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Comparative study of established test methods for aggregate strength and durability of Archean rocks from Botswana

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ABSTRACT

Comparative study of established test methods for aggregate strength and durability of Archean rocks from Botswana

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In the current situation, river sand is used for building of roads and as raw material for concrete in Botswana. River sand is a finite resource and important to preserve as it acts as natural water purification, groundwater aquifer and protection against soil erosion. Mining of bedrock may be a good alternative to replace the river sand with crushed rock (aggregates) in concrete and as road materials.

The main purpose of this thesis was to determine if the rock grain size can be used as a parameter to indicate durability and rock strength. It was also of interest to find out if the grain size correlates with established technical analysis and strength test methods. This knowledge can be used as a prospecting tool when searching for new quarry sites in the future.

In this master's thesis, rock samples from the Gaborone granite complex have been analysed to examine how established test methods and the mineral grain size corresponds with the rock strength. By comparing technical properties (Los Angeles (LA) value , aggregate crushing value (ACV), aggregate impact value (AIV) and 10 percent fines aggregate crushing test (10 % FACT)) with quantitative analysis (mineral grain size and mineral grain size distribution), it is possible to determine the mineral grain size correspondence to rock strength. Generally the result show that more fine-grained granites show better technical properties than more coarse-grained granites. The calculated mean grain size show weak negative correlation to ACV value, and a positive correlation to LA-, AIV- and 10 % FACT values. Best correlation can be seen between mean grain size and LA values (R^2= 0.61) and AIV values (R^2= 0.58). Low mean grain size tend to give better technical properties in form of lower LA- and AIV values. The cumulative distribution curve show that a high concentration of very fine material or fine material tend to contribute to a lower LA value. The results indicate that equigranular rocks with low mean grain size contributes to good technical properties, but when it comes to uneven grained rock more factors must be taken into account to estimate technical properties.

Keywords: Los Angeles value, Aggregate crushing value, Aggregate impact value, 10 percent aggregate crushing value test, mean grain size, mean grain size distribution

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REFERAT

Jämförande studie av etablerade testmetoder för ballastmaterials styrke- och hållbarhetsegenskaper hos Arkeiska bergarter i Botswana

Jessica Stålheim

I dagsläget används flodsand i Botswana vid byggnation av vägar samt råmaterial för betongkonstruktioner. Flodsand är en ändlig resurs och viktig att bevara då den med nuvarande brytningstakt kommer att försvinna inom ett årtionde. I vissa områden utgör sanden dessutom en akvifär för grundvatten. Ett alternativ till den viktiga flodsanden är att ersätta denna med krossat berg (aggregat).

Huvudsyftet med detta examensarbete var att undersöka om bergets kornstorleken kan användas som parameter för att indikera ballastmaterialets styrke- och hållbarhetsegenskaper. Det är också av intresse att undersöka om kornstorleken korrelerar med redan etablerade styrketestmetoder. Denna kunskap kan användas som prospekteringsverktyg för att hitta lämpliga bergtäkter i framtiden.

I detta examensarbete har bergartsprover från Gaboronegraniten analyserats för att bestämma hur bergkrossmaterialets styrka påverkas av bergets kornstorleken. Genom att jämföra tekniska egenskaper (Los Angeles (LA) value, aggregate impact value (AIV), aggregate crushing value (ACV), 10 percent fines aggregate crushing test (10 % FACT)) med kvantitativa analyser (kornstorlek och kornstorleksfördelning) för graniterna så kan kornstorlekens betydelse för dessa parametrar bestämmas. Resultaten visar generellt att mer finkorniga graniter uppvisar bättre tekniska egenskaper än mera grovkorniga. Den uträknade medelkornstorleken för granitproverna visar negativ svag korrelation med ACV-värderna, och positiv korrelation med LA-, AIV- och 10 % FACT-värdena. Bäst korrelation visar medelkornstorleken med LA-värdena (R^2= 0,61) och AIV-värdena (R^2= 0,58). Låg medelkornstorlek tenderar att ge bättre tekniska egenskaper i form av lägre LA- och AIV-värden. Kumulativa distributionskurvor påvisar att hög andel mycket fint eller fint material i granitproven tenderar bidra till ett lägre LA-värde. Resultaten visar att jämnkorniga bergarter med finare kornstorlek generellt bidrar till bra tekniska egenskaper, men för ojämnkorniga bergarter spelar fler faktorer in för de tekniska egenskaperna.

Nyckelord: Los Angeles value, Aggregate crushing value, Aggregate impact value, 10 percent aggregate crushing value test, medelkornstorlek, kumulativ distribution

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PREFACE

This master's thesis is the last part of the Master of Science program in Water and Environmental Engineering of 30 ECTS at Uppsala University. It started in April 2013 and was performed during the summer. The major part of the thesis was carried out in Uppsala, Sweden, one week was spent in Botswana doing field studies and three days was spent at CBI Betonginstitutet (CBI) in Borås performing microscopic analysis. The thesis was made in cooperation with Sveriges Geologiska Undersökning (SGU) and CBI, and was a part of MeetingPoints Mining (MPM) project in Southern Africa financed by SIDA (Swedish International Development Agency). The supervisors of the thesis was Mattias Göransson at SGU and Karin Appelquist at CBI. The subject reviewer was Karin Högdahl at the Department of Earth science at Uppsala University. In order to evaluate the obtained results from the performed measurements complementary data were needed. This data were supplied by several people at the Geological survey of Botswana (DGS) in Lobatse.

I would like to express my special thanks and gratitude to my supervisor Mattias Göransson for all geological knowledge, review of the report and all the help and guidance he has given me during this time. I also thank my co-supervisor Karin Appelquist for her guidance and assistance with the microscopic analysis at CBI, and her review of the report. Jan-Erik Lindqvist, thanks for your help with the 3D distribution at CBI. A special thanks to Karin Högdahl who critically examined my report and helped me improve my thesis. In addition, I would like to thank all the people from SGU and DGS for sharing their expertise before, during and after the trip to Botswana. Thank you for an interesting and valuable stay, this thesis would not have been done without your guidance and help.

POPULÄRVETENSKAPLIG SAMMANFATTNING

Botswana är en av de snabbast växande ekonomierna i världen och runt huvudstaden Gaborone pågår ett ständigt byggande av fler bostäder och bättre vägar. Även fast Botswana består av 70 % öken råder det brist på rätt sandmaterial för ballast i betong och vägar. Ökensanden är för finkornig för att kunna används som betongmaterial och därför oanvändbar. I dagsläget tas sand från Botswanas floder och används som ballast i betong. Denna sand fungerar väldigt bra som betongmaterial men den är en ändlig resurs som kommer att ta slut inom ett årtionde om samma byggnadstempo hålls. Flodsanden bör även bevaras av miljömässiga skäl och för att Botswana ska kunna fortsätta sin utvecklingstakt även om tio år krävs en lösning på ballastproblemet. En lösning på problemet är att krossat berg kan ersätta flodsanden och på så vis kan utvecklingen av Botswana fortsätta.

MeetingPoints Mining med ekonomisk finansiering av SIDA håller i dagsläget på att kartlägga Botswanas berggrund för att finna lämpliga platser för att bryta berg. Olika bergarter har skilda egenskaper när det gäller styrka och hållbarhet och är därför olika lämpade som användning i ballast. För att ta reda på om en bergart är lämpad som ballastmaterial har en rad etablerade styrketester utförts på 28 graniter av den geologiska undersökningen i Botswana.

Huvudsyftet med detta examensarbete är att undersöka om mineralkornstorleken hos en bergart kan användas som indikator för att uppskatta ett bergmaterials styrke- och hållbarhetsegenskaper. Tidigare studier tyder på att en mindre medelkornstorlek ger ett starkare bergsmaterial än berg med större medelkornstorlek.

I detta examensarbete har 28 bergartsprover från Gaboronegraniten analyserats. Styrketestmetoderna som dessa granitprover genomgått är Los Angeles value test (LA), aggregate impact value test (AIV), aggregate crushing test (ACV) och 10 percent fines aggregate crushing value test (10 % FACT). För varje prov finns även data för grain densitet samt vattenabsorption. Alla prover har tyvärr inte resultat från alla styrketester. Av dessa 28 bergartsprover har sex prover även genomgått en petrografisk analys där mineralinnehåll och textur bestämts, samt en mineralkornstorleksfördelning. Mineralkornstorleksfördelningen delar in kornen i olika storleksintervall så det blir möjligt att se hur många procent av kornen som är fin-, medel-, respektive grovkorniga. Genom att jämföra de tekniska styrkeparametrar med kvantitativa analyser såsom mineralkornstorlek och mineralkornstorleksfördelning så kan kornstorlekens betydelse för dessa parametrar bestämmas.

Resultaten visar generellt att mer finkorniga graniter uppvisar bättre tekniska styrkeegenskaper än mera grovkorniga graniter. Medelkornstorleken korrelerar bra med både LA-värdena (R^2= 0,66) och AIV-värdena (R^2= 0,58). Låg medelkornstorlek tenderar att ge bättre tekniska egenskaper i form av lägre LA- och AIV-värden. Fördelingen av mineralkornen visar att hög andel väldigt fint eller fint material i granitproven tenderar att bidra till ett lägre LA-värde. Resultaten visar att bergarter som är väldigt jämnkorniga och finkorniga generellt bidrar till bra tekniska egenskaper hos ballastmaterialer, men för ojämnkorniga bergarter spelar fler faktorer in än kornstorlek för de tekniska egenskaperna. Kornstorleken kan alltså ge en grov uppskattning om bergets tekniska egenskaper och kan på så vis användas som indikator för att hitta lämpliga platser att bryta berg för ballast. Det är dock rekommenderat att utföra någon slags mikroskopisk undersökning innan beslut fattas eftersom endast makroskopisk bedömning är osäker.

WORDLIST

10 % FACT	Ten percent fines aggregate crushing test.
ACV	Aggregate crushing value.
Aggregates	Crushed rock.
Inselberg	An isolated hill or small mountain that rises abruptly from a gently sloping or virtually level surrounding plain. Erosion remnant from an earlier mountain-range.
AIV	Aggregate impact value .
Archean	Geologic eon 2500-4000 million years ago.
CBI	The Swedish Cement and Concrete Research Institute (CBI).
DGS	Department of Geological Surveys – Republic of Botswana.
Equigranular	An equigranular rock is mainly composed by mineral of equal size.
Felsic	A felsic rock is dominated by quartz and feldspar.
Fennoscandian shield	The Fennoscandian shield is a stable rock area composed by rocks of Precambrian age.
Granophyre	Subvolcanic rock type.
Hydrothermal	Hydrothermal alteration is the result of the interaction of a rock with a high-temperature fluid.
LA	Los Angeles value.
Matrix	The Matrix is a fine grained mass of material which contain significantly larger embedded grains.
MPM	MeetingPoints Mining
Permian	The Permian is a geologic period which extends from 299 to 252 million years ago.
Porphyritic	A porphyritic rock has a distinct difference in the size of the crystals, with at least one group of crystals obviously larger than another group, phenocrysts.
Proterozoic	Geologic eon 542-2500 million years ago.
QAP	Quartz, Alkali feldspar, Plagioclase.
Sericite	Sericite is a fine grained mica of Orthoclase or Plagioclase feldspars.
SGU	Sveriges Geologiska Undersökning; Swedish geological survey.
Syenogranite	Granite poor in quartz.
Transvaal supergroup	Sedimentary rocks of an age of 2600 to 2065 million year located in northern South Africa and southern Botswana.
Waterberg-formation	Red sandstones of an age of 2045 to 1990 million years located in northern South Africa.

Contents

1 INTRODUCTION

Sand and gravel are the basic materials used in most construction projects such as roads. In Botswana the major raw material for road construction is the local river sand. Due to poor, annual inflow of sand and the urban development of the capital Gaborone area has escalated, the few resources that exist today are decreasing rapidly. Consequently, rivers are eroding and may cause significant damage to the environment and delicate ecosystems. To supply the society with a proper raw material for building the transport distance increases each year with the result of higher costs and higher carbon dioxide releases. A major change from the use of river sand to crushed rock (aggregates) is urgently needed in the near future to prevent a halt in development due to lack of material.

MeetingPoints Mining (MPM) has been working together with the Department of Geological Survey of Botswana (DGS) since 2010 in order to find appropriate aggregates in Botswana for roads and concrete in building structures. The main focus of the MPM-project, of which one is the area of Greater Gaborone, is to put forward suitable quarry locations. A systematic sampling of dominating rocks of the Gaborone area has been completed. According to national requirements of aggregates, a set of different test methods have been established and performed to evaluate the proper use of the sample material. Strength test methods that have been carried out in this project include Los Angeles (LA) value test, aggregate crushing value (ACV) test, aggregate impact value (AIV) test and 10 percent fines aggregate crushing value test (10 % FACT). Descriptions for all rock samples are based on field observations, study of rock samples and microscopy analysis. As strength properties of aggregates in most cases are crucial requirements for the end use, a proper understanding of the underlying, geological parameters will be very helpful for societal planning. The results of the analysis will determine whether granite is suitable as aggregates for road.

The main purpose of this thesis is to determine if the grain size can be used as a parameter to indicate durability and aggregate strength. It was also of interest to investigate how established technical analysis correlate with each other and quantitative analysis as mineral grain size, mineral distribution and mineral content. This knowledge can be used as a prospecting tool when searching for new quarry sites, and assess whether the local granite rock samples in this study are suitable as aggregate for road construction.

As earlier studies have pointed out, the grain size and the grain size distribution are important parameters for explaining the mechanical properties for aggregates derived from rock material of different status (Åkesson, et al,. 2001). In general a more fine-grained rock is stronger than a coarse grained one (Lundqvist and Göransson, 2001). Earlier studies are comparing different rock types, but in this thesis a "single-rock type" study has been performed comparing only granites.

2 GEOLOGICAL BACKGROUND AND SAMPLING

The investigation area is located in the greater Gaborone (Fig. 1). The river sand resources are decreasing rapidly and every day means longer transport to supply the infrastructure development in greater Gaborone. Today the sand is collected from the Serowe area, a transport distance of almost 200 km. The price for one tonne sand has doubled due to the transport distance from Gaborone, and will increase further as the collection of river sand goes farther and farther up north.

Figure 1: Map over Botswana.

