RELATIONSHIP BETWEEN LOS ANGELES ABRASION VALUE AND MINERALOGY OF ROCKS

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Science in Mining and Mineral Exploration

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Abstract

This research includes study of the relationship between Los Angeles Abrasion Value and the mineralogy of rock aggregates narrowed down to the commonly found high grade metamorphic rocks in Sabaragamuwa Province. The study was carried out minimizing the effect of other factors as much as possible. Los Angeles Abrasion Test and Mineral content of each rock sample selected was determined at the laboratory. Thin section analysis was carried out to determine the mineral content with the help of electronic microscope equipped with a digital camera and the AutoCAD software.

Most of the rock quarries in the study area consist of biotite gneisses. Two samples are selected to represent them. Most of the other samples were selected from waste rock piles of quarries to have samples with varying content of minerals.The Regression Analysis was carried out to develop a relationship between Los Angeles Abrasion Value with engineering and mineralogical properties such as Relative Dry Density, Quartz Content, Feldspar Content as well as Mica Content.

The best regression line fit for the test results is a third order polynomial line between Quartz Content and Los Angeles Abrasion Value which shows coefficient of determination as 0.7952. Another important achievement of this study was developing a field guide to assist the personnel at the field work. It was completed with the photograph of each rock sample , microscopic view of the sample and their respective engineering and mineralogical properties such as Los Angeles Abrasion Value, Dry Density, Quartz Content, Feldspar Content and Mica Content.

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List of Abbreviations

ASTM	American Standard for Testing Materials
ICTAD-	Institute for Construction, Training and Development
LAAV -	Loss Angeles Abrasion Value
GSMB	Geological Survey And Mines Bureau

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Analysis of Mineral Content with AutoCad Software.

1 INTRODUCTION

1.1 General

In Sri Lanka, during past decade, demand for construction aggregates increases significantly with the rapid development in the road network and other infrastructures. Crushed rock aggregates of granite and granite gneisses are the major aggregates used in road construction works. Variety of engineering properties such as high strength, abrasion resistance and structural and textural characteristics ensures their continued existence as a construction material.

With the lasting high demand for construction aggregates hundreds of new metal quarries of medium scale were started within Sabaragamuwa Province. Some of the quarries could not achieve expected demand and were shut down due to lack of required quality of its aggregate produced while few others are operating in small scale supplying materials for regional demand resulting financial losses to the owner.

Therefore, when selecting an aggregate source, knowledge of the quarry rock's mineral properties can provide an excellent clue as to the suitability of the resulting aggregate (Cordon 1979). It is very beneficial if there is a possible methodology for identifying the aggregate properties by visually observing the mineralogical properties of the rock at the site itself.

There are four major types of aggregates used in Sri Lankan construction industry. This classification entirely depends on the size of the crusher output and particular usage of the aggregates. None of the physical properties are considered for this classification.

Table 1-1 The basic types of crushed rock aggregates used in Sri Lankan Construction industry

Particle Size (mm)	General Identity
20 - 15 or 22 - 17	¾ (Thunkala Gal)
15 -10 or 17 -12	½ (Bage Gal)
10 – 5 or 12 – 5	Chip Gal
5 – 0	Quarry Dust

Anyhow, local demand for aggregates changes with the colour of rock changes. That means most of the consumers have an idea on the strength of different rock types at an eye glance based on their experience. But still there is no proper legal methodology to ensure the particular use of aggregates produced in hundreds of rock quarries all over the country, to safeguard the consumer. As the licensing authority for quarrying Geological Survey and Mines Bureau of Sri Lanka has the responsibility and authority to develop such procedure for both consumer protection and the long last of the infrastructures. The successful implementation of such procedure positively depends on the amount of research and experiments carried out on that regards.

According to the Special Provisions provided for the ICTAD – Construction and Maintenance of Roads and Bridges, "The Contractor shall sample, in the presence of the Engineer initially one set of 3 representative specimens for each source of supply and subsequently when warranted by changes in the quality of aggregates for Aggregate Crushing Value or Los Angeles Abrasion Value and at least every 50 m3 for Grading and Particle shape (flakiness & elongation). Additional samples shall be taken for testing where visible changes in the properties of the cover aggregates are observed by the Engineer". The knowledge of different rock types and their physical and chemical properties are necessary to determine it. In case of any discrepancy samples obtained should be re-tested in laboratory scale which may take several hours to confirm the difference resulting lost time for the contractor, delaying projects or construction failure.

Provide a series of photograph with different rock types and their properties as a field guide to the site engineers would be beneficial to overcome these types of problems. In this short project I aimed to develop such a field guide for some basic rock types found in Sabaragamuwa province restraining to Los Angeles Abrasion Value which can be broaden for the other important tests and rock types.

1.2 Objectives

Major objectives of this research work are listed below.

1. To develop relationship between quartz content and Los Angeles Abrasion Value of rocks.
2. To develop relationship between non quartz mineral content and strength properties of crushed rock aggregates pertained to Los Angeles Abrasion Test
3. To determine the optimum content of minerals which, results higher value of LAAV.
4. To develop field guide for varieties of metamorphic rocks available in the Sabaragamua Province

Study of such relationship will have direct benefit to the Mining Engineers engaged in quarrying and crushing industries, consultant Mining Engineers of quarrying and crushing and the Mining Engineers in regulatory Authorities as well. Besides, the Civil Engineers those who engaged in construction industries can also use this study to have an idea about the suitability of aggregates supplied to them or purchased by them for construction work.

