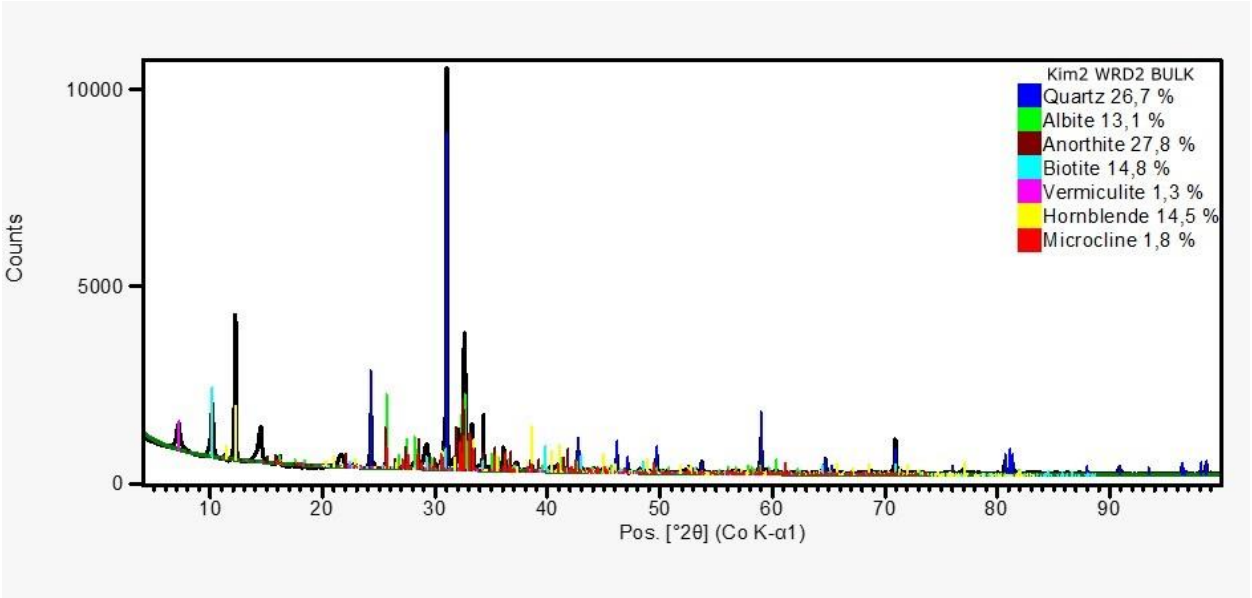
Kimberlite 2

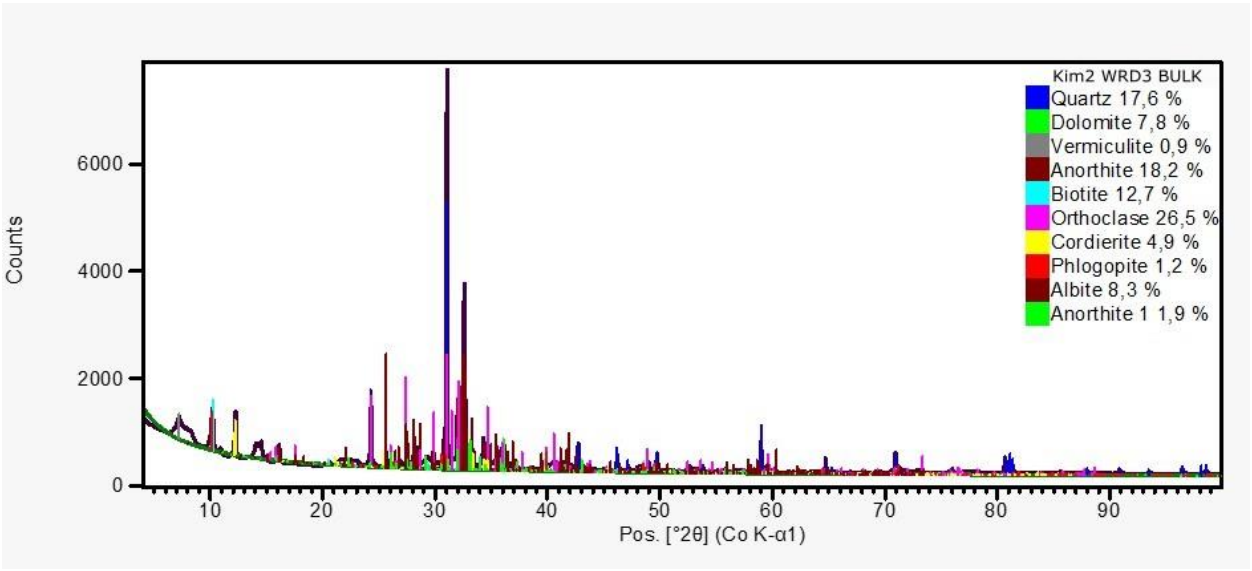



Kim2 CRD BULK
Phlogopite 16,3 %
Vermiculite 0,3 %
Albite 2,9 %
Diopside 14,2 %
Anorthite 13,5 %
Actinolite 7,3 %
Enstatite 0,5 %
Biotite 3,3 %
Clinochlore 41,0 %
Siderophyllite 0,6 %
Counts
Pos. [°2θ] (Co K-α1)

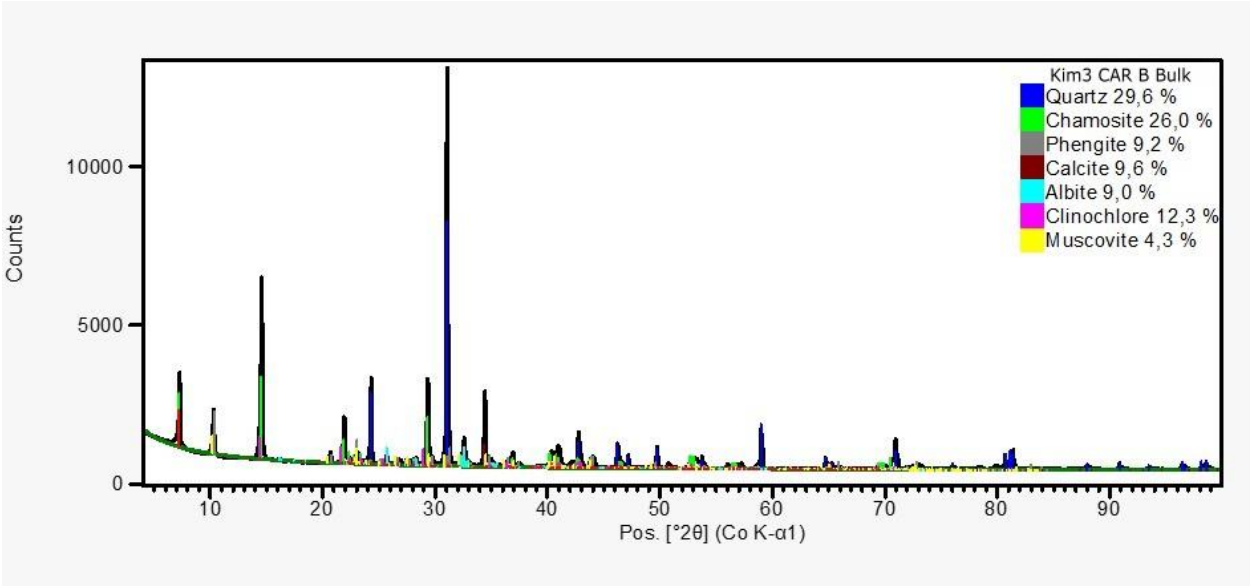

Kim2 FRD BULK
Biotite 20,7 %
Antigorite 10,3 %
Clinochlore 20,5 %
Ganophyllite 1,2 %
Sepiolite 1,5 %
Diopside 31,8 %
Quartz 9,1 %
Cordierite 4,8 %
Counts
Pos. [°2θ] (Co K-α1)