2.1 REGIONAL GEOLOGY

Most of the basement rocks in the area of Gaborone belong to the Kaapvaal Craton which is an ancient stable segment that also is found in the northern parts of South Africa and southern Zimbabwe. The Kaapvaal domain consists of old Archean metamorphic gneisses and felsic volcanic rocks, the Kanye Volcanic both intruded by granites and minor gabbros, the Gaborone complex. The gneisses are suggested to be the country rock to the younger Archean, intrusive igneous rocks, the Gaborone granite complex. The Archean basement is covered by the Proterozoic, Waterberg- and Vendertorps-formation, and younger non-metamorphic sedimentary and volcanic supracrustal rocks. Locally the older rocks have been intruded in Perm by ultramafic to felsic igneous complexes, sills and dykes.

2.2 GEOLOGY OF THE GABORONE GRANITE

A major part of the bedrock in the Gaborone area consists of the Gaborone granite complex. This granite pluton of south east Botswana and adjacent parts of South Africa has a surface area of over 5000 km^2 (Key and Wright, 1982). Several varieties, regarding grain-size, exist within the complex. The whole granitic complex is believed to have been formed from a single, highly viscous magma emplaced at a high crustal level (Key and Wright, 1982) at about 2780 Ma (Moore, et al,. 2002). The central part of the complex consists of a coarse grained, in some places mantled rapakivi textured granite (Thamaga granite), (Fig. 2). The Thamaga granite is similar to the Fennoscandian rapakivi granites.

The dominating rapakivi textured granite is surrounded by successive shells of more fine-grained rocks of granitic composition. An equigranular, medium-grained granite (Kgale granite) (Fig. 2), a small-porphyritic granophyre (Ntlhantlhe granite) and an aphanitic felsic volcanic rock (Kanye volcanics). The Gaborone granite, especially the Kgale and the Ntlhantlhe type, is highly enriched in quartz and microcline. It is quite common for semi-arid regions that sole hills, inselberg, that persists the weathering better than its surrounding, is highly enriched in microcline. As pointed out by Pye (1986), if "other things being equal, microcline and quartz enriched granitoid rock weather more slowly than their less microcline counterparts", for example tonalities. For this reason, rocks like the Gaborone granite most likely will stand out as an alternative material to river sand as a commodity for road constructions.

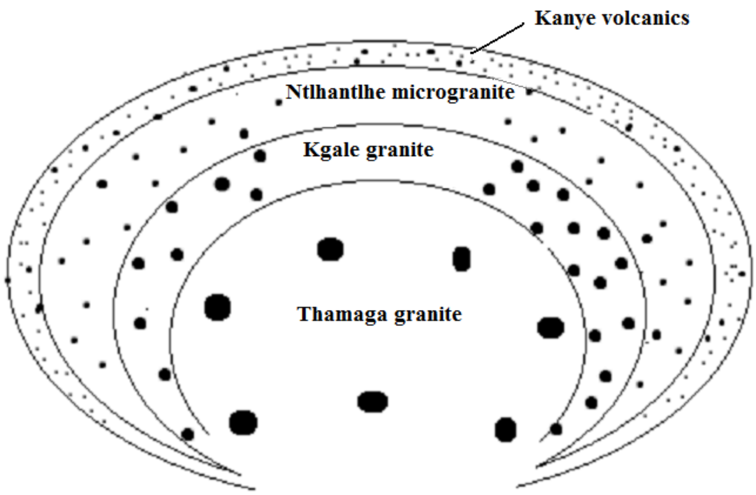


Figure 2: Gaborone granite complex. Illustrative image of the magma body. Modified from Key & Wright (1982).

2.2.1 Thamaga granite

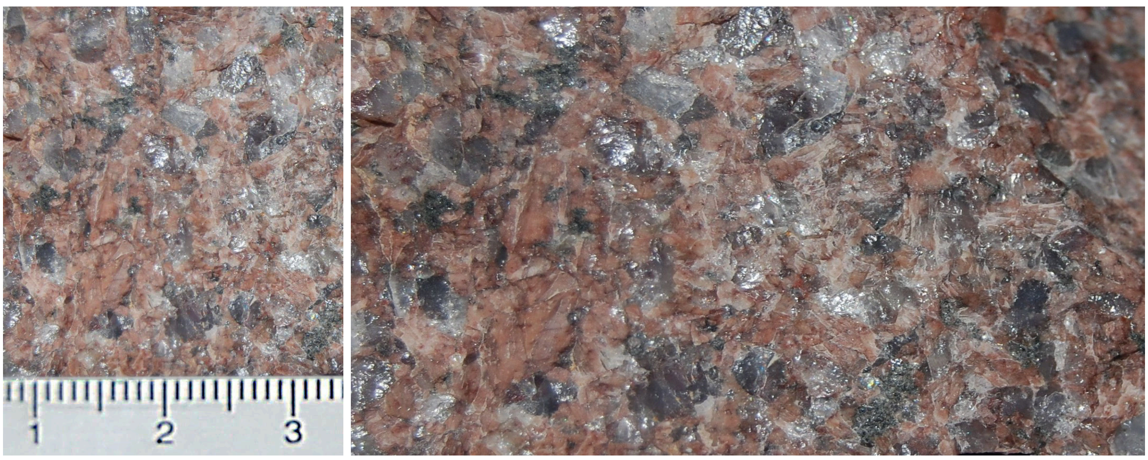
Thamaga granites consist of coarse grained, porphyritic rapakivi textured granites and subordinate microgranites. The ground mass of the porphyritic granophyres and micro-granite accords mostly with the interior Thamaga granite (Key and Wright, 1982) although the latter contain more mafic minerals (Fig. 3a). The petrography of the Thamaga granite is very complex. Feldspar occurs either in the ground mass or as phenocrysts and contains microcline microperthite and albitic plagioclase (Key and Wright, 1982). The phenocryst varies considerably in size but rarely exceed 2 cm in length and the shape range from tabular to ovoidal (Fig. 3b). The Thamaga granite has a similar texture as the Kgale granite except for the lack of regular lamellar intergrowths and the occurrence of zonal plagioclase.

(a) (b)

Figure 3: a) Thamaga granite, coarse-grained. b) Mantled phenocryst about 2 cm length.

2.2.2 Kgale granite

The leucocratic Kgale granite is an equigranular, homogeneous, medium-grained granite commonly with phenocrystal quartz in the peripheral parts of the granites (Fig. 4a). The Kgale granite has similar mineralogy as the Thamaga granite consideration of both main and accessory minerals, but in different proportions (Key and Wright, 1982). Quartz and feldspar together constitute 96-98 vol. % (Key and Wright, 1982) and other minerals, such as muscovite, biotite, sercite, chlorite, zircon, apatite, flourite and opaque phases are mainly of small portions. Quartz may constitute more than 40 % (Key and Wright, 1982) of the rock and occurs as granular individuals with round, ovoidal, subhedral to euhedral forms (Fig. 4b). Feldspar occurs mostly as microcline host grains with intergrowths of small albite crystals, microperthite. The fine-grained peripheral parts of the granite contains regular and inter growths of feldspar in porphyritic granophyres. In the inner coarse-grained granite, the perthitic plagioclase occurs irregularly in patches, braided nets, veins and stripes (Key and Wright, 1982).

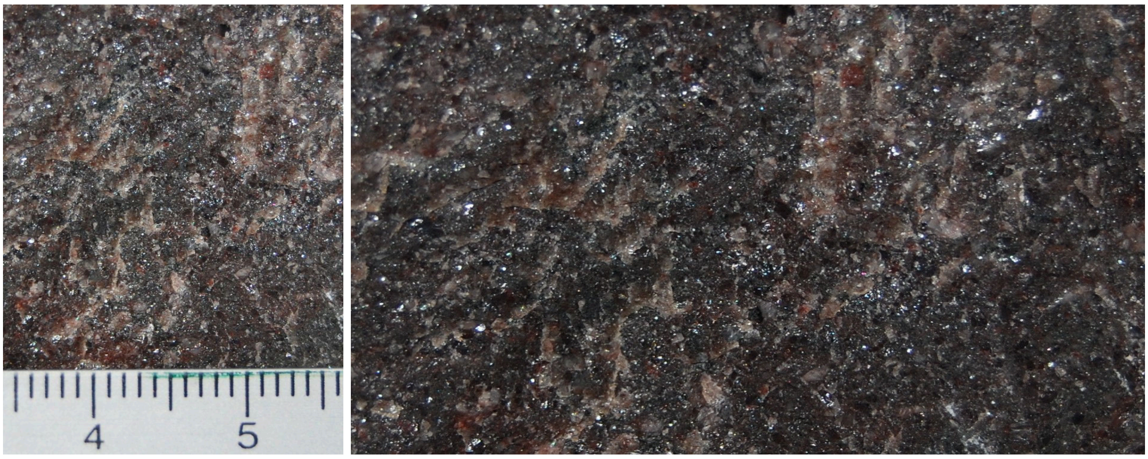


(a) (b)

Figure 4: a) Kgale granite, medium grained. b) Kgale granite close up.

2.2.3 Ntlhantlhe Microgranite

The Ntlhantlhe Microgranite represents a border zone between the Kgale granite and the Kanye Volcanics, it is rarely very persistent, usually less than 20 meters but can sometimes be up to 80 meters wide. Just over a few meters the felsites changes into the Ntlhantlhe Microgranite (porphyritic granophyre or microgranites) and the texture of the rock becomes more granular and often complemented with feldspar phenocrysts. The phenocrysts are randomly oriented and up to 5 mm in length (Fig. 5a and Fig. 5b) and occasionally include pyroxene (Key and Wright, 1982).



(a) (b)

Figure 5: a) Microgranite, fine-grained. b) Microgranite close up.

2.2.4 Kanye Volcanics

Kanye Volcanics are rhyolites (felsites) comprising strongly jointed, homogeneous fine-grained to aphanitic rocks with sporadic feldspar phenocrysts (Key and Wright, 1982). The thickness of the Kanye Volcanics is unknown but has an estimated range of between 500 and 1300 m (Moore, et al., 2002). The Felsite shows feldspar phenocrysts which are heavily jointed and corroded, and often with a marked elongation (Fig 6). The Felsitic ground mass shows bands and streaks of intersected mineral aggregates consisting combinations of quartz, feldspar, biotite, calcite, opaque phases, leucoxene, titanite, apatite and zircon (Key and Wright, 1982).

Figure 6: Felsite, very fine-grained. Photo Mattias Göransson, SGU.

3 METHODS

3.1 SAMPLING AND MACRO ANALYSIS

Granites were collected from 28 different sites in the Gaborone granite complex by the Geological survey of Botswana (DGS). Approximately 80 kg of fresh, non-weathered rock boulders were collected from each site using a sledgehammer and an iron-rod. Every sample is connected to specific gps-coordinates and has been given a name according to the nearby local village name. A macro description for every sample site was done by DGS and contain description of the grain size divided into fine-, medium-, and coarse-grained rock (fine grained < 1.0 mm, medium grained = 1.0 - 5.0 mm, coarse grained > 5.0 mm), as well as a description of the color, obvious minerals and textures. A macro description describes what has been observed in field with no microscopical analysis. The granites were divided into the four Gaborone granite complex varieties of granites, regarding grain-size (Thamaga granites, Kgale granites, Ntlhantlhe Microgranite and felsites from Kanye Volcanics).

Six granite samples were selected from the 28 samples for closer examinations regarding mineral grain size distribution analysis (Fig.7). These samples were chosen due to already existing thin-section and modal analysis from each sample site. The selected samples are located within the Gaborone granite complex, see coordinates in Table. 1. One sample is located in Letlhakane area (LTKWF1), one sample in Bokaa (BKGR1), two samples in Fikeng (FKNGR1 and FKNGR2) and two samples in Kgomokasitwa (KMSTGR1 and KMSTGR2). The samples represent different varieties of felsite, Kgale granite and Nthantlhe microgranite. Unfortunately no Thamaga granite is within the selected sample sites due to too few technical data of AIV, ACV, LA and 10 % FACT.

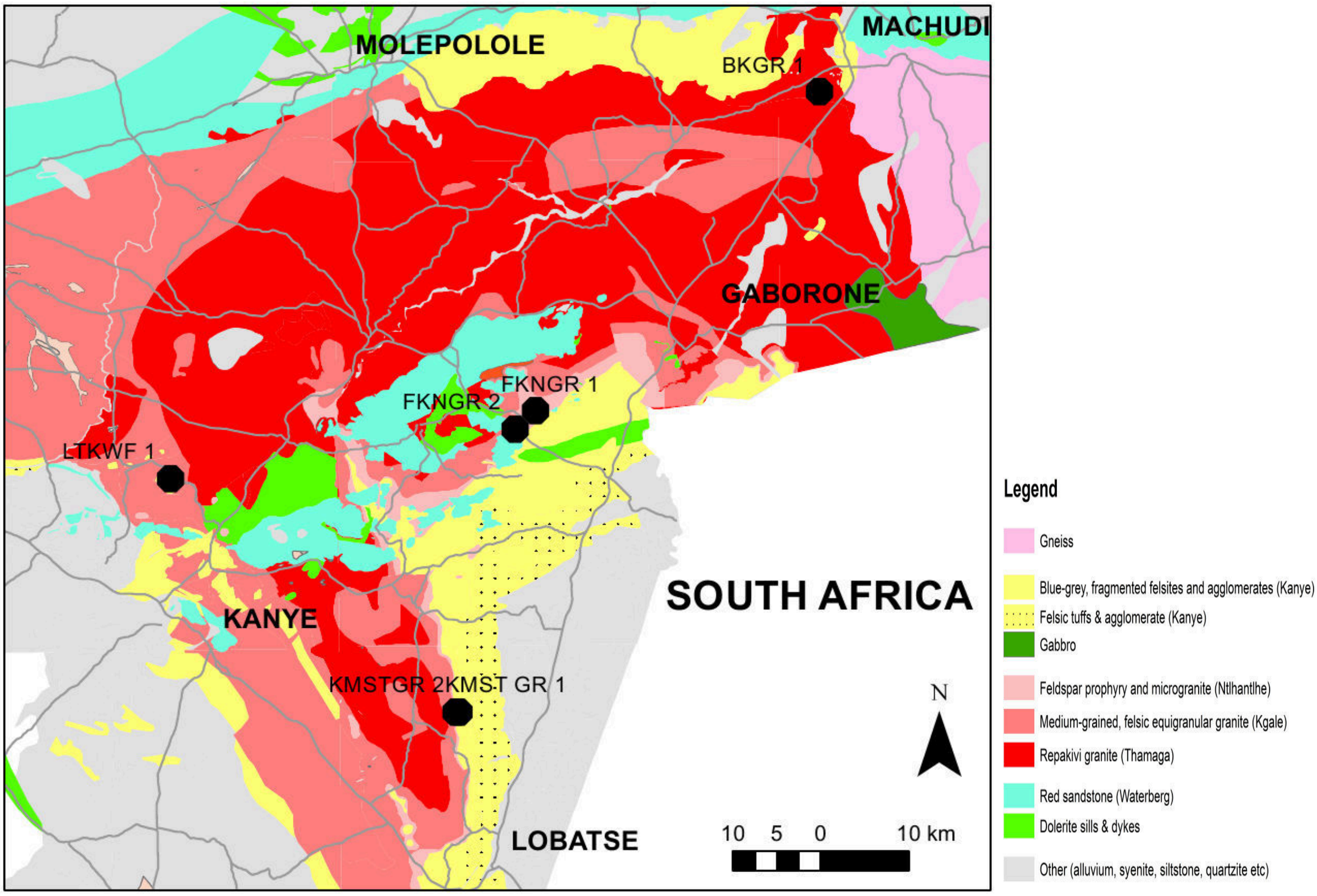


Figure 7: Bedrock map over Gaborone area. The figure show the location of the six selected granites.