2 LITRATURE REVIEW

2.1 Aggregates in Construction Industry

Aggregates are fine to coarse grained particulate materials used in construction industry, including sand, gravel, crushed stone, slag, recycled concrete and geo-synthetic aggregates. Typically, they are used together with a binding medium such as water, bitumen, Portland cement, lime, etc. to form compound materials such as asphalt concrete and Portland cement concrete. There the aggregates add strength to the overall composite material. Aggregates are also used for base and sub-base courses for both flexible and rigid pavements.

Table 2-1 Classification of aggregates based on their particle size gradation

Size Limits	Grain Size	Qualification	Classification
	Cobble		
64 mm			
16 mm	Pebble	Coarse	Coarse aggregates (gravel)
		Fine	
5 mm			
1 mm	Sand	Coarse	Fine aggregates (Sand)
0.5 mm		Medium	
0.063 mm		Fine	
	Fines (silt & clay)		

(T. H. Skaggs , L. M. Arya, P. J. Shouse and B. P. Mohanty, 2000).

Crushed rock aggregates are the most widely used coarser aggregates used in Sri Lanka in concrete and road works. Rock aggregates are produced by open pit quarries in law lands associated with underlying bedrock and open quarries in high lands associated with exposed bed rock both with explosive blasting and sub-sequential size reduction by mechanical means such as breakers and crushers. Rock quarries were located all over the country in association with high grade metamorphic rocks. All are operated in medium scale compared with the other countries.

Aggregate particles have certain physical and chemical properties which make them acceptable for specific uses and conditions. The basic physical properties are absorption, porosity and permeability, surface texture, strength and elasticity, density and specific gravity, hardness, particle shape, coatings and undesirable physical components.

A series of engineering properties along with the standard tests methods are defined to verify these physical properties of aggregates in laboratory scale. Among them Los Angeles Abrasion Test which measures resistance to weathering by impact, abrasion and crushing is one of the most important engineering property to verify the strength of rock aggregates.

Los Angeles Abrasion value is one of the key engineering properties governing the use of aggregates in road construction work along with the other properties such as Aggregate Impact Value (AIV), particle size gradation, clay, silt and dust fraction, flakiness index, specific gravity and soundness of aggregates.

Specially, in case of road construction works “Standard Specification for Construction and Maintenance of Roads and Bridges” published by Institute for Construction Training and Development of Sri Lanka (ICTAD Sri Lanka) provides the guidelines for selecting aggregates in each and every application in construction of roads and bridges. This is the guideline used by every construction firm unless otherwise specified by the relevant local authority.

Table2-2 Specifications for aggregates used in surface course as specified in Annex iii of ICTAD specification.

Particle Density (Specific Gravity)	Generally > 2.65
Water Absorption (an indicator of porosity)	< 2%
Flakiness index (shape factor)	<25 (for wearing course) <35 (for general purposes)
Aggregate impact value (AIV strength test)	Generally <25
Aggregate crushing value (ACV strength test)	Generally <24 or <30
10% fines value (strength test)	>160kN
Loss Angeles abrasion value (LAAV attrition test)	<40 for wearing course <50 for base course
Aggregate abrasion value (AAV surface wear test)	<14 for lightly trafficked sites Or <10 for potentially dangerous sites
Polished stone value (PSV skid resistance test)	>60 for potentially dangerous sites >45 for low risk sites
Sulphate soundness test (disintegration by weathering test)	<18% magnesium sulphate test

(UNOPS Sri Lanka Operations Centre, 1989)

The specifications of aggregates are basically two types as source properties and consensus properties. LAAV is one of major consensus property of aggregates with universal acceptance.

The physical strength of rocks has profound influence on the properties of aggregates produced. Hence the aggregate properties are typically related to the type of rock, mineral content of the rock, degree of weathering upon which the rock strength depends and production process used for aggregate production.

The properties of aggregates are basically determined by the type of rock used to produce it. Metamorphic and igneous rocks have usually high strength than sedimentary rock and are good for aggregate production.

Sedimentary Rock Aggregates

Dolomites and limestone are hard and durable and are useful as aggregates. Sand stones, gritstones, arkoses (feldspathic sandstones) and greywackes (impure sandstones) are also used as aggregates, although their strength and durability directly depends on degree of cementation. (Adlam et al, 1984)

Igneous Rock Aggregates

Igneous rocks are widely quarried for crushed rock aggregates. The finegrained varieties such as dolerite, basalt and porphyry are often preferred due to their high strength. The suitability of these rocks for aggregates depends on mineralogy, texture and degree of alterations.

Metamorphic Rock Aggregates

A wide range of metamorphic rock types are used as aggregates . Coarser or medium grained massive, granular rocks such as gneisses, quartzite and marbles generally produce high quality aggregates. Foliated and platy rocks such as schists and phyllites are usually weaker and may be less durable.

The Island of Ceylon is composed almost entirely of crystalline rocks of