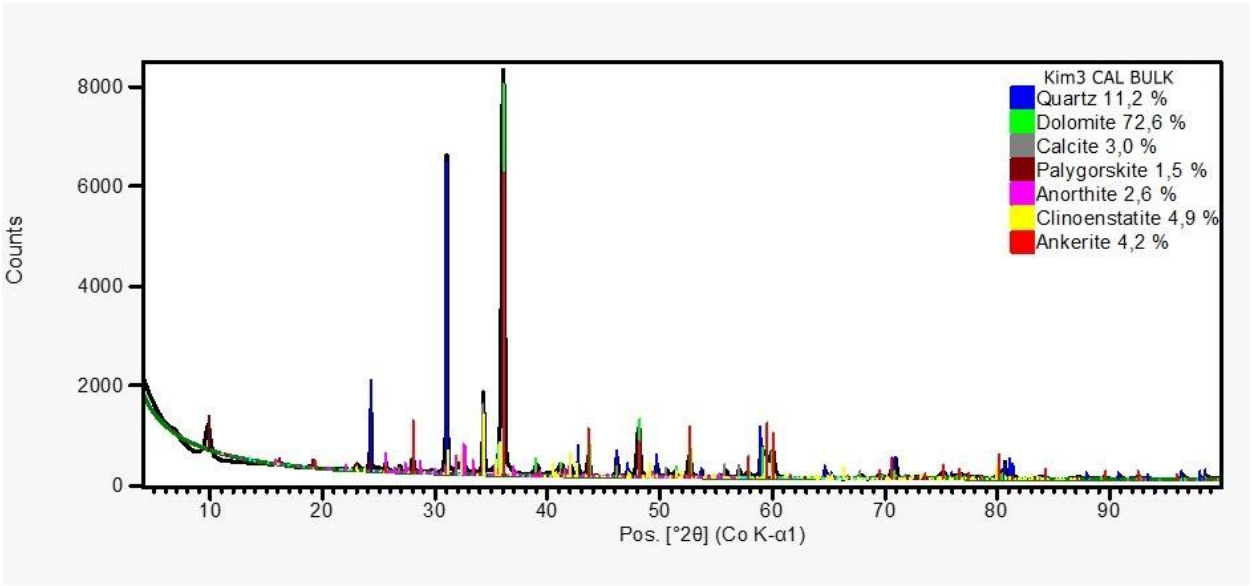

Kim2 WRD1 BULK
Quartz 28,6 %
Bytownite 16,8 %
Vermiculite 0,9 %
Biotite 34,2 %
Anorthite 16,3 %
Maricopaite 0,5 %
Diopside 1,9 %
Clinochlore 0,8 %
Counts
10000
5000
0
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)

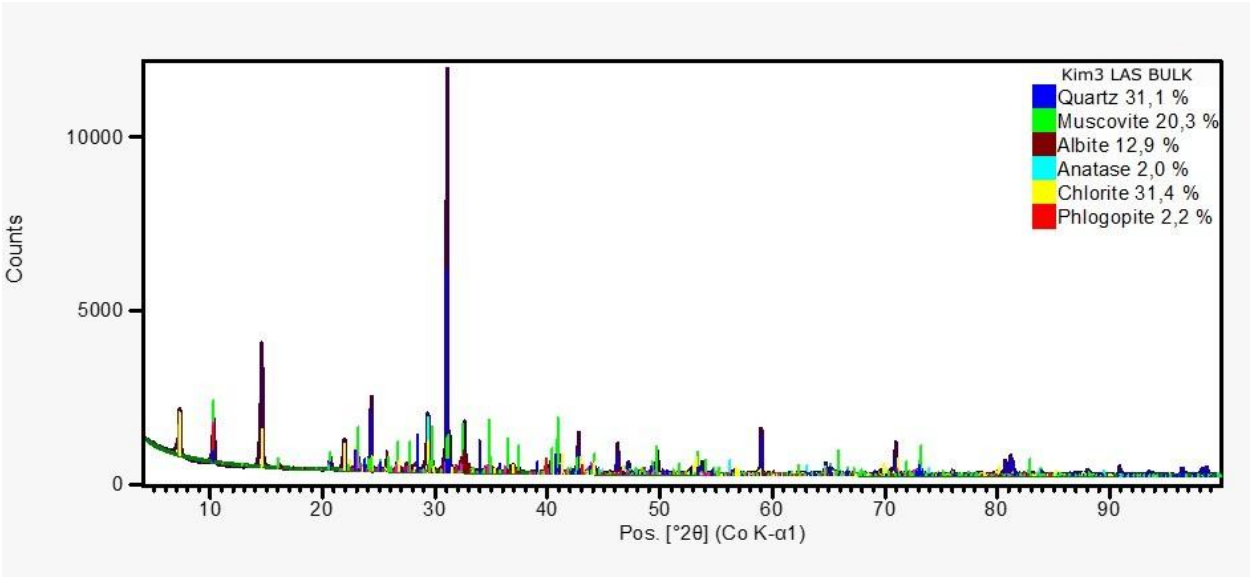

Kim2 WRD2 BULK
Quartz 26,7 %
Albite 13,1 %
Anorthite 27,8 %
Biotite 14,8 %
Vermiculite 1,3 %
Hornblende 14,5 %
Microcline 1,8 %
Counts
10000
5000
0
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)