Table 1: Locality name, sample codes and coordinates.

Locality name	Sample code	Granite type	Coordinates	
			Latitude	Longitude
Letlhakane	LTKWF 1	Felsite	-24.823	25.312
Bokaa	BKGR 1	Kgale granite	-24.432	26.047
Fikeng	FKNGR 1	Kgale granite	-24.758	25.724
Fikeng	FKNGR 2	Kgale granite	-24.776	25.701
Kgomokasitwa	KMSTGR 1	Kgale granite	-25.066	25.632
Kgomokasitwa	KMSTGR 2	Microgranite	-25.066	25.634

3.2 TECHNICAL ANALYSIS

It is essential to be able to assess the quality of the rock material and thereby its suitability for use as aggregates for road construction. This is done by examining the technical properties of the rock through standard methods. This study is focused on technical analysis which are used for quantitative evaluation of aggregate quality for road construction. The technical methods are described below and all technical analyses except aggregate crushing value test and 10 percent fines aggregate crushing test have been carried out by

DGS in their laboratory. The ACV and 10 % FACT have been carried out in a commercial laboratory. All technical analysis described are approved methods and included in the national transport administrations requirements for aggregates in different parts of the world. However, only the Los Angeles value test is still being used in Sweden and the European Union.

3.2.1 Aggregate impact value test (AIV)

Aggregate impact value test correspond to the aggregates toughness to resist breaking into smaller pieces and are carried out according to SANS 6239:2012 (South African national standard, 2012b). Aggregate impact values below 10 are regarded as strong, and aggregate impact values above 35 represent poor technical values and too weak for use in road surfaces. The test sample should be crushed into 10-12.5 mm fractions before the test begin. The aggregate test sample should be oven-dried at a temperature of 100-110^{0}C for four hours. After the sample has been cooled the measure should be about one-third full with the test samples in a cylindrical measure and tamped with 25 strokes of the tamping rod. The tamping rod is a straight metal rod of circular cross section, 10 mm in diameter and 230 mm long, rounded at one end. Further quantity of sample aggregates is then added up to two-third full in the cylinder and further tamping of 25 strokes are given. At last the the cylindrical measure is filled to overflow with test sample and tamped 25 more times with the tamping rod. The tamping rod is used to strike off the excess aggregates and the net weight of the remaining aggregates is measured as m_0. The weight of the aggregates is used to split the aggregates in two identical tests. One of these identical tests samples are then placed in a cup at the base of the machine at a fixed position (Fig. 8a). To complete the tamping procedure the test is tamped with 25 strokes of the tamping rod before a 14 kg hammer is allowed to fall freely on the aggregates for 15 times at a hight of 380 mm the upper surface of the aggregates in the cup. Finally the crushed aggregates are removed and sieved on a 2.36 mm sieve. The aggregates which passed the sieve are weighed as m_1, and the aggregates still on the sieve are also weighed, m_2 . If these two masses together weigh less than the initial weight m_0 by more than 1 gram, a fresh test should be done and the result discarded.

The aggregate impact value is expressed as a percentage of the original mass (Equation 1).

$$AIV = 100 * \frac{m_1}{m_0} \tag{1}$$

3.2.2 Los Angeles value test (LA)

The Los Angeles value reflects the rock's resistance to fragmentation and were carried out according to SANS 5846:2006 (South African national standard, 2006b). Los Angeles values below 15 % are regarded as good and values above 25 % are regarded as poor resistance with regard to fragmentation. The aggregates for the Los Angeles test should be crushed into 10-14 mm fractions before the test begin. For the Los Angeles test it is necessary to have approximately 5 kg of this fraction. The sample is weighed and the weight note as m_0. The test aggregates are placed in the Los Angeles machine all together with 11 steel spheres (390-445 g). After 500 revelations the sample content should be emptied in a bowl and the steel spheres be put out and laid aside. The sample content is now sieved though a 10.0 mm, 6.7 mm and 1.6 mm sieve in a machine shaker for 10 minutes. The content is removed from the sieves, weighed and the weight note as m_1. The Los Angeles value is calculated as a percentage of the original mass of the sample (Equation. 2).

$$LA = \frac{m_0 - m_1}{50} \tag{2}$$

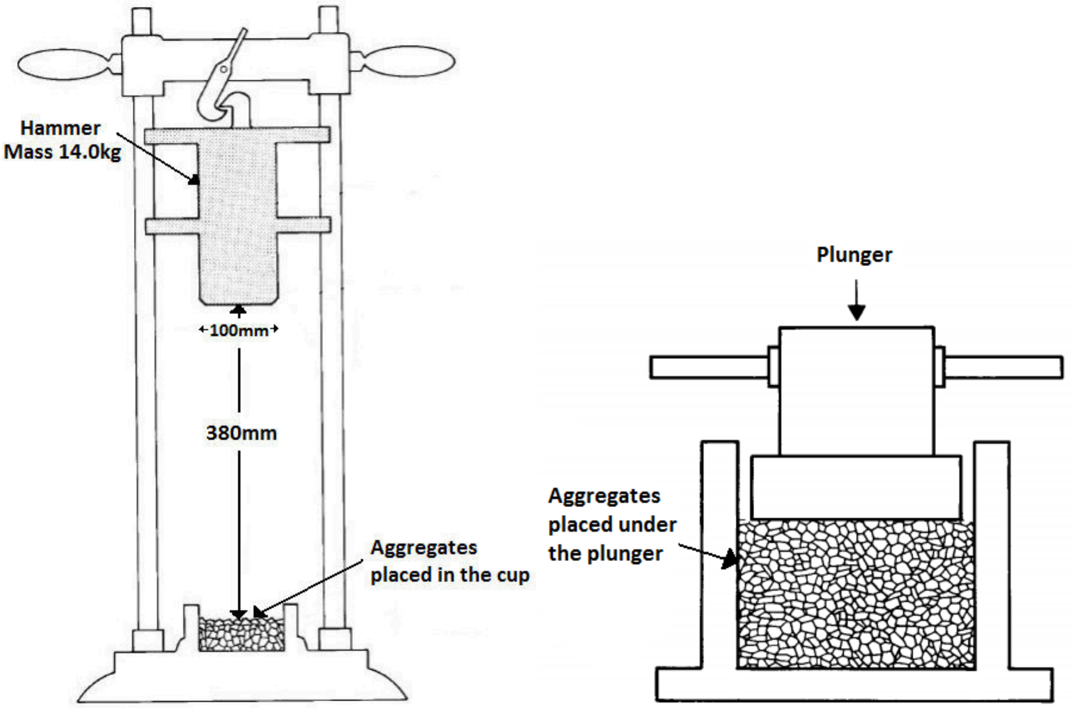
3.2.3 Aggregate crushing value test (ACV)

The aggregate crushing value is a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. The ACV tests were carried out according to SANS 3001-AG10:2012 (South African national standard, 2012a). ACV determines the percent of fines produced under a prescribed load. Low values indicate a more resistant rock and a higher quality of pavement. An aggregates crushing value under 29 is regarded adequate for road materials. The aggregates should be crushed and then sieved through 12.5 mm and retained on 10.0 mm sieve, the sample fraction. The sieved rock aggregates should thereafter be oven dried for 3-4 hours at 100 to 110^0C. After the sample is cooled the weight of the aggregates is measured as m_0. The cylindrical measure apparatus is filled with 3 layers, each layer tamped 25 times of a tamping rod. The apparatus is then placed in the compression testing machine (Fig. 8b). The surface of the aggregates is leveled and the plunger installed. The compression testing machine is loaded to achieve 400 kN in 10 minutes. When this step is done the load is released and the sample is sieved through a 2.36 mm IS Sieve. The aggregates which passed the sieved should be weight and the weight is noted as m_1. Two values are produced for each sample and values should be within a value of 1 (South African national standard, 2012).

The aggregate crushing value is expressed as a percentage of the original mass (Equation 3).

$$ACV = 100 * \frac{m_1}{m_0} \tag{3}$$

To assess the durability of an aggregate the sample is also undertaken an ACV-wet test. The sample undergoes the same procedure as the dry test except that it is immersed in water to make the rock soaked. A wet/dry ratio greater than 75 % indicates satisfactory durability.



(a) (b)

Figure 8: a) Apparatus for the aggregate impact value test, Modified from Millard (1993). b) Apparatus for the ACV and 10 %FACT test. Modified from Millard (1993).

3.2.4 Ten percent fines aggregate crushing test (10 % FACT)

Ten percent fines value is a measure of the resistance of aggregate crushing subject to loading. The 10 % FACT test determines the force necessary to produce 10 % fines and were performed according to SANS 5842:2006 (South African national standard, 2006a). A 10 %$\geq$110 kN is required for base layer for road, and 10 %$\geq$190 kN i required for surface layers. The test is applicable to both weak and strong aggregate. The test is very similar to the aggregate crushing test when a 400 kN force is used and fine aggregates are expressed as a percentage of the original mass. In the ten percent fines value test the aim is to look for the force required to produce 10 % of fine values. Aggregate which passes a 2.36 mm sieve are defined as fine aggregates. The aggregates are crushed, sieved, oven dried and tamped exactly like in the test for aggregate crushing value. The aggregates are weighed after oven drying and the mass note as m_0. The test sample is placed under the compression testing machine, the surface leveled and the plunger installed (Fig. 8b). The load is applied at a uniform rate so as to cause a total penetration of the plunger of about 20 mm for normal crushed aggregates in 10 minutes. After maximum force is reached, the load is released and the aggregates sieved through a 2.36 mm IS sieve. The maximum force in kN are expressed as x. The passing aggregates are weight and the mass note as m_1 and the mean percentage fines from two tests at are expressed as y (Equation 4).To assess the durability of an aggregate the sample is also undertaken a 10 % FACT-wet test. The sample undergoes the same procedure as the dry test except that it is immersed in water to make the rock soaked. A wet/dry ratio greater than 75 % indicates satisfactory durability (South African national roads agency Ltd, 2011).

$$y = 100\% * \frac{m_1}{m_0} \tag{4}$$

Two values are produced for each test and the mean percentage fines should be used in the equation to calculate the force required to give 10 % fines (Equation 5).

$$Force\,required\,to\,produce\,ten\,percent\,fines = \frac{14x}{(y+4)} \tag{5}$$

x = maximum force used (kN)
y = percentage fine aggregates from the test (%)

3.2.5 Grain density

Grain density is a measure of the weight of the aggregates in a unit volume. The grain density were carried out according to SANS 3001-AG20:2011 (South African national standard, 2011). The density for rocks varies approximately from 2.6 g/cm^3 (sandstones, granites) to 3.2 g/cm^3(mafic/black rocks). The test method is based on Archimedes principle. Two samples are needed for density analysis. Each dry sample should weight around 0,5-1 kg, depending on the rock fraction. Note the dry weigh, m_d. Each sample is then placed in a bucket attached underneath the balance. The bucket is then immersed in water until the whole basket is submerged completely. Weight the sample in the water and note the wet weight, m_w. The density (ρ) is calculated as in (Equation 6).

$$\rho = \frac{m_d * 0.998}{m_d - m_w} \tag{6}$$

3.3 WATER ABSORPTION ANALYSIS

This test is done by the SANS 3001-AG20:2011 (South African national standard, 2011), and indicates the water absorption capability of coarse aggregates. The test was carried out by DGS in their laboratory. For this test a minimum of 2 kg is required, two tests must be done and the individual and mean results should be reported. The aggregates have to be washed to remove fine particles and dust and then drained. The aggregate sample is placed in a wire basket and immersed in distilled water at a temperature between 22 and 32 degrees. The entrapped air in and between the aggregates must be removed and this is done by lifting the basket and allow it to drop 25 times in 25 seconds. The aggregates in the basket should remain immersed for a period of 24 + ½ hours afterwards. When this time range is reached, the basket and aggregates are removed from the water and allowed to drain for a couple of minutes. The aggregates are gently surface-dried by a cloth and then change to a new cloth when the first one no longer can remove more moisture. The aggregates should be layed spread on the second cloth in room temperature, away from direct sunlight, until it appears to be completely dry on the surface. The aggregates are weighed and the mass noted as m_0. To obtain the dry weight of the aggregates, the aggregates are placed in an oven of 100 to 120 degrees for 24 hours. It is then removed from the oven, cooled and weighed. The mass is noted as m_1. The water absorption is calculated (Equation 7).

$$Water\,absorption = \frac{m_0 - m_1}{m_1} * 100 \tag{7}$$

3.4 MICROSCOPY ANALYSIS

Manufacturing of the thin-sections was made by Minoprep in Hunnebostrand. Thin section is a polished piece of rock so thin that it allows penetration of light through it, and it makes it possible to study individual minerals and fragments in a polarization microscope. The rock sample is sawed and prepared to a “match box” sized sample with two parallel sides. One side is attached after polishing to a glass slide. After this the other side of the sample is grind to a thickness of approximately 30μm and then this side is also polished. All rocks in this study are isotropic, so only one thin-section have been prepared from each sample (Hirsch, 2012).

3.4.1 Modal analysis and mineralogical composition of rock type determination

The modal analysis and the mineralogical composition of rock type determination was carried out at the Geological Survey of Sweden by Julio Gonzales. The modal analysis is based on both hand specimen and thin-section examination. The determination of the mineralogical composition of a sample is done by counting mineral points of thin section images. At least 500 points were counted. The results are reported as an amount of points for each mineral, as well as a percentage. Secondary phases such as sercitision of feldspar was reported. If the identification of opaque mineral occurs, it indicates that sulphide minerals might be present and should be noted. The mineralogical composition contributes to a specific rock type, where the rock type naming was done according to EN 932-3. Igneous rocks are classified by a QAP diagram, where QAP stands for "Quartz, Alkali feldspar and Plagioclase (Streckeiser, 1972).

3.4.2 Mineral grain size distribution analysis

Six granite samples were selected from the 28 samples for closer examinations regarding mineral grain size distribution analysis. These samples were chosen due to already existing thin-section and modal analysis from each sample site. Cumulative grain size distribution curves was made for each sample and mean grain size were calculated for each sample.The grain size and grain size distribution were determined quantitatively by measuring the mineral grains that cut traverse lines (Figure 9) conducted at the Swedish Cement and concrete Research Institute (CBI) in Borås. The traverse lines have the same length in both directions and are perpendicular to each other (Figure 9). The analysis was done on printed images taken from thin-sections. The longest diameter of the mineral grains is measured and the result put in a table of distribution for the desired range. At least 200 mineral grains were measured in each thin section sample to obtain a representative distribution and the length of the traverse lines should be equally long in both directions.

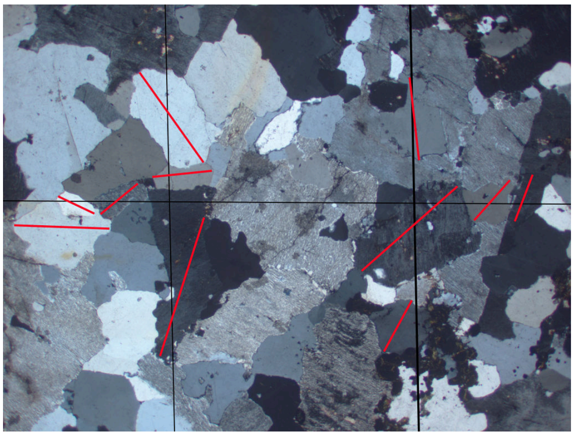


Figure 9: Grain size measurement from thin-section image. Red lines shows longest diameter and black lines are the traverse lines. The traverse lines have the same length in both directions and are perpendicular to each other.

4 RESULTS

4.1 MACRO ANALYSIS

In this section the results from the macro analysis of the six selected samples are presented. The macro descriptions of the 28 sample sites can be seen in Table. 4 in Appendix A.

4.1.1 Bokaa (BKGR1)

The medium grained Kgale granite at Bokaa is composed primarily of K-feldspar, plagioclase, blue grey quartz, and minor biotite (Fig. 10a). The quartz appears as rounded phenocrysts in a medium grained matrix (Tlhabiwe, 2012a). The outcrop is located by a road cut.

(a)

(b)

Figure 10: a) Bokaa granite. Photo Mattias Göransson, SGU. b) FKNGR1. Photo Mattias Göransson, SGU.

4.1.2 Fikeng (FKNGR1)

This outcrop is slightly weathered and it is difficult to sample a totally fresh rock unless drilling or careful blasting technique is used. The brown Kgale granite is medium-grained, equigranular, jointed and weathered to a light brown color. It is composed primarily of quartz, feldspar, plagioclase and some mafic minerals, Fig 10b (Tlhabiwe, 2012a).

(a) (b)

Figure 11: a) FKNGR2. Photo Mattias Göransson, SGU. b) KMSTGR1. Photo Mattias Göransson, SGU.

4.1.3 Fikeng (FKNGR2)

The outcrop is an extensively jointed and slightly weathered Kgale granite located in the area of Fikeng. The rock is a dark red brown equiangular, holocrystalline, medium grained granite (Fig. 11a). The granite contains primarily of quartz, feldspar, plagioclase, some greenish minerals (very likely hornblende) and some other mafic minerals. There are some vertical or sub vertical quartz veins across most of the stacked boulders. The granite appears to be very strong and can only be chipped with a very good hammer (Tlhabiwe, 2012a).

4.1.4 Kgomokasitwa (KMSTGR1)

The rock at Kgomokasitwa KMSTGR1 is a pinkish grey Kgale granite with phenocrystic blue grey quartz grains and twinning plagioclase. The dominating minerals are K-feldspar, plagioclase, quartz, hornblende and some other mafic minerals. It contains small green minerals which likely are biotite or hornblende. The outcrop is massive with no or few joints (Fig. 11b). There are some dolerite sills of microgranite within the rock (Göransson and Persson, 2013).

4.1.5 Kgomokasitwa (KMSTGR2)

The microgranite at Kgomokasitwa is fine-grained, bluish grey, jointed and appears to be moderately brittle (Fig. 12a). The outcrop is oriented in a south to north direction and appears to be intrusive in the nearby the Kgale granite, KMSTGR1. The rock contains primarily of K-feldspar, plagioclase and quartz. The plagioclase tend to be zoned and sericitised. The quartz phenocrysts are similar as the quartz phenocrysts in the Kgale granite and with a bluish color. The rock is weathered to angular boulders and surfaces (Göransson and Persson, 2013).

(a) (b)

Figure 12: a) KMSTGR2. Photo Mattias Göransson, SGU. b) Felsite, very fine-grained. Photo Mattias Göransson, SGU.

4.1.6 Letlhakane (LTKWF1)

The rock of Letlhakane is bluish grey colored (Fig. 12b), fine-grained, porphyritic homogeneous and highly brittle Felsite. It contains euhedral twinned plagioclase feldspar and some visible quartz veins (Tlhabiwe, 2012a).

4.2 TECHNICAL ANALYSIS

For an easier overview over the results, the different granite types have been assigned a color (Thamaga granites = blue, Kgale granites = purple, Ntlhantlhe micrогranite = red and Kanye volcanics = green). The sample sites in each category have been assigned a color in the same tonality but in different color tint and a unique logo. This is shown in Fig. 13.

Thamaga granites	Kgale granites		Ntlhantlhe micrогranite		Kanye volcanics	
	BKGR1	■	KMSTGR2	✚	LTKWF1	✖
	FKNGR1	◆				
	FKNGR2	▲				
	KMSTGR1	●				

Figure 13: Color representations used in this section.

Result from the microscopy describe how the four groups of Gaborone granites (Thamaga granites, Kgale granites, Ntlhantlhe Micrогranite and Kanye Volcanics) correlate with the technical analysis. This is done in order to investigate whether any of the four Gaborone granites generally have better technical properties than the others. All the data from the technical analysis were carried out by DGS, can be seen in in Table. 5 in Appendix B. There are no significant differences between dry or wet values (aggregate crushing- and 10 % FACT values) when comparing with other technical properties, hence only dry values have been compared. Some of the samples have not been analysed by all methods thus affect the reliability of the results and makes it difficult to make a reliable analyses of some of the diagrams due to too little data. Comparison of the results show a positive correlation between aggregate impact value and Los Angeles value (Fig. 14). Low aggregate impact value gives a low Los Angeles value.

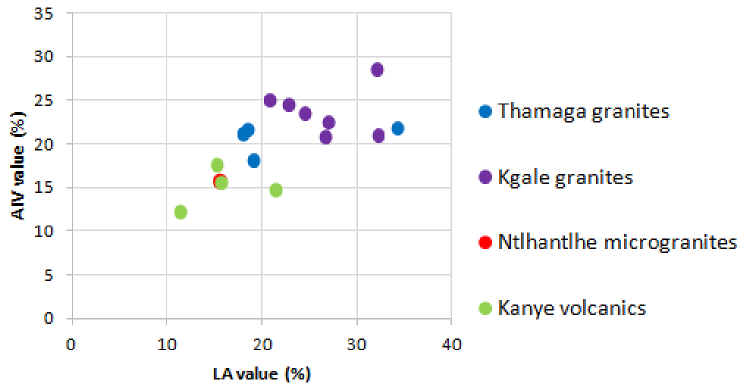
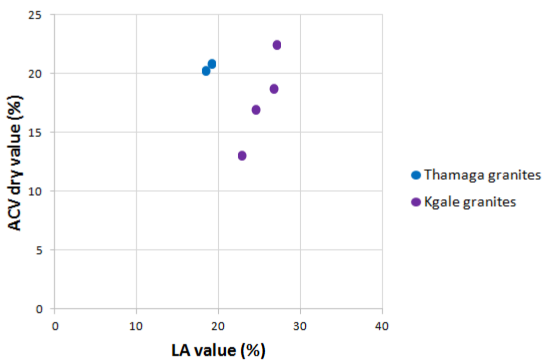
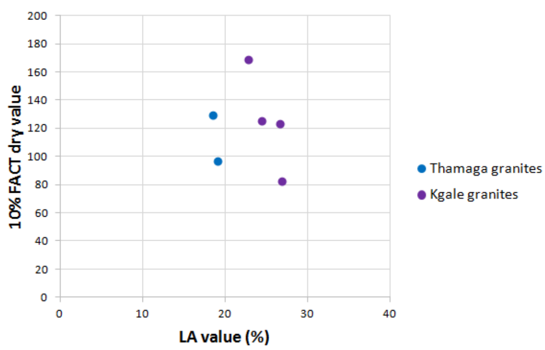


Figure 14: The aggregate impact values and Los Angeles values tend to have a positive correlation.

The Aggregate crushing value and Los Angeles value for Thamaga and Kgale granites are shown in figure 15a. It shows a positive correlation, which also has been shown at the Road Research Laboratory (1959), who showed a 1:1 correlation between Aggregate crushing value and Los Angeles value. The 10 % FACT- and Los Angeles values for Thamaga and Kgale granites are shown in figure 15b. A negative correlation can be observed by study the Thamaga granites and Kgale granites separately. The Thamaga granites tend to have lower Los Angeles values than Kgale granites. Numbers for 10 % FACT- and AIV values (Fig. 30a), respectively 10 % FACT values and grain density (Fig. 30b), show no, or very weak, correlation (Appendix C).



(a)



(b)

Figure 15: a) The aggregate crushing values and Los Angeles values tend to have a positive correlation, similar to[**?**]. b) Figure shows 10 % FACT and LA value for Thamaga and Kgale granites. No obvious correlation.

Figure 16 show grain density vs Los Angeles values. Higher density generally results in lower Los Angeles value. More fine-grained granites tend to have lower Los Angeles value and higher density. However, there are exceptions with three of the Thamaga samples which can be found between the Kanye volcanics and the Kgale samlpes. Figure 17 show similar correlation as figure 16. Higher density tend to give lower AIV value. Figure 17 contain more data than figure 16 and if the amount data would have been the same in the two diagram, they probably would look very alike according to the good correlation between LA and AIV values. Grain density and ACV show no or weak correlation (Fig. 31), and can be seen in Appendix C.

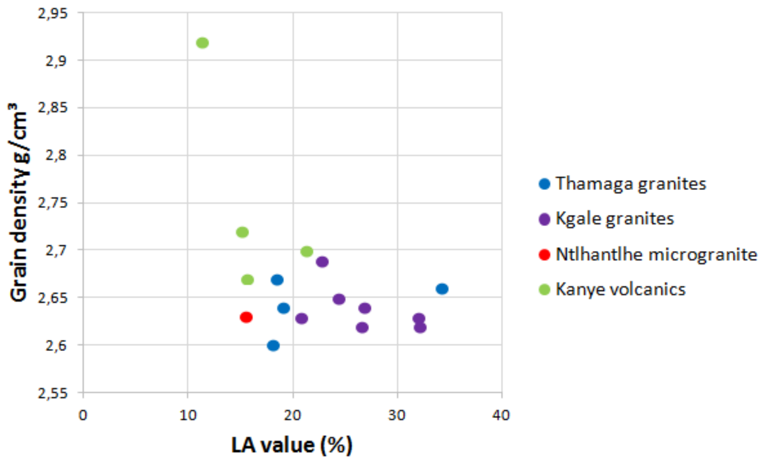


Figure 16: Figure show grain density and LA value for all granite types. Higher density tend to give lower LA value.

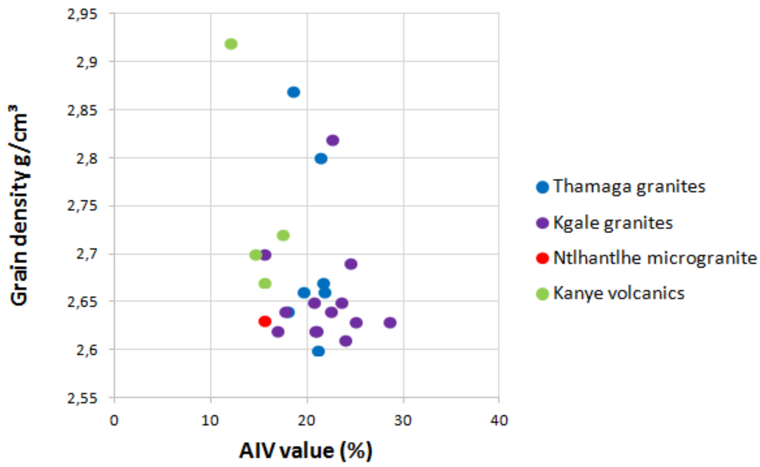
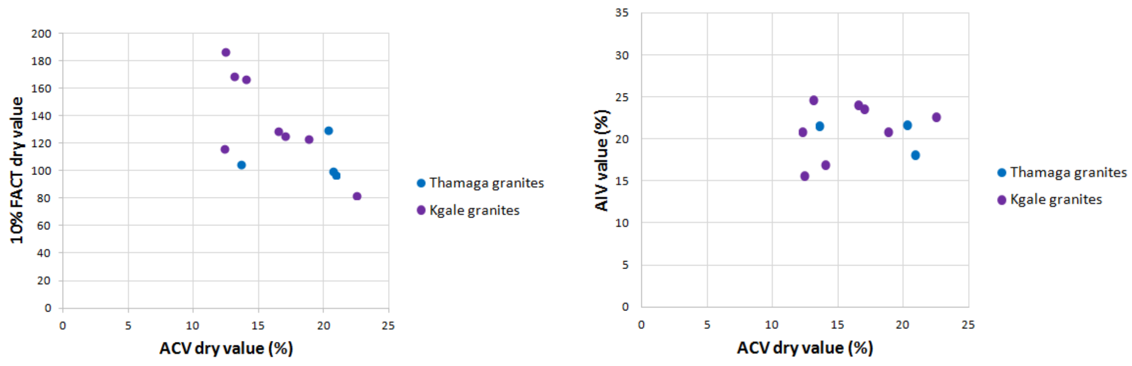


Figure 17: Figure show grain density and AIV value for all granite types. Higher density tend to give lower AIV value.