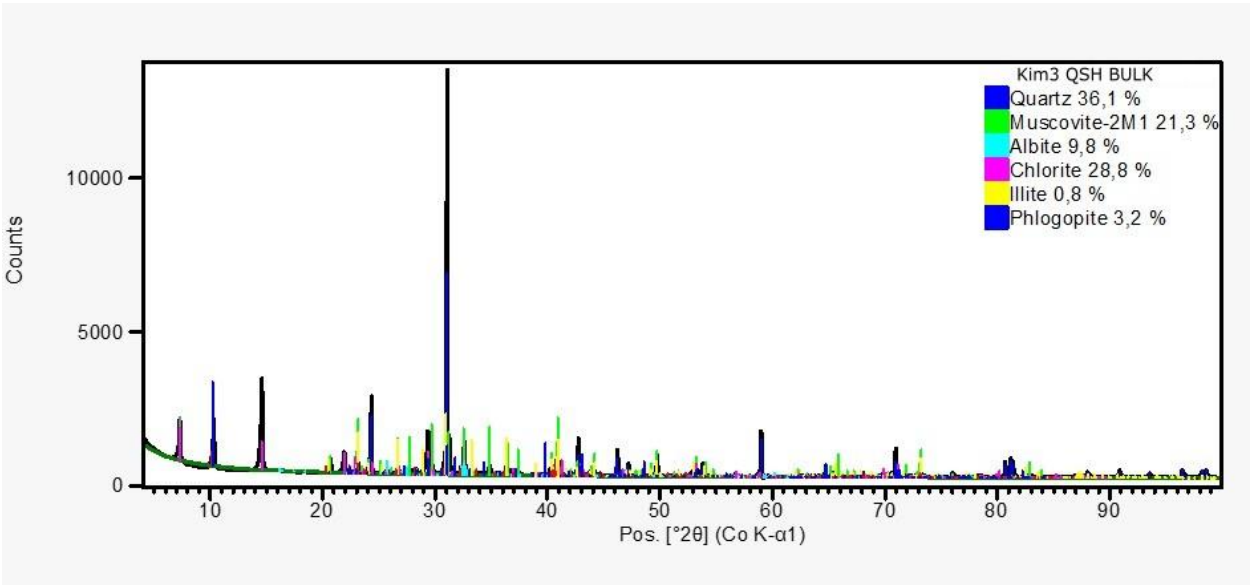


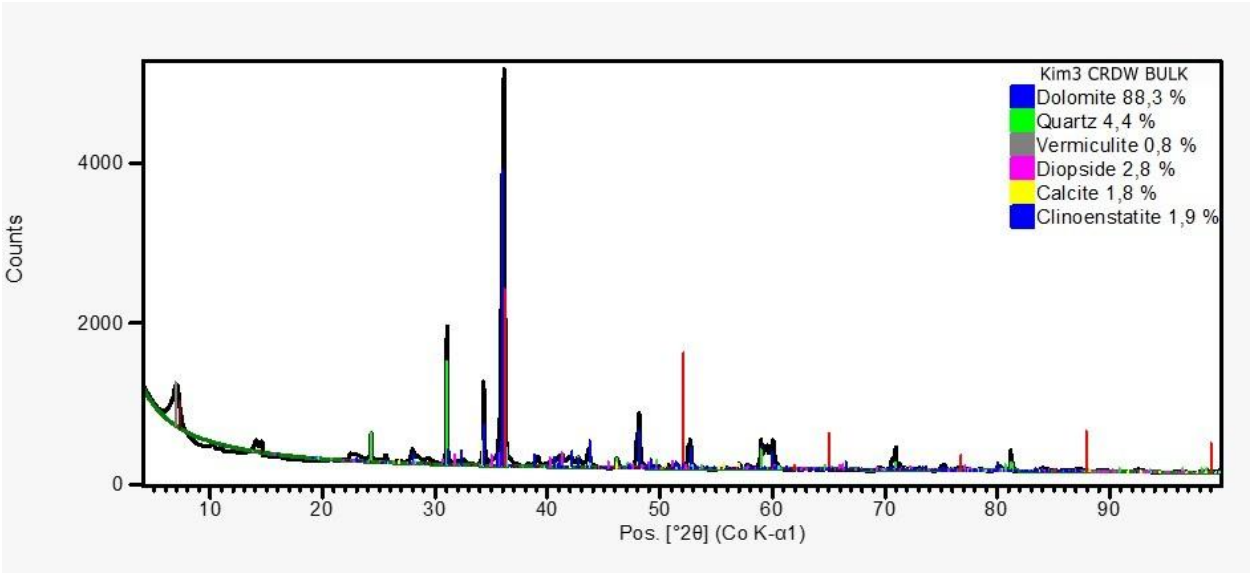
Kimberlite 3

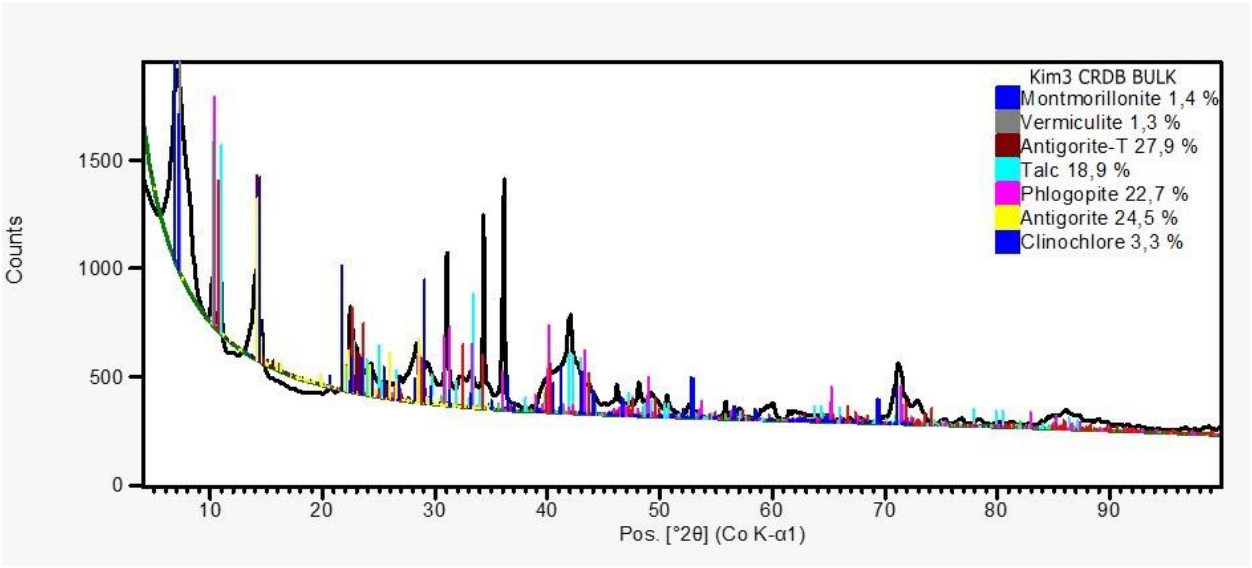


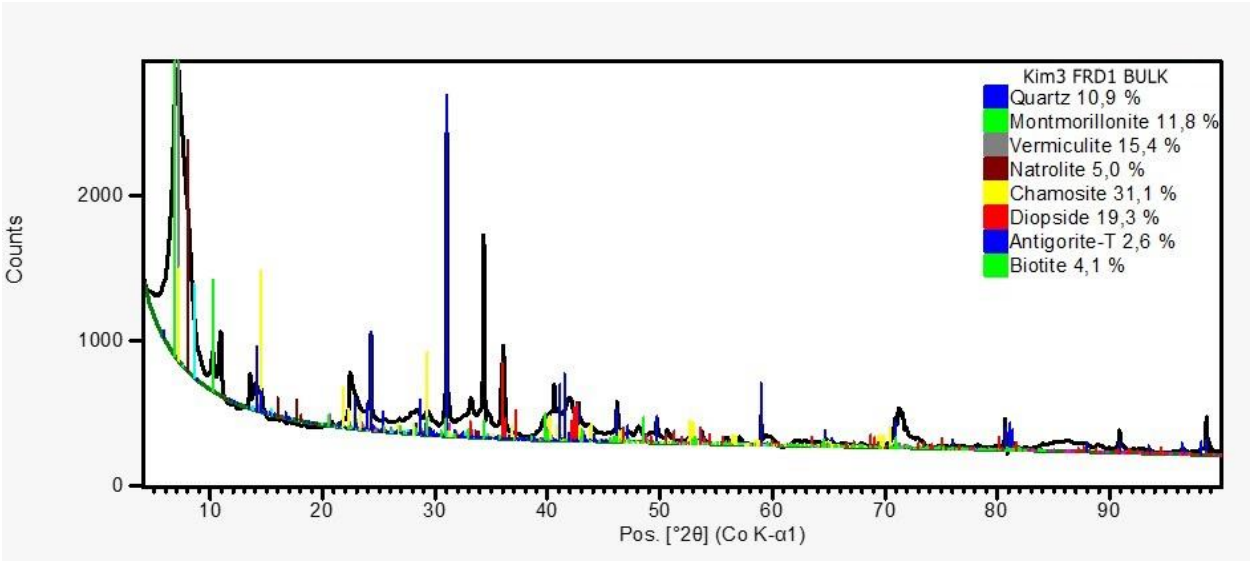

Kim3 CAL BULK
Quartz 11,2 %
Dolomite 72,6 %
Calcite 3,0 %
Palygorskite 1,5 %
Anorthite 2,6 %
Clinoenstatite 4,9 %
Ankerite 4,2 %
Counts
8000
6000
4000
2000
0
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)

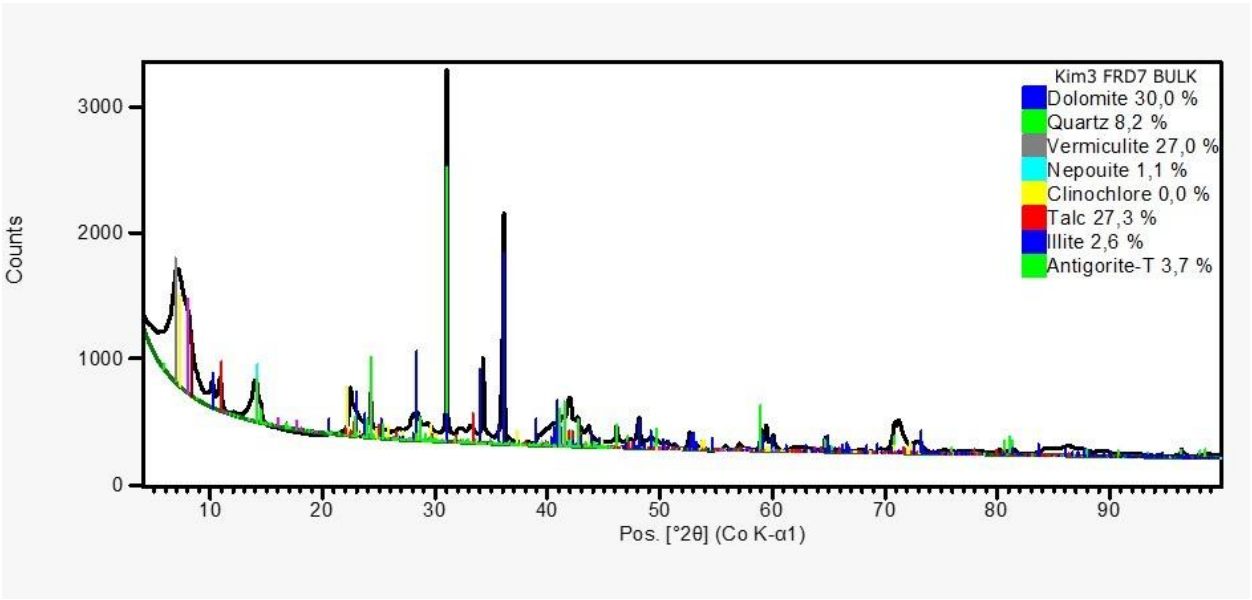

Kim3 LAS BULK
Quartz 31,1 %
Muscovite 20,3 %
Albite 12,9 %
Anatase 2,0 %
Chlorite 31,4 %
Phlogopite 2,2 %
Counts
10000
5000
0
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)

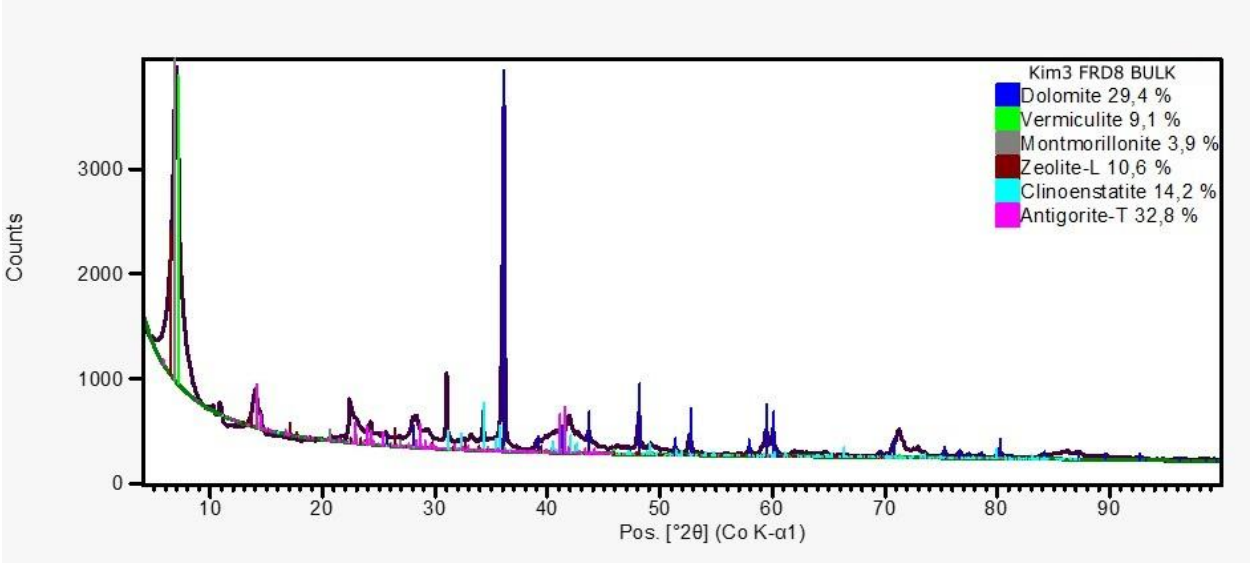

Kim3 QSH BULK
Quartz 36,1 %
Muscovite-2M1 21,3 %
Albite 9,8 %
Chlorite 28,8 %
Illite 0,8 %
Phlogopite 3,2 %
Counts
10000
5000
0
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)


Kim3 CRDW BULK
Dolomite 88,3 %
Quartz 4,4 %
Vermiculite 0,8 %
Diopside 2,8 %
Calcite 1,8 %
Clinoenstatite 1,9 %
Counts
4000
2000
0
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)