The 10 % fines values and aggregate crushing value tend to have a good negative correlation and are shown in Fig.18a. The methology of these tests are closely related and provides a good indication that the results for these technical properties are correct. A good rock material is characterized by a high 10 % FACT value and a low aggregate crushing value. The aggregate impact value and the aggregate crushing value show a positive correlation, as can be seen in Fig.18b.



(a) (b)

Figure 18: a) The 10 % FACT and ACV values tend to have a significant negative correlation, this according to closely related test methods. b) AIV and ACV values tend to have a weak correlation.

4.3 WATER ABSORPTION ANALYSIS

The data from the water absorption analysis, carried out by DGS, can be seen in Table.2. The felsite from Letlhakane (LTKWF1) shows the lowest water absorption value 0.3 %, table 2, and the Kgale granite from Kgomokasitwa (KMSTGR1) show the highest value of 0.95 %. The water absorption tend not to correlate with any of the technical properties. All water absorption values are low to moderate except for KMSTGR1 (0.95 %). It cannot be excluded that a slight weathering of the top surface may effect the water absorption values and increase the analysed Kgomokasitwa granite sample.

Table 2: Locality name, sample ID and water absorption values for each sample. The water absorption value A_b is presented in weight percent.

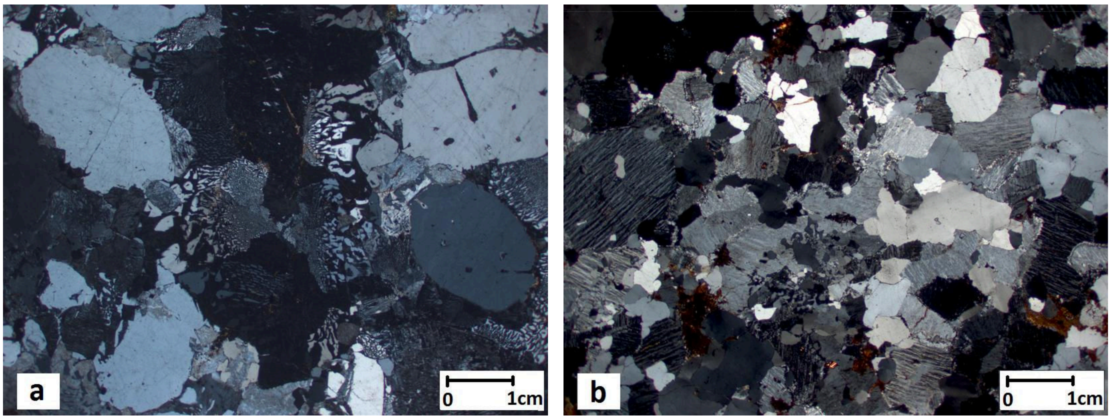
Locality name	Sample code	Ab
Bokaa	BKGR1	0.44
Fikeng	FKNGR1	0.57
Fikeng	FKNGR2	0.67
Kgomokasitwa	KMSTGR1	0.95
Kgomokasitwa	KMSTGR2	0.40
Letlhakane	LTKWF1	0.30

4.4 MICROSCOPY ANALYSIS

4.4.1 Modal analysis

The modal analysis was carried out by Julio Gonzales at SGU. A summary of the results is presented below.

4.4.1.1 Bokaa (BKGR1) The red Bokaa granite (sample BKGR1) is a coarse-grained, unequigranular, porphyritic and weakly hydrothermally altered granite. The rock consists of 38 % K-feldspar as phenocrysts and matrix, 31 % quartz and 25 % granophyric aggregates containing K-feldspar and quartz (Gonzalez, 2013). The major constituents of the granite are up to 10 mm crystals of K-feldspar, quartz and minor amounts of hornblende in a matrix (Fig. 19a). The matrix consists of a granophyric aggregate of K-feldspar and quartz. The feldspar phenocrysts also host small amounts of mica, biotite, epidote and calcite in cracks. Opaque phases do not occur throughout the rock. The greatest concentrations are limited to aggregates of dark mineral. The grain boundaries are principally lobated and irregular. Some subgrains in quartz is present. The dominating grain size varies from 0.01 mm to 3 mm (Gonzalez, 2013).

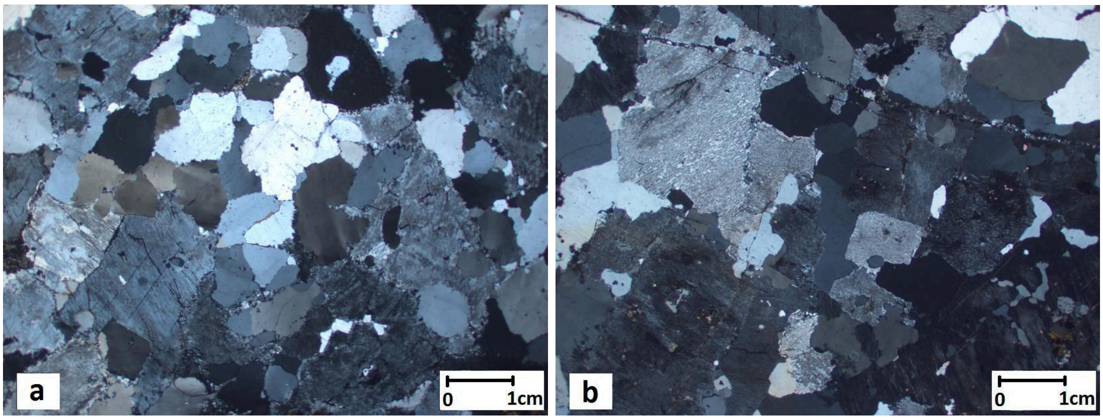


(a) (b)

Figure 19: a) Microscopic image of thin-section of BKGR1 of a red granite at Bokaa. b) Microscopic image of thin-section of FKNGR1 of a red syenogranite-quartz syenite at Fikeng.

4.4.1.2 Fikeng (FKNGR1) Sample FKNGR1 is a red, medium to coarse-grained, hydrothermally altered syenogranite to quartz syenite, that is slightly porphyritic with quartz and K-feldspar phenocrysts in a matrix of the same minerals. The rock contains of 2 % plagioclase, 60 % K-feldspar and 35 % quartz (Gonzalez, 2013). The rock has been subject to a alteration in terms of relatively intense hematitisation (Fig. 19b). The majority of the K-feldspar crystals are surrounded by quartz or fine-grained K-feldspar grains. The feldspar crystals are sericitised to some extent. The thin-sections shows one single muscovite crystal and one big K-feldspar phenocryst, the latter one surrounded by a halo composed by granophyric grains containing quartz and K-feldspar. The grain boundaries are principally lobated and irregular but a minor part of them have a regular character. Some quartz grains have been subjected to ductile strain and contain minor amounts of subgrains. The majority of the quartz grains expose a deformational banding and an undulose extinction. The dominating grain size varies from 0.25 mm to 2 mm (Gonzalez, 2013).

4.4.1.3 Fikeng (FKNGR2) Sample FKNGR2 is a medium grained hydrothermally altered, porphyritic syeno-granite from the Fikeng suite. The rock is pink with a purpure tint, slightly unequigranular, isotropic and leucocratic. The granite has gone through a hematitisation and sericitisation. The mineral composition of the granite is dominated by 59 % K-feldspar and 38 % quartz (Gonzalez, 2013). The K-feldspar crystals are often surrounded by a fine-grained halo consisting of quartz and small grains of K-feldspar (Fig.20a). Most mafic minerals are altered. In many cases the opaque minerals are surrounded solely by epidote grains. Small cracks and grain boundaries in the K-feldspar often contain different amounts of chlorite, sercite, opaque minerals and epidote. The grain boundaries are principally irregular. Lobated boundaries occur but are less common. A very small part of the grain boundaries have a regular character. Most of the quartz grains expose a deformational banding and an undulose extinction. Subgrains in quartz is rather common. The dominating grain size varies from 0.1 mm to 1.5 mm (Gonzalez, 2013).



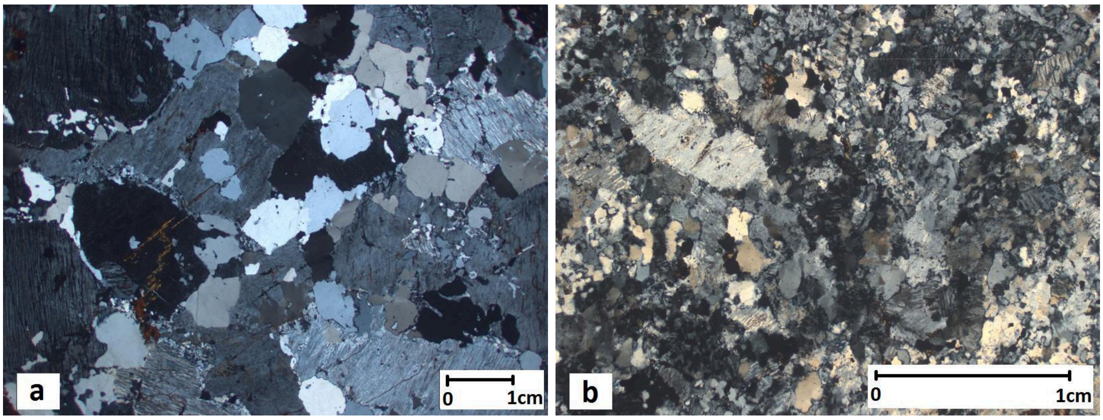
(a) (b)

Figure 20: a) Microscopic image of thin-section of FKNGR2 of a pink porphyritic syenogranite at Fikeng. b) Microscopic image of thin-section of KMSTGR1 of a veined syenogranite- quartz syenite in Kgomokasitwa.

4.4.1.4 Kgomokasitwa (KMSTGR1) Sample KMSTGR1 is a veined syenogranite to quartz-syenite belonging to the Kgomokasitwa suite. It is unequigranular, isotropic and has a weakly developed porphyritic texture. The red colored, medium-grained granite contain of 58 % K-feldspar and 38 % quartz (Gonzalez, 2013). Also some plagioclase and minor amounts of biotite and opaque minerals are present. The crystals of K-feldspar are surrounded by a fine-grained halo consisting of quartz and small grains of feldspar (Fig.20b). Calcite grains up to 0.1 mm are commonly found inside the K-feldspar grains. The calcite also appears in aggregates along with sericite, epidote, chlorite, titanite and allanite. The grain boundaries are principally irregular. However regular and lobated boundaries are also common. The majority of the quartz grains expose undulose extinction. Deformational banding is present in some of the quartz grains. Subgrains in quartz is present, but rare. The dominating grain size varies from 0.25 mm to 3 mm (Gonzalez, 2013).

4.4.1.5 Kgomokasitwa (KMSTGR2) The major constituents of the granite in Kgomokasitwa (KMSTGR2) are 59 % K-feldspar and 37 % quartz (Gonzalez, 2013). The rock is also very rich in apatite. The pink, medium-grained rock is described as a fractured and hydrothermally altered granite. The microscopic analysis shows an unequigranular, isotropic and weakly developed porphyritic texture (Fig.21a). The K-feldspar is often sercitised and in some extent also kaolinised, often surrounded by a fine-grained halo composed of small grains of quartz and K-feldspar. No primary mafic minerals have been observed. Some small dark mineral aggregates of chlorite, sericite, epidote, titanite, iron-oxides and allanite are though present - all expected to be of a secondary origin.

Small amounts of chlorite, sericite, opaque mineral and epidote are present at grain boundaries, in small cracks and cleavage planes in feldspar. The grain boundaries are principally irregular. Lobated boundaries occur but are less common. A very small part of the grain boundaries have regular character. Most of the quartz grains have deformational banding and undulose extinction. Some subgrain building of quartz is present. The dominating grain size varies from 0.5 mm to 2.5 mm (Gonzalez, 2013).



(a) (b)

Figure 21: a) Microscopic image of thin-section of KMSTGR2 of a fractured pink hydrothermally altered granite in Kgomokasitwa. b) Microscopic image of thin-section LTKWF1 of a volcanic rock at Letlhakane.

4.4.1.6 Letlhakane (LTKWF1) The sample LTKWF1 is a hydrothermally altered volcanic rock belonging to the Letlhakane suite. It is unequigranular, porphyritic and has an felsic composition. The rock is feldspar phenocrystic (Fig. 21b). Both K-feldspar crystals abundant as phenocrysts or in the matrix are altered (sericitised). In the most sericitised parts of the phenocrysts calcite grains are quite common. Cracks in the K-feldspar phenocrysts holds mica and a smaller amount of kaolinite may also be present. Opaque phases occur throughout the rock and the greatest concentrations are restricted to the aggregates of the dark minerals. The opaque minerals are often surrounded by a titanite aggregate. The grain boundaries are principally lobated and irregular. A lot of the quartz grains have been subject to subgrain formation. The majority of the quartz grains exposes an undulose extinction and yields a deformational banding. The dominating grain size varies from 0.01 mm to 0.1 mm (Gonzalez, 2013).

4.4.2 Mineralogical composition of rock type determination

The purpose of the mineral composition analysis was to examine how the knowledge of rock type classification can give more explanations of the technical analysis. The felsite (LTKWF1) and the Bokaa granite (BKGR1) contain a matrix and it was not possible to determine the proportion of quartz, K-feldspar and plagioclase during the modal analysis. All four granite samples were classified as alkali feldspar granites according to the Streckeiser diagram Fig. 22.