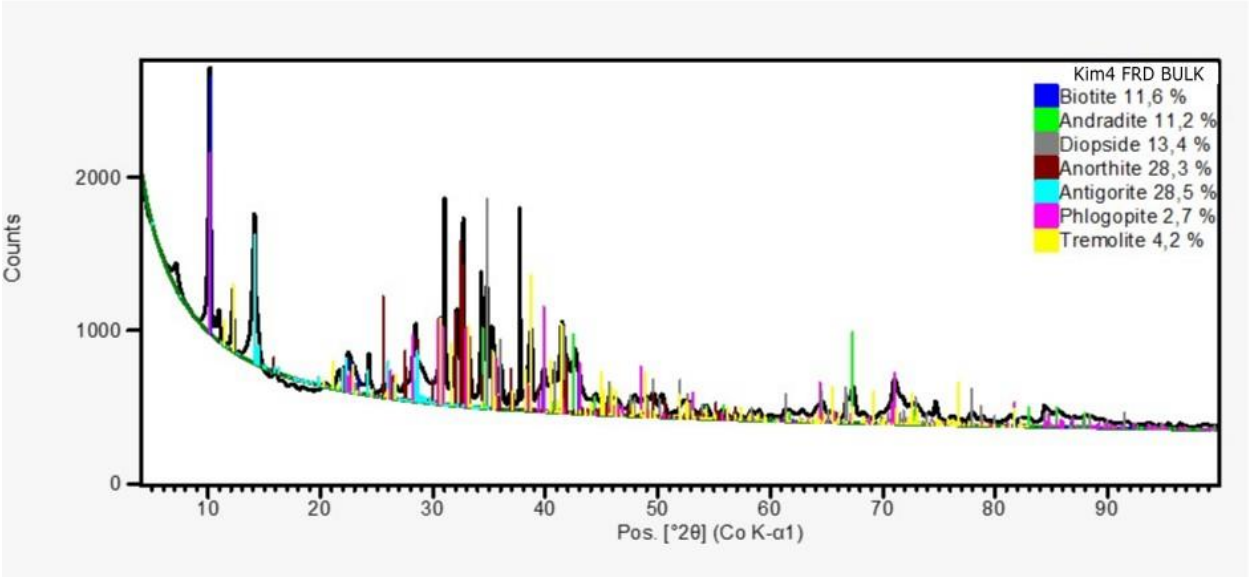

Kim3 CRDB BULK
Montmorillonite 1,4 %
Vermiculite 1,3 %
Antigorite-T 27,9 %
Talc 18,9 %
Phlogopite 22,7 %
Antigorite 24,5 %
Clinochlore 3,3 %
Counts
0
500
1000
1500
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)

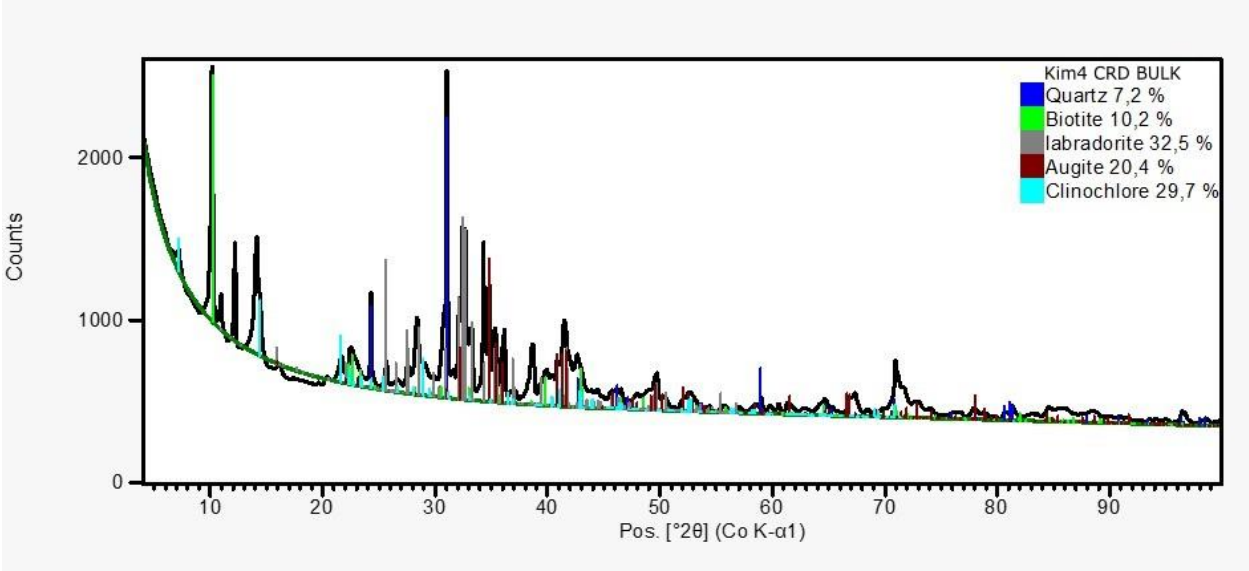

Kim3 FRD1 BULK
Quartz 10,9 %
Montmorillonite 11,8 %
Vermiculite 15,4 %
Natrolite 5,0 %
Chamosite 31,1 %
Diopside 19,3 %
Antigorite-T 2,6 %
Biotite 4,1 %
Counts
0
1000
2000
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)