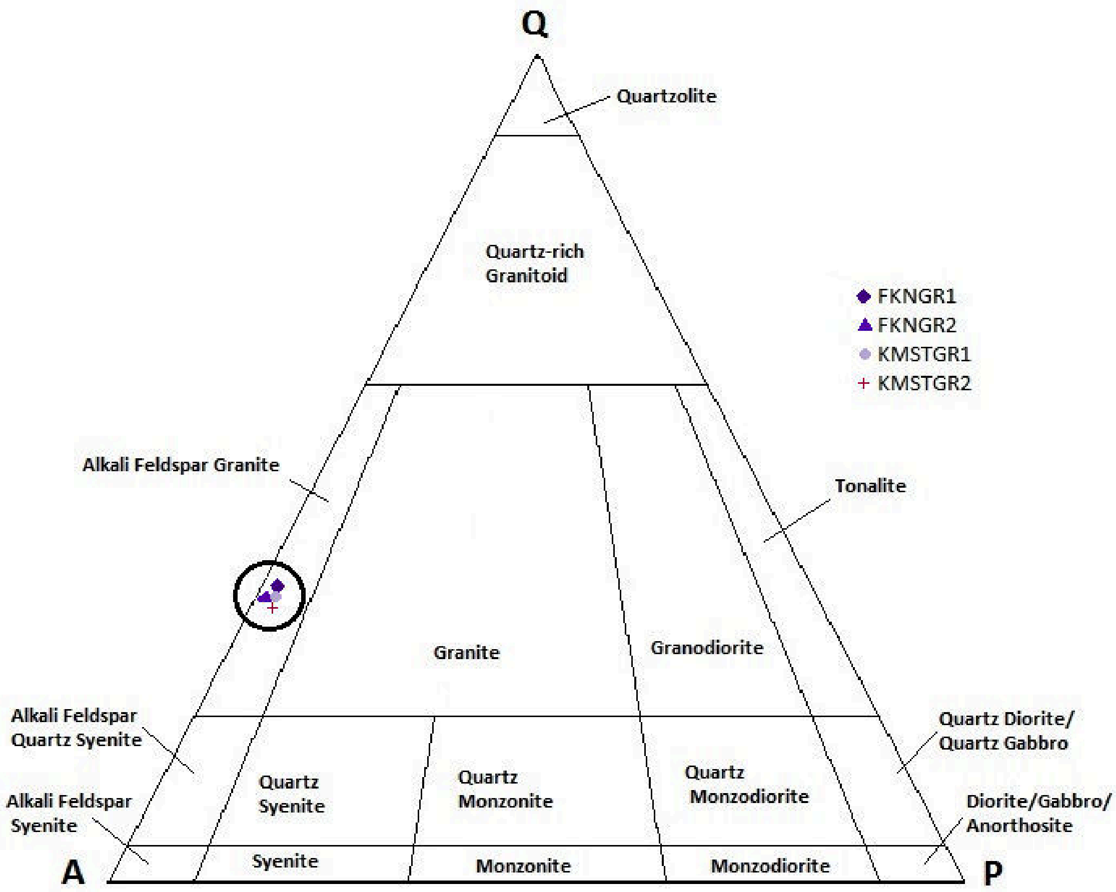


Figure 22: QAP (Quartz, Alkali-feldspar, Plagioclase) classification diagram shows the normative mineralogy for the samples from Fikeng (FKNGR1 and FKNGR2) and Kgomokasitwa (KMSTGR1 and KMSTGR2). Modified from Le Maitre (1989).

4.4.3 Mineral grain size distribution analysis

This section present all the results from macro-, modal and mineral grain size distribution analysis. The different analyses have been assigned a color (Macro = brown, Modal = orange, mineral grain size distribution = yellow, Table 3). Mineral grain size is a significant parameter to determine rock strength. According to Lundqvist and Göransson (2001), a more fine-grained rock is stronger than a more coarse-grained one. The mean grain size from the mineral grain size distribution analysis can be assumed to be the most correct mean value due to carefully calculations from thin-sections. Table 3 shows the results from the macro-, modal and mineral grain size distribution analysis for all the investigated samples.

Table 3: The results from the macro-, modal-, and mineral grain size distribution analysis.

Sample code	Macro description	Macro analysis	Macro analysis	Modal analysis	Modal analysis	Mineral grain size distrubution
		Grain size interval (mm)	*Mean grain size (mm)*	*Grain size interval (mm)*	*Mean grain size (mm)*	*Mean grain size (mm)*
BKGR1	Medium- to coarse- grained	1.0-8.0	4.5	0.01-3	1.505	1.36
FKNGR1	Medium- granied	1.0-5.0	3	0.25-2	1.125	0.9
FKNGR2	Medium- grained	1.0-5.0	3	0.1-1.5	0.8	1.12
KMSTGR1	Medium- granied	1.0-5.0	3	0.25-3	1.625	1.14
KMSTGR2	Fine- grained microgranite	0.01-1.0	0.505	0.5-2.5	1.5	0.87
LTKWF1	Fine- grained	0.01-1.0	0.505	0.01-0.1	0.055	0.2

The macro and modal analysis are estimated results and presumably contain some measurement uncertainties. The macro description is very uncertain at greater grain sizes but show better results at smaller grain sizes. Figure 22 shows how the macro- and modal analysis differ from the mineral grain size distribution calculations. The macro analysis show too high mean grain size values. The modal analysis shows mean size values similar to the mineral grain size distribution mean grain size.

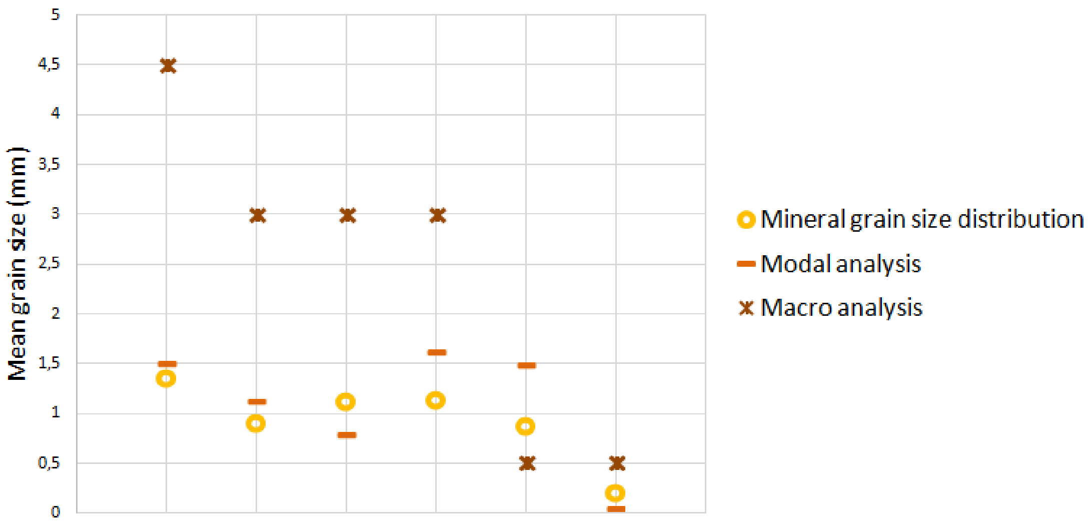
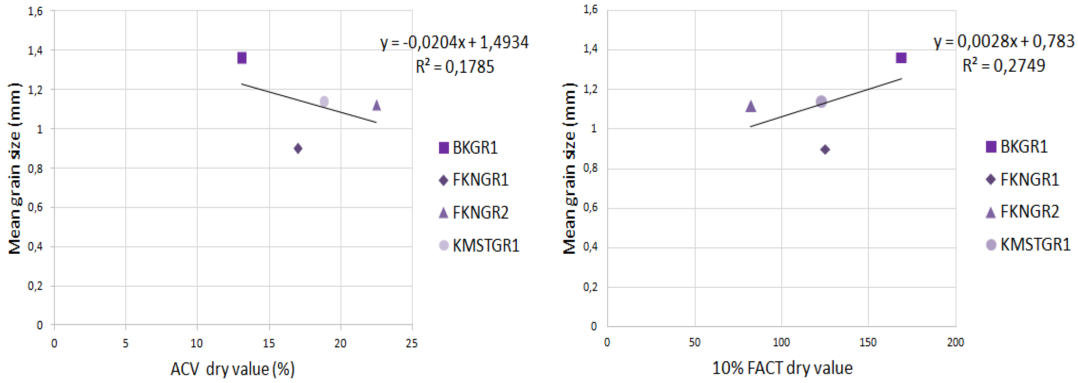


Figure 23: The diagram show the difference between macro-, modal-, and mineral mean grain size distribution analysis. The macro and modal analysis show estimated grain size intervals and mineral grain size distribution show calculated mean grain sizes.

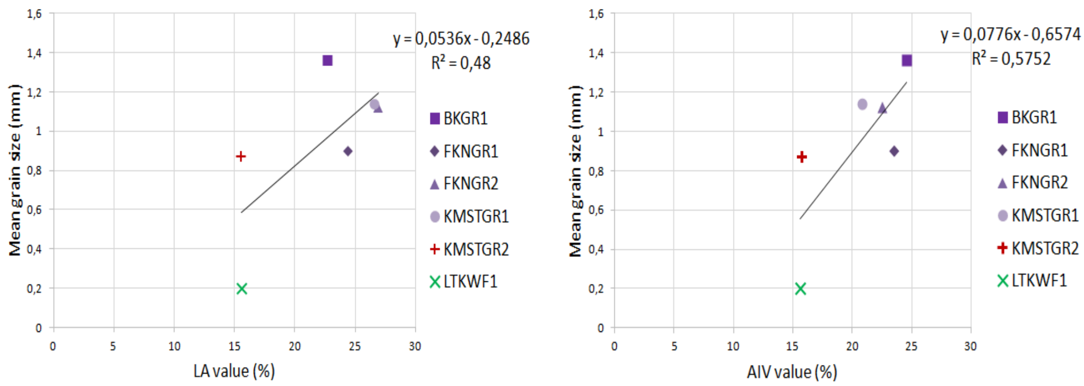
The mean mineral grain size of the mineral grain size distribution analysis were compared with the aggregate crushing, 10 % FACT values, Los Angeles and aggregate impact values. The results are shown in figure 24a to 25b. Figure 24a tend to have a weakly negative correlation (R^2= 0.18) between the mean grain size and the aggregate crushing value. This diagram lacks results from the felsite (LTKWF1) and the microgranite (KM-STGR2) due to no test result of ACV for these samples. For aggregate crushing value the requirement for road material is ACV≤29, which all samples achieve. The mean grain size correlates weakly with the 10 % FACT value where a low mean grain size give a low 10 % FACT value, figure 24b. Requirement for road aggregate is 10 % FACT≥110 for base layer, and 10 % FACT≥190 for road surface. None of the samples can be used as road surface aggregates according to 10 % FACT value, but all except FKNGR2 can be used as base layer.



(a) (b)

Figure 24: a) The ACV tend to have a weak correlation with the mean grain size. A low mean grain size seem to give high a ACV. b) The mean grain size tend to have a weak correlation with the 10 % FACT value. A low mean grain size seem to give a low 10 % FACT value.

A positive correlation (R^2= 0.48) between the mean grain size and the Los Angeles values is shown in figure 25a. The same type of correlation has been achieved by Lundgren (2012). None of the the samples yielded a Los Angeles value$\leq$15 which is regarded as good material for road construction. KMSTGR1 and FKNGR2 holds Los Angeles values over 25 which is considered as poor resistant regarding to fragmentation and hence unusable for roads.



(a) (b)

Figure 25: a) The LA value tend to correlate with mean grain size. Low mean grain size seems to give low LA value. b) AIV value tend to correlate with mean grain size. Low mean grain size seems to give low AIV value.

Figure 25b shows a correlation between mean grain size and aggregate impact value with a R^2 value of 0.58. Samples with AIV value less than 15 are regarded as being very good commodity for road aggregates. All of the granites samples are expected to meet the requirement for roads according to the aggregate impact value, however the felsite (LTKWF1) and the microgranite (KMSTGR2) are preferable.

Figure 26 show the mean grain size from the modal analysis and how it correlates with the Los Angeles value for all the granites. Due to the very similar results from the mean grain size at the modal analysis and the calculated mineral grain size (Fig. 23), it is interesting to see how the estimated modal analysis correlates with the Los Angeles. The modal analysis contain data from more granites than the calculated mean grain size analysis, and therefore is it interesting to use these mean values and compare with LA values. The mean grain size from the modal analysis correlates well with the Los Angeles values, with a R^2 value of 0.61.

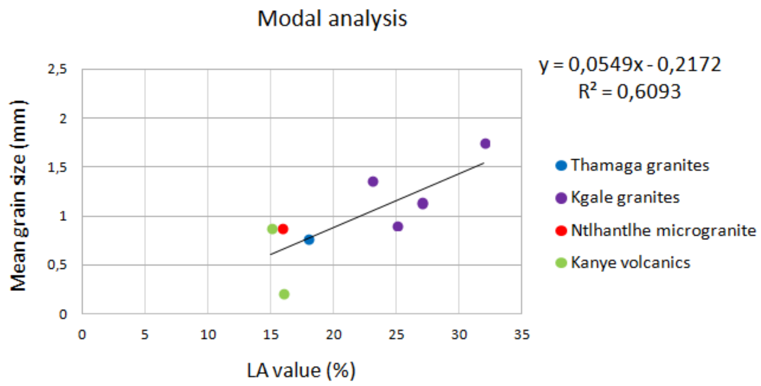


Figure 26: The LA value from the modal analysis tend to correlate well with mean grain size, $R^2 = 0.61$. Low mean grain size seems to give low LA value.

Figure 27 show how the Los Angeles value correlates with the aggregate impact value and mean grain size of mineral grain size distribution analysis for respective sample. The mean grain size corresponds to the size of the circles, larger circle diameter correlates to larger mean grain size. The mean grain size of the macro analysis (Fig. 32b), and modal analysis (Fig. 32a) corresponds similar to Los Angeles- and aggregate impact value and can be seen in Appendix D.

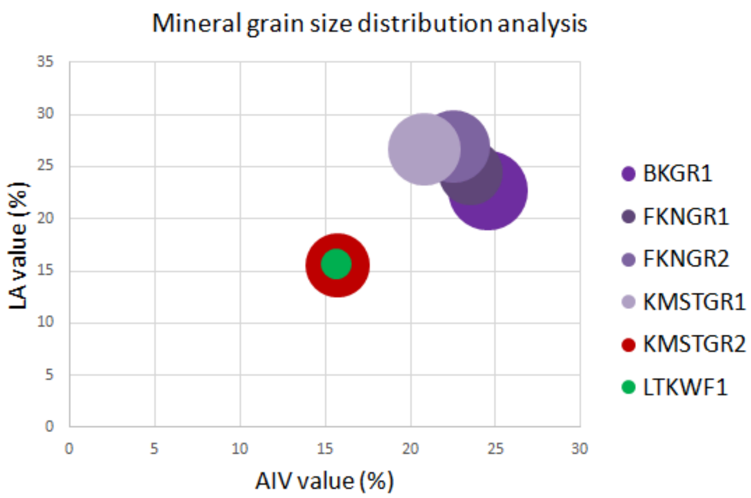


Figure 27: The LA value correlates with the AIV and mean grain size of mineral grain size distribution. The mean grain size corresponds to the size of the circles, larger circle diameter correlates to larger mean grain size.