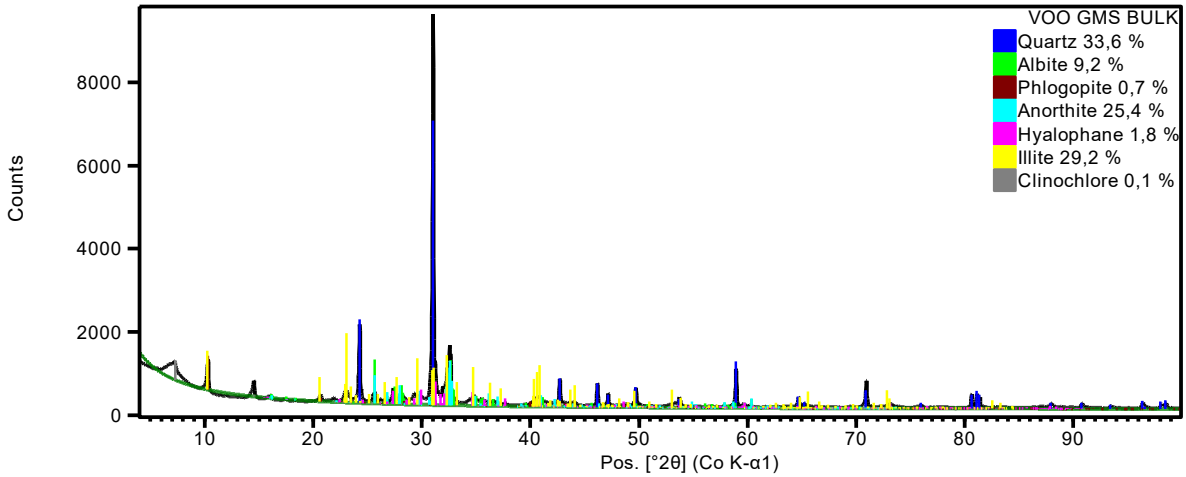


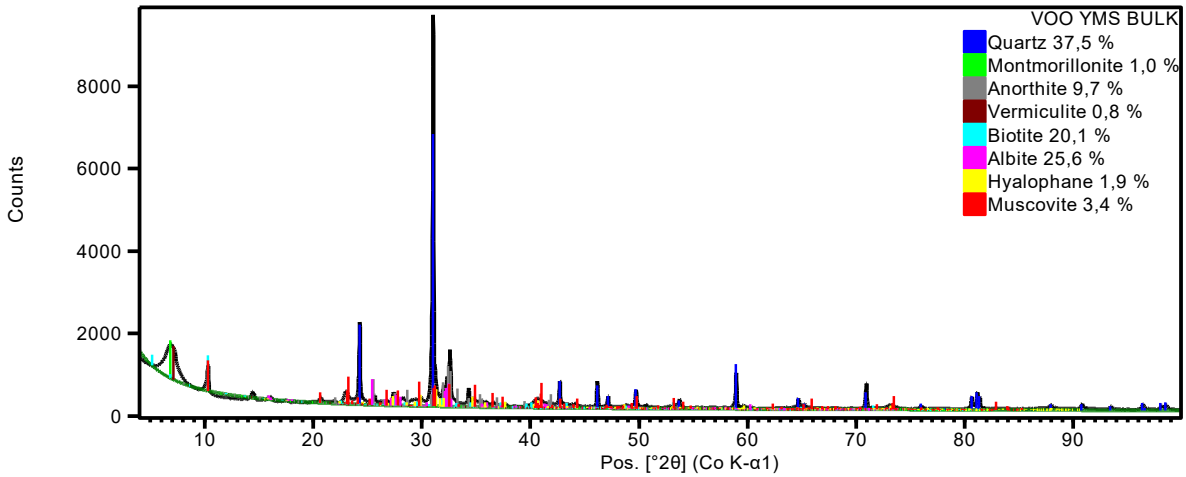
Kimberlite 4

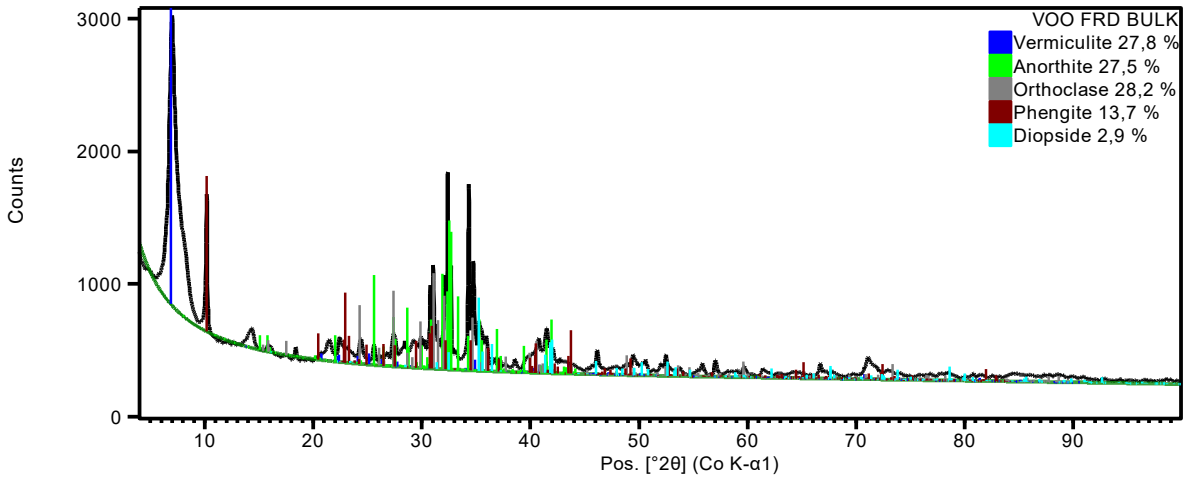

Kim4 FRD BULK
Biotite 11,6 %
Andradite 11,2 %
Diopside 13,4 %
Anorthite 28,3 %
Antigorite 28,5 %
Phlogopite 2,7 %
Tremolite 4,2 %
Counts
2000
1000
0
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)

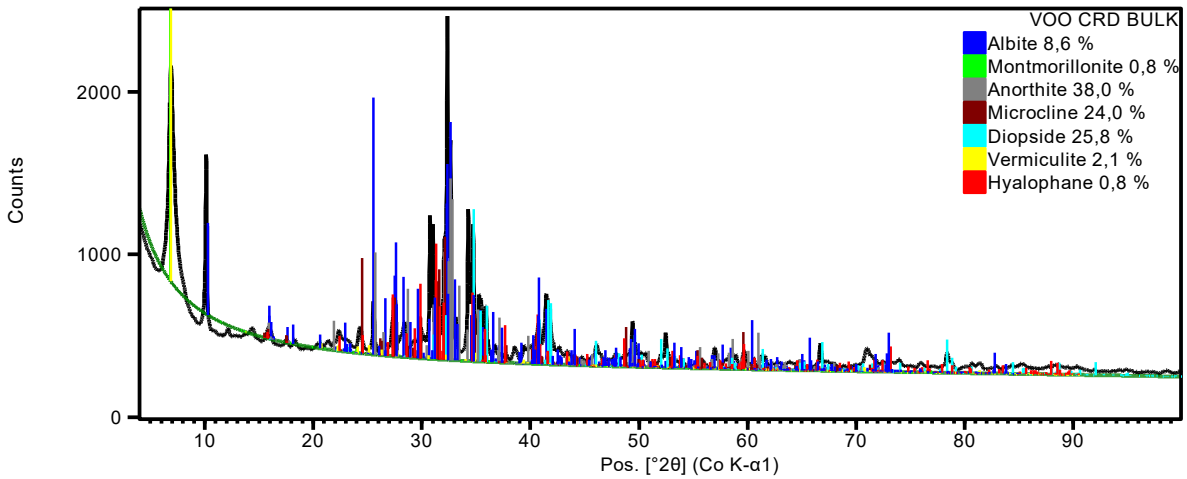

Kim4 CRD BULK
Quartz 7,2 %
Biotite 10,2 %
labradorite 32,5 %
Augite 20,4 %
Clinochlore 29,7 %
Counts
2000
1000
0
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)