The grain size distribution curve (Fig.28) show the cumulative distribution for all samples. As expected, the fine-grained (99 % $\leq$ 1 mm and 79 % $\leq$ 0.05 mm) felsite (LTKWF1) can be found almost entirely within the fine-grained interval. The micro-granite (KMSTGR2), and the Fikeng granite (FKNGR1) also contain a large portion of fine-grained material (88 % and 87 % $\leq$ 1 mm respectively). The Fikeng (FKNGR1) also contain some of the largest grains in this study, see figure 29. The Bokaa granite (BKGR1) is the most coarse- grained granite (77 % $\leq$1 mm) followed by KMSTGR1 (76 % $\leq$ 1mm) and FKNGR2 (81 % $\leq$ 1 mm). A large proportion of very fine-grained or fine-grained material seem to contribute to a lower Los Angeles value.

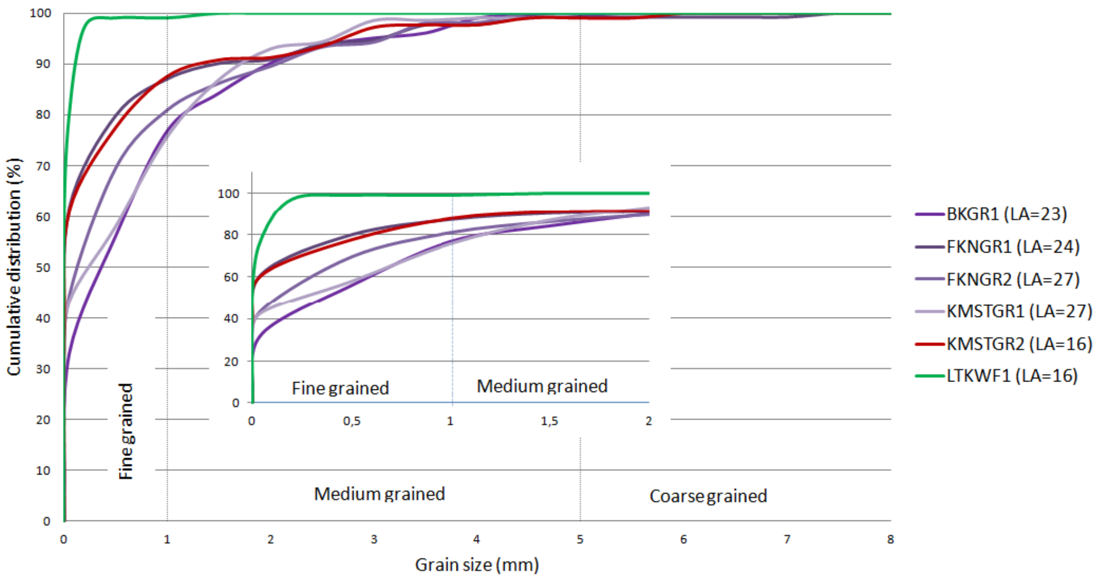


Figure 28: Grain size distribution curve with LA value in parenthesis next to each sample

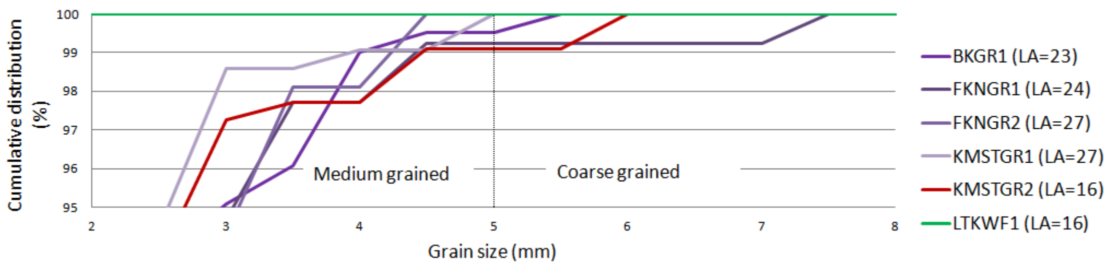


Figure 29: Grain size distribution curve which only show the upper limits (95 %-100 % cumulative distribution). The Fikeng FKNGR1 contain the largest grains.

5 DISCUSSION AND CONCLUSIONS

Technical properties

The technical data showed correlation between aggregate impact and Los Angeles values. More fine- grained rock types such as Kanye volcanics and Ntlhantlhe Microgranite tend to have both low aggregate impact values and low Los Angeles values. This indicates that more fine- grained rock tend to yield better technical properties than more coarse- grained rock with similar mineralogy. The Thamaga and Kgale granites showed mixed results where some of the Thamaga seemed to be stronger than the more fine-grained Kgale granite. According to the macro analysis, one of these Thamaga samples contain a fine grained matrix, and according to the modal analysis one sample contain 70 % granophyric aggregates. This can be the explanation to why these Thamaga granites achieve better results than Kgale granites. Tests at the Road Research Laboratory (1959) showed that there is a 1:1 correlation between the aggregate crushing values and Los Angeles values. Due to too few data it is difficult to see an obvious correlation between aggregate crushing values and Los Angeles values in this study. The same problem can be seen with 10 % FACT value and Los Angeles value, due to few data correlation is difficult to decipher. Rocks with a high grain density seem to give low Los Angeles and aggregate impact values. The high density can be explained by the fact that they constitute more mafic mineral than the low- density rocks. The correlation between the 10 % FACT value and aggregate crushing value is obvious. Higher 10 % FACT values correlate with lower aggregate crushing values. It is also clear that Kgale granites tent to have better 10 % FACT values and better aggregate crushing value than Thamaga granites, although there are some exceptions. The technical analysis generally show that fine-grained granites tend to have better technical properties than more coarse-grained granites. This is also consistent with previous studies such as Lundqvist and Göransson (2001).

Mineral grain size and the mineral grain size distribution

The mean grain size affects both the aggregate crushing value, 10 % FACT value, Los Angeles value and the aggregate impact value. However, low mean grain size gives high ACV which contradicts the theory that granites with lower mean grain size have better technical properties. Unfortunately this diagram lacks aggregate crushing value data from the felsite (LTKWF1) and the microgranite (KMSTGR2), which might prove the theory that more fine grained rock have better technical properties than more coarse grained rocks. Generally the granites with the greatest mean grain size have a higher Los Angeles value and a higher aggregate impact value.

The cumulative grain size distribution curve showed that the rock types with narrower grain size distribution (LTKWF1, KMSTGR2 and FKNGR1) hold lower Los Angeles values (Fig. 28). Even though FKNGR1 is a Kgale type it contains a large portion of fine-grained material, but it also contains some of the largest grains in this study, which probably is why the Los Angeles value is higher than the Los Angeles value for the felsite- and microgranite (Fig. 29). The more coarse grained rock samples, (BKGR1, KMSTGR1 and FKNGR2), are more heterogeneous with a broader grain size distribution spectra and generally hold a higher Los Angeles values.

The macro analysis gives very doubtful mean grain sizes due to its large grain size range. The macro analysis tend to show too large grain sizes when comparing it with the mean grain size from the mineral grain size distribution. The error in the macro estimation depend on the grain size classifications. The modal analysis and the mineral grain size distribution analysis tend to give very similar values due to the mean grain sizes. These two methods used the same thin-section, even though the modal analysis used estimated grain sizes and the mineral grain size distribution analysis used calculated grain sizes.

The calculated mean grain size from the mineral grain size distribution tend to be a good prospecting tool, hence it is suggested to use this type of investigations rather than to base the prospecting on macro analysis divided into different varieties of granites (Thamaga-, Kgale-, Ntlhantlhe granites or Kanye Volcanics). I would recommend to use both calculated mean grain sizes together with technical test methods as LA, AIV, ACV and 10 % FACT. The calculated mean grain size would be a good monitoring tool to probate, or to explain ambiguities, in the technical results. The mean grain size from the modal analysis, also tend to be a good prospecting tool, this depends, of course, on how carefully the modal analysis is performed. Some Thamaga granites have lower mean grain size than some Kgale granites and also show better technical properties. This may be that these Thamaga granites are actually Kgale granites, incorrectly defined in the macro analysis in field.

Future studies

It is obvious that the grain size is correlated to strength as well as durability of the studied granites. To obtain an even better understanding of how one from thin section specimen can estimate strength and durability of a rock I recommend to measure the total grain shape and perimeter. Even though the granites from Botswana are the perfect study area with respect to different grain size in rocks generated from the same magma source, I would prefer that the 28 granites had data from all technical analyses. This in order to get more reliable and statistically comparable results. It would also be preferable to make duplicates of all tests so that measurement errors are minimized.

6 REFERENCES

Appelquist, K., Eliasson, T. (2011). *Karaktärisering av Bohusgranit i samband med utbyggnad av E6, norra Bohuslän.* Borås: CBI Betonginstitutet (CBI uppdragsrapport 2011:PX00536).

Gonzalez, J. (2013). *Petrografisk beskrivining*. Unpublished manuscript. Sveriges geologiska undersökning.

Göransson, M., Persson, L. (2013). *Recommended quarry site*. Unpublished manuscript. Sveriges geologiska undersökning.

Hirsch, D. (2012). *How to make a thin-section.* Bellingham: Western Washington University.
Available at: http://geology.wwu.edu/dept/faculty/hirschd/other/thinsections/ (2013-08-23)

Key, R. M., and E. P. Wright. (1982). *The Genesis of the Gaborone Rapakivi Granite Complex in Southern Africa*. London: The Geological Society of London (Journal of the geological society 1982, vol. 139). Available at: http://jgs.lyellcollection.org/ (2013-03-7).

Liu, H., Kou, S., Lindqvist, P.A. (2005). *Microscope Rock Texture Characterization and Simulation of Rock Aggregate Properties.* Uppsala: Sveriges geologiska undersökning (SGU Project 2004:60-1362).

Lundgren, L. (2012). *Variation in rock quality between metamorphic domains in the lower levels of the Eastern Segment, Sveconorwegian Province*. Lund University. Department of Geology (Master's thesis 2010: 324)

Lundqvist, S., Göransson, M. (2001). *Evaluation and interpretation of microscopic parameters vs. mechanical properties of Precambrian rocks from the Stockholm region, Sweden*. Athens: Department de geologie Athens

Maitre, Roger Walter Le. (2002). Igneous Rocks: *A Classification and Glossary of terms. Recommendations of the International Union of Geological Sciences, Subcommission on the Systematics of Igneous Rocks.* Cambridge: Cambridge University Press 2002.

Millard, R.S. (1993). *Road building in the Tropics*. London: H.M. Stationery Office (Transport Research Laboratory, series State of the art review ; 9)

Moore, M., Davis, D.W., Robb, L. J., Jackson, M. C., and Grobler, D. F. (1993). *Archean Rapakivi Granite-anorthosite-rhyolite Complex in the Witwatersrand Basin Hinterland, Southern Africa*. Geological Society of America (1993;21;1031-1034).

Pye, K. (1986). *Mineralogical and Textural Controls on the Weathering of Granitoid Rocks*. Cambridge: Cambridge University Press 1986.

Road Research Laboratory. (1959). *Roadstone test data presented in tabular form*. London: H.M. Stationery Office (Road notes;no.24)

South African national standard. (2006a). *FACT value (10 % fines aggregate crushing value) of coarse aggregates*. Pretoria: SABS Standards Division. (SANS 5842:2006)

South African national standard. (2006b). *Abrasion resistance of coarse aggregates (Los Angeles machine method)*. Pretoria: SABS Standards Division. (SANS 5846:2006)

South African national standard. (2011). *Civil engineering test methods. Part AG20: Determination of the grain density, apparent density and water absorption of aggregate particles retained on the 5 mm sieve for road construction materials.* Pretoria: SABS Standards Division. (SANS 3001-AG20:2011).

South African national standard. (2012a). *Civil engineering test methods Part AG10: ACV (aggregate crushing value) and 10 % FACT (fines aggregate crushing test) values of coarse aggregates*. Pretoria: SABS Standards Division. (SANS 3001-AG10:2012).

South African national standard. (2012b). *Aggregate impact value of coarse aggregate.* Pretoria: SABS Standards Division. (SANS 6239:2012).

South African national roads agency Ltd. (2011). *South African Pavement Engineering Manual: Chapter 3 - Material testing.* South Africa: South african national roads agency Ltd. Available at:
http://www.csir.co.za/Built_environment/Transport_Infrastructure/22RPF/05b.%20K-
%20Jenkins.pdf (2012-08-21).

Tlhabiwe, K. (2012a). *Macro descriptions*. Unpublished manuscript. Geological survey of Botswana.

Tlhabiwe, K. (2012b). *Data from technical analyses*. Unpublished manuscript. Geological survey of Botswana.

Åkesson, U., Lindqvist, J.E., Göransson, M., and J. Stigh. (2001). *Relationship Between Texture and Mechanical Properties of Granites, Central Sweden, by Use of Image-analysing Techniques.* Bulletin of Engineering Geology and the Environment.Volume 60, Issue 4. Germany: Springer Berlin Heidelberg, pp. 277-284.

7 APPENDIX

Appendix A

Table 4: Macro description of sampling sites (Tlhabiwe, 2012a)

Sample Code	Granite type	Description
KPNF 2	Felsite	Porphry felsite black in colour with some white euhedral white feldspars,fine grained (more finer than KPNF1), very brittle with a lot of overbudden.
LTKWF 1	Felsite	Bluish grey ,fine grained porphyritic homogeneous highly brittle felsites.euhedral twinning plagioclase feldspars. There are also visible quartz veins.good quarrying site.
KPNF 1	Felsite	Dark purple - black, fine grained, homogeneous hard rock that readily breaks with a concoidal fracture into irregular pieces. The felsites are strongly jointed and most boulders have an angular shape with some crimson-brown coloured weathering surfaces. There are some vertical-subvertical quartz filled veins with a general NEE-SWW orientation that cut across the rock unit. There are some Quartz phenocrysts (~2mm) within a dark purple- black fine groundmass.
MKLDF 1	Felsite	Dark purple - black, fine grained, homogeneous hard rock that readily breaks with a concoidal fracture into irregular pieces. The felsites are strongly jointed and most boulders have an angular shape with some crimson-brown coloured weathering surfaces. Its mainly composed of quartz, feldspar and small amounts of amphibole, biotite and chlorite
LTKWGR 1	Kgale	Greyish granite with dominant blue grey quartz. It is finer grained at the contact with the intruding dolerite bt becomes medium to coarser as moving away from the contact.The rock is highly weathered on the surface with angular loose boulders and experiencing exfoliation type of weathered in massive outcrops.
FKNGR 1	Kgale	Medium grained,equigranular, jointed medium brown granite which weathers to a light brown colour. The granite is composed primarily of Qtz blue grey), K-feldspar (pink), plagioclase, mafic minerals (black clots). It is difficult to sample an unweathered rock at this locality, one can be forced to use drilling equipment or careful blasting technique to get a fresh sample.
BKGR 1	Kgale	Road cut type of exposure. Medium to coarse grained.The granite is composed primarily of K-feldspar (pink),Plagioclase, blue-grey Qtz (as rounded phenocrysts in a medium grained matrix), hornblend and biotite mica.
KNYGR 1	Kgale	Dark red brown, holocrystalline, medium to coarse grained granite. The granite is extensively jointed and it is slightly weathered. Big boulders making a small hill and a fresh sample was collected from a road cutting next to the small hill. The granite is composed primarily of Qtz, K-felspar, plag, and some small mafic minerals (black clots)
SPTGR 3	Kgale	Medium grained,blue -grey quartz,brownish-orange weathering coat having the porphyritic texture.homogeneos hilly type of exposure with some joints on the surface. Good quarrying site.composed of Plag,K-felspar and quartz.good quarrying site.
FKNGR 2	Kgale	Dark red brown, holocrystalline, equigranular, medium grained granite. The granite is extensively jointed and it is slightly weathered. There are some random variably spaced small vertical to subvertical Qtz filled veins cutting across most of the stacked boulders making a small hill. The rock unit is very strong and can be chipped with very strong hammer blows and this rock unit breaks into a coincodal manner. The granite is composed primarily of Qtz, K-felspar, plag, some greenish mineral, probably hornblende (amphibole) and some small mafic minerals (black clots)
KMST GR 1	Kgale	Pinkish grey kgale granite with phenocrystic blue grey quartz grains and twinning plagioclase feldspars.the are also green spots which may be the green biotite.the outcrop is massive with no or less joints. It resort to brown orange weathering coat.There are some sills of microgranite. The granite is composed primarily of K-feldspar, Plag, blue-grey quartz (~40%), hornblende (green), and some mafic minerals (black clots). Good quarrying site.
NTLGR 1	Kgale	Pinkish grey kgale granite with some outstanding blue grey quartz grains.it a medium grained granite with less or no joints on the massive hill outcrop experiencing exfoliation type of exposure.
KNY GR 2	Kgale	Dark red brown, holocrystalline, equigranular, medium grained granite. The granite is extensively jointed and it is slightly weathered. There are some random variably spaced small vertical to subvertical Qtz filled veins cutting across most of the stacked boulders making a small hill. The rock unit is very strong and can be chipped with very strong hammer blows and this rock unit breaks into a coincodal manner. The granite is composed primarily of Qtz, K-felspar, plag, some greenish mineral, probably hornblende (amphibole) and some small mafic minerals (black clots)
TLOA GR 1	Kgale	Medium grained, equigranular, heavily jointed granite. The granite is pink to brownish colour and weathers to crimson brown colour. There are boulders stacked (exfoliation joints) sitting on top of the granite whaleback. The granite is composed primarily of K-feldspar (pink),Plagioclase, blue-grey Qtz (as rounded phenocrysts in a medium grained matrix), hornblend and biotite mica. There are some random Qtz filled veins (vertical and subvertical) with variable spacing cutting through this rock unit. The rock unit is moderately weathered, i.e, the rock substance is affected by weathering to the extent that staining extends throughout the whole rock substance and the original colour of the fresh rock can barely be recognised. it is difficult to get a fresh sample at this locality, coring is recommended.
KGRGRN	Kgale	Well jointed rock, with fine to medium grained matrix. It consists of quartz and feldspar giving it a pink grey colour with minor mafic grains. Highly weathered material, which may create a lot of overburden.
SPTGR 2	Kgale	Highly weathered homogeneous granite composing of blue grey subhedral quartz,plag and k-feldspars.
KMSTGR 2	Micro granite	Fine grained bluish grey microgranite.jointed and moderatly brittle. Weathered to angular boulders and surfaces.The granite is composed primarily of K-feldspar and plagioclase which tend to be zoned and sericitised, and the quartz phenocrysts are typically bluish as in the Kgale granite. The outcrop follow the South-North trend and it appears to be intruding the kgale granite which is sampled as KMSTGR2.
NTL GR 2	Micro granite	fine grained bluish grey typical microgranite.jointed and moderatly brittle. Weathered to angular boulders and surfaces. Also has a porphyritic texture.
MSPGR 2	Thamaga	Pinkish in a fresh sample with some large cream-white euhedral felspars. Medium steep hilly type of exposure. There are some sills of the microgranite intruding the coarse grained rapakivi textured granite. The petrology of the granite entails green biotite, plagioclase feldspars, quartz and the dominance of pinkish K-feldspars.the granite is moderatly weathered with some loose huge boulders at the foot of the exposure.
MNYGR 1	Thamaga	Pinkish-grey rapakivi feldspar, coarse grained, holocrystalline granite. This rock unit contains predominantly K-feldspar, plagioclase (cream white), pale grey Qtz and some mafic minerals (biotite, hornblende and/or amphibole). The groundmass is medium to coarse grained and constitutes of plagioclase, Qtz and some mafic minerals. The outcrops form a whaleback morphology. the rock unit is in places cut by some thin (~3mm) Qtz filled veins with a general E-W orientation. The spacing of the joints and the jointing system is variable as observed on the rock unit.
MSPGR 3	Thamaga	Greyish-blue, homogeneous, course grained rapakivi textured with the twinning cream white plagioclase.road type of exposure
MEHAGR 1	Thamaga	Light-grey rapakivi feldspar, coarse grained, holocrystalline granite. This rock unit consists of light grey k-feldspars, cream coloured plagioclase, light grey quartz,intergrowth of irregular grains of green/black biotite or hornblende. Some traces of pink colouring can be observed within the matrix which is probably the fine grained K- feldspar with quartz.
SPTGR 1	Thamaga	Homogeneous,rapakivi texture, subhedral white plag feldspars.twining plag,black biotite,pinkish k feldspars and flacky muscovite.
SPTGR 4	Thamaga	Coarse grained rapakivi texture,large whitish plag and green/black biotite. Homogeneous,composed of dominant K-feldspars which gives the rock an outstanding pinkish colour.
SPTGR 5	Thamaga	Pinkish homogeneous porphyritic thamaga granite with the white spot of plagioclase feldspars with some green spot of green biotite. Huge boulders that have been diffracted from the main body.it is mainly composite of k-feldspars, quartz, biotite, quartz and plagioclase feldspar with a complex shaped euhedrals/subhedral grains.
TMGR 1	Thamaga	Light-grey rapakivi feldspar, coarse grained, holocrystalline granite. This rock unit consists of light grey k-feldspars, cream coloured plagioclase, light grey Qtz, black biotite, and/or hornblende. Some traces of pink colouring can be observed within the matrix. The granite also contain light yellowish green feldspars megacrysts in a course matrix of the grey-blue Qtz. the k-feldspar megacrysts are in places surrounded by cream coloured plagioclase rims. The outcrop (whale-back) of this rock unit moderately weathered with characteristic solution pits. Parallel, widely spaced, subvertical to vertical Qtz filled veins running in an E-W direction across the oucrops were observed. Microfractures can be observed on the rock unit.
RSSGR 1	Thamaga	pinkish grey in colour,highly fractured with blue grey quartz

Appendix B

Table 5: Results of technical analysis (Tlhabiwe, 2012a).

Sample Code	Type	Place	AIV	LA	ACV (DRY)	10% (DRY)	BULK DENSITY	WATER ABS
KPNF 2	Felsites	Kopong	17.6	15.25			2.72	
LTKWF 1	Felsites	Letlhakane	15.64	15.65			2.67	0.3
KPNF 1	Felsites	Kopong	14.77	21.4			2.7	0.8
MKLDF 1	Felsites	Mokolodi	12.14	11.39			2.92	0.37
LTKWGR 1	Kgale	Letlhakane	17.68				2.64	0.47
FKNGR 1	Kgale	Fikeng	23.53	24.46	17	125	2.65	0.57
BKGR 1	Kgale	Bokaa	24.58	22.77	13.1	169	2.69	0.44
KNYGR 1	Kgale	Kanye	20.79		12.3	116	2.65	0.9
SPTGR 3	Kgale	Sephatlhaphatl	22.65				2.82	0.75
FKNGR 2	Kgale	Fikeng	22.53	26.92	22.5	82	2.64	0.67
KMSTGR 1	Kgale	Kgomokasitwa	20.81	26.62	18.8	123	2.62	0.95
NTLGR 1	Kgale	Ntlhantlhe	20.94	32.18			2.62	0.74
KNY GR 2	Kgale	Kanye	28.58	32.08			2.63	0.99
TLOAGR 1	Kgale	Tloaneng	25.05	20.84			2.63	0.56
KGRGRN	Kgale	Kgoro	15.58		12.4	187	2.7	0.74
SPTGR 2	Kgale	Sephatlhaphatl	23.97		16.5	129	2.61	0.29
MSPGR 1	Kgale	Moshupa	16.91		14	167	2.62	0.79
KMSTGR 2	Microgranite	Kgomokasitwa	15.71	15.57			2.63	0.4
NTL GR 2	Microgranite	Ntlhantlhe	14.7					0.33
MSPGR 2	Thamaga	Moshupa						
MNYGR 1	Thamaga	Manyana	21.79	34.27			2.66	0.65
MSPGR 3	Thamaga	Moshupa			20.7	100		
MEHAGR 1	Thamaga	Mehane	18.03	19.08	20.9	97	2.64	0.46
SPTGR 1	Thamaga	Sephatlhaphatl	21.63	18.43	20.3	130	2.67	0.56
SPTGR 4	Thamaga	Sephatlhaphatl	19.68				2.66	1,00
SPTGR 5	Thamaga	Sephatlhaphatl	18.56				2.87	0.5
TMGR 1	Thamaga	Thamaga	21.48		13.6	105	2.8	1.29
RSSGR 1	Thamaga	Rasesa	21.18	18.09			2.6	0.35

Appendix C

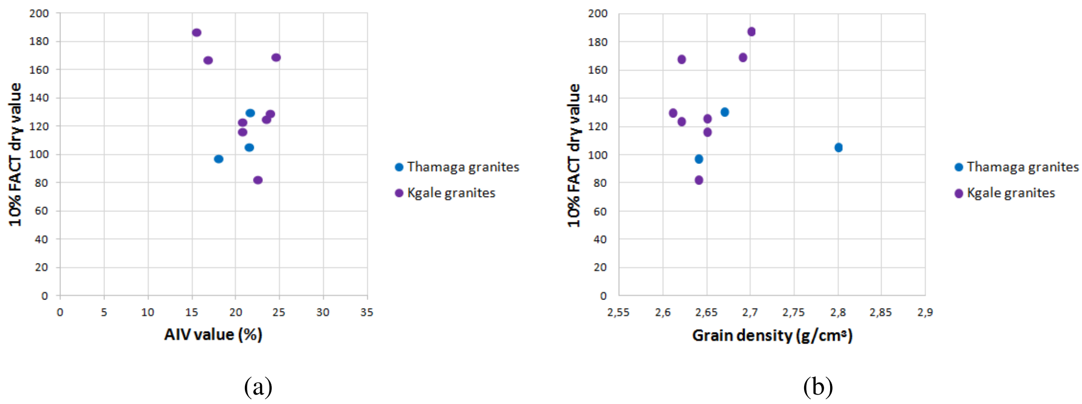


Figure 30: a) 10 % FACT value and AIV value for Thamaga and Kgale granites. b) 10 % FACT value and grain density for Thamaga and Kgale granites.

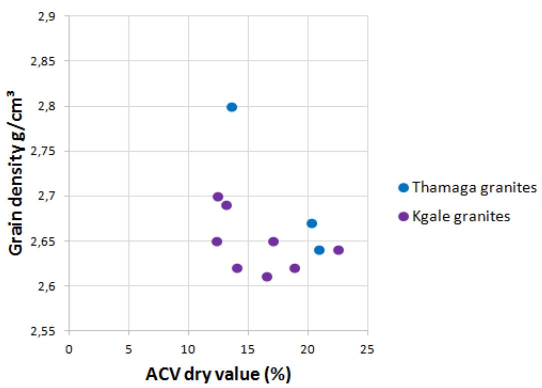
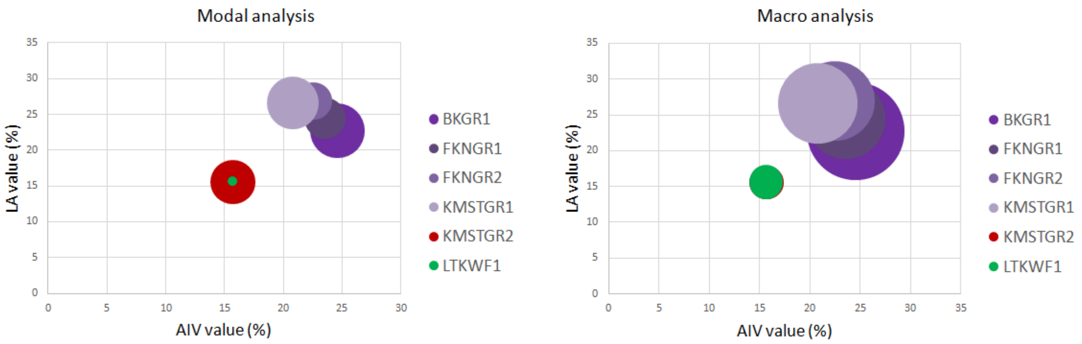


Figure 31: Grain density and ACV value for Thamaga and Kgale granites.

Appendix D



(a) (b)

Figure 32: a) The LA value correlates with the AIV and mean grain size of the modal analysis. b) The LA value correlates with the AIV and mean grain size of the macro analysis. The mean grain size corresponds to the size of the circles, larger circle diameter correlates to larger mean grain size.