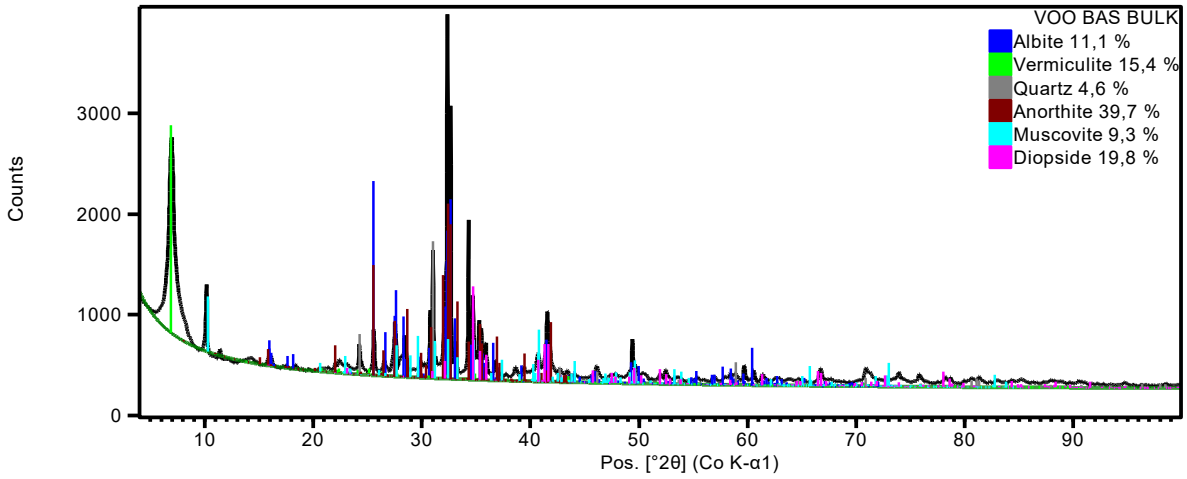
Voorspoed


VOO GMS BULK
Quartz 33,6 %
Albite 9,2 %
Phlogopite 0,7 %
Anorthite 25,4 %
Hyalophane 1,8 %
Illite 29,2 %
Clinochlore 0,1 %
Counts
Pos. [°2θ] (Co K-α1)


VOO YMS BULK
Quartz 37,5 %
Montmorillonite 1,0 %
Anorthite 9,7 %
Vermiculite 0,8 %
Biotite 20,1 %
Albite 25,6 %
Hyalophane 1,9 %
Muscovite 3,4 %
Counts
Pos. [°2θ] (Co K-α1)


VOO FRD BULK
Vermiculite 27,8 %
Anorthite 27,5 %
Orthoclase 28,2 %
Phengite 13,7 %
Diopside 2,9 %
Counts
Pos. [°2θ] (Co K-α1)


VOO CRD BULK
Albite 8,6 %
Montmorillonite 0,8 %
Anorthite 38,0 %
Microcline 24,0 %
Diopside 25,8 %
Vermiculite 2,1 %
Hyalophane 0,8 %
Counts
0
1000
2000
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)


VOO BAS BULK
Albite 11,1 %
Vermiculite 15,4 %
Quartz 4,6 %
Anorthite 39,7 %
Muscovite 9,3 %
Diopside 19,8 %
Counts
0
1000
2000
3000
10
20
30
40
50
60
70
80
90
Pos. [°2θ] (Co K-α1)

ANNEXURE F: Mineralogy - Grouped

	Quartz	Feldspar	Biotite	Muscovite	Pyroxene	Amphibole	Garnet	Cordierite	Titanium oxide	Carbonate	1:1 Clay	2:1 clay	2:1:1 clay	Beryllium silicate	Zeolite
Kof.S	0	10.2	15.6	0	36.8	0	0	0	0	0	15.4	18.5	0	3.5	0
Kof.F	4.7	50.6	3.1	4.2	0	0	0	0	0	0	0	37.3	0	0	0
Kof.C	16.2	40.8	1.7	0	2.2	0	0	0	0	0	6.3	1.8	31	0	0
Kim2.UGW	14.3	17.7	7.6	0	0	3.5	0	0	0	55.6	0	0	1.3	0	0
Kim2.CRD	0	16.4	20.2	0	14.7	7.3	0	0	0	0	0	0.3	41	0	0
Kim2.FRD	9.1	0	20.7	0	31.8	0	0	4.8	0	0	10.3	1.5	20.5	0	0
Kim2.WRD1	28.6	33.1	34.2	0	1.9	0	0	0	0	0	0	0.9	0.8	0	0.5
Kim2.WRD2	26.7	42.7	14.8	0	0	14.5	0	0	0	0	0	1.3	0	0	0
Kim2.WRD3	17.6	54.9	13.9	0	0	0	0	4.9	0	7.8	0	0.9	0	0	0
Kim3.Carb	29.6	9	0	13.5	0	0	0	0	0	9.6	0	0	38.3	0	0
Kim3.Cal	11.2	2.6	0	0	4.9	0	0	0	0	79.8	0	1.5	0	0	0
Kim3.Las	31.1	12.9	2.2	20.3	0	0	0	0	2	0	0	0	31.4	0	0
Kim3.QSH	36.1	9.8	3.2	21.3	0	0	0	0	0	0	0	0.8	28.8	0	0
Kim3.CRDW	4.4	0	0	0	4.7	0	0	0	0	90.1	0	0.8	0	0	0
Kim3.CRDB	0	0	22.7	0	0	0	0	0	0	0	52.4	21.6	3.3	0	0
Kim3.FRD1	10.9	0	4.1	0	19.3	0	0	0	0	0	2.6	27.2	31.1	0	5
Kim3.FRD7	8.2	0	0	0	0	0	0	0	0	30	4.8	56.9	0	0	0
Kim3.FRD8	0	0	0	0	14.2	0	0	0	0	29.4	32.8	13	0	0	10.6
Kim4.FRD	0	28.3	14.3	0	13.4	4.2	11.2	0	0	0	28.5	0	0	0	0
Kim4.CRD	7.2	32.5	10.2	0	20.4	0	0	0	0	0	0	0	29.7	0	0
Voo.GMS	33.6	36.4	0.7	0	0	0	0	0	0	0	0	29.2	0.1	0	0
Voo.YMS	37.5	37.2	20.1	3.4	0	0	0	0	0	0	0	1.8	0	0	0
Voo.FRD	0	55.7	0	13.7	2.9	0	0	0	0	0	0	27.8	0	0	0
Voo.CRD	0	71.4	0	0	25.8	0	0	0	0	0	0	2.9	0	0	0
Voo.Bas	4.6	50.8	0	9.3	19.8	0	0	0	0	0	0	15.4	0	0	0

ANNEXURE G: Mineralogy – Primary Vs Secondary (WT%)

	Primary Mineral	Secondary Mineral
Kof.S	62.6	37.4
Kof.F	62.6	37.3
Kof.C	60.9	39.1
Kim2.UGW	43.1	56.9
Kim2.CRD	50.7	49.2
Kim2.FRD	66.4	33.5
Kim2.WRD1	97.8	2.2
Kim2.WRD2	84.2	1.3
Kim2.WRD3	91.3	8.7
Kim3.Carb	78.5	47.5
Kim3.Cal	21.7	74.1
Kim3.Las	66.5	33.4
Kim3.QSH	70.4	29.6
Kim3.CRDW	10.9	89.1
Kim3.CRDB	22.7	77.3
Kim3.FRD1	65.4	65.9
Kim3.FRD7	8.2	91.7
Kim3.FRD8	14.2	85.8
Kim4.FRD	71.4	28.5
Kim4.CRD	70.3	29.7
Voo.GMS	70.7	29.3
Voo.YMS	98.2	1.8
Voo.FRD	58.6	41.5
Voo.CRD	97.2	2.9
Voo.Bas	84.5	15.4

ANNEXURE H: Chemical Composition (ppm)

	Mo	Zr	Sr	U	Rb	Th	Pb	Au	Se	As	Hg	Zn	W	Cu	Ni	Co	Fe	Mn	Cr	V	Ti	Sc
Kof.S	0	362	1058	0	67	9	17	0	0	0	0	87	134	55	1498	0	118775	1569	804	125	9709	181
Kof.F	0	272	934	0	71	10	16	0	0	8	0	77	242	54	827	259	108727	1291	584	143	9393	242
Kof.C	0	275	534	0	77	17	21	0	0	12	0	95	231	70	490	0	106126	1089	355	123	7198	115
Kim2.UGW	0	87	122	0	47	8	29	0	0	0	24	124	748	89	225	260	67560	3520	359	83	4244	516
Kim2.CRD	0	226	833	0	70	15	0	0	0	9	0	78	136	74	1414	324	125973	2183	1129	151	8224	209
Kim2.FRD	0	232	668	0	70	12	0	0	0	8	0	114	88	97	950	299	119146	1990	861	153	8066	245
Kim2.WRD1	0	371	237	0	94	29	40	0	0	0	0	259	651	100	362	399	111608	1519	314	159	9050	0
Kim2.WRD2	0	196	182	0	70	14	19	0	0	8	18	115	779	56	200	0	105002	1952	187	173	7185	115
Kim2.WRD3	0	261	393	0	75	17	19	0	0	11	23	89	612	118	484	342	87648	1286	449	98	7017	187
Kim3.Carb	8	262	225	0	114	25	183	0	0	151	0	129	74	419	315	430	139523	2603	289	172	8584	0
Kim3.Cal	0	245	672	0	39	0	15	0	0	0	0	0	333	37	150	137	24809	468	0	92	1814	500
Kim3.LAS	8	386	99	14	147	28	12	0	0	21	0	107	123	114	221	284	116664	1308	286	187	10937	0
Kim3.QSH	0	286	371	0	136	31	24	0	0	35	0	194	95	61	230	0	110033	961	184	167	6645	0
Kim3.CRDW	0	169	666	0	29	9	13	0	0	12	0	30	161	42	804	258	67594	1694	859	114	9566	689
Kim3.CRDB	0	262	813	0	54	11	16	0	0	0	0	73	0	58	1350	383	115841	1722	1550	161	13096	261
Kim3.FRD1	0	289	788	0	57	12	9	0	0	14	0	78	253	60	1322	357	110538	1828	1426	148	13191	198
Kim3.FRD7	0	261	916	0	45	9	16	0	0	15	0	68	184	84	1421	360	110966	1915	1873	143	17139	242
Kim3.FRD8	0	191	626	0	31	0	0	0	0	9	0	60	0	36	1299	379	107538	1141	1068	176	8066	285
Kim4.FRD	0	219	647	0	77	8	8	0	0	0	0	85	80	100	1042	441	118683	2049	1361	184	21384	293
Kim4.CRD	8	210	643	0	74	0	17	0	0	0	0	83	178	65	795	329	115780	1885	1005	145	11363	292
Voo.GMS	0	437	414	0	154	22	30	0	0	10	0	98	0	0	0	0	62041	403	179	99	7846	0
Voo.YMS	0	449	350	0	124	17	33	0	0	0	0	83	0	0	102	0	51818	972	117	103	7267	0
Voo.FRD	0	364	936	0	75	0	0	0	0	8	0	100	0	117	460	417	140615	2298	507	194	12625	294
Voo.CRD	0	286	670	0	57	8	0	0	0	0	0	106	105	141	382	405	141138	2398	342	232	12251	284
Voo.Bas	0	268	527	0	39	0	0	0	0	7	0	101	120	182	320	0	153097	2544	227	270	12839	258

ANNEXURE H: (CONTINUED)

Ca	K	S	Ba	Cs	Te	Sb	Sn	Cd	Ag	Pd	Nb	Bi	Re	Ta	Hf	Al	P	Si	Cl	Mg
70260	20071	6264	1073	53	0	0	0	0	0	0	117	0	0	0	0	60137	2536	555172	0	149866
75561	21395	4963	843	50	43	34	24	0	0	0	69	0	0	0	0	78855	2898	559717	0	132398
38029	19434	4018	1110	92	104	38	27	0	0	0	50	14	0	0	0	115165	2619	617831	0	84642
294805	22433	7858	1065	128	155	67	41	0	0	0	8	0	0	0	0	59879	0	433552	0	101962
101478	20137	3872	1238	91	127	0	18	0	0	0	135	0	0	0	0	52232	2189	500104	0	177329
115725	23529	7090	774	27	0	0	0	0	0	0	116	0	0	0	0	57013	2856	492079	271	167520
41520	32904	12552	1211	87	90	40	32	0	0	0	46	25	0	0	0	114478	980	609685	0	61142
71358	22156	4072	640	57	80	35	0	0	0	15	15	0	0	0	0	105376	0	637742	0	42172
90794	24381	4054	923	55	58	0	22	0	0	0	48	15	0	0	0	84993	1609	601572	0	92346
59010	24745	5741	1475	102	115	53	29	0	0	17	23	21	0	0	0	127482	1395	593724	0	32562
405093	11018	4229	767	78	83	0	23	20	0	0	17	0	0	0	0	34377	0	416512	0	98472
7006	32511	2771	1584	61	69	32	26	0	0	0	35	27	0	0	0	149577	2252	644968	0	28135
9961	31154	2828	1700	65	79	35	23	0	0	0	32	28	0	0	0	139173	2298	666340	0	26833
330623	11363	3032	1395	62	65	0	0	0	0	0	87	0	0	0	0	37981	1668	353176	0	177839
77456	15286	6672	878	29	0	0	0	0	0	0	125	0	0	0	0	44995	1611	505323	0	211973
82092	14114	11268	1251	34	0	0	0	0	0	0	134	0	0	0	0	47480	1317	532257	506	178979
105171	12004	6692	1455	36	0	0	0	0	0	0	158	0	0	0	0	37574	1094	485619	0	214540
131792	8032	4229	589	0	0	0	0	0	0	0	102	0	0	0	0	38709	792	510295	214	184345
110006	17102	2942	1207	68	0	0	0	0	0	0	152	0	0	0	0	41521	2715	465596	0	212031
101068	18588	3450	1058	52	53	0	0	0	0	0	99	0	0	0	0	53849	2966	505252	0	180694
14290	39155	2706	394	0	0	0	0	0	0	10	29	23	0	0	0	110381	0	751938	0	9343
28486	31845	2151	1959	13	0	0	0	0	0	0	27	15	0	0	0	108096	870	750833	0	14270
118987	29047	3842	1644	60	76	0	18	0	0	0	63	0	0	0	0	87898	5169	506702	0	87485
112851	23192	4217	1927	128	146	51	36	0	0	21	36	0	0	0	0	104753	4186	515689	0	73963
101904	16067	3355	1301	108	133	60	39	0	0	0	24	0	0	0	0	106501	2638	535498	0	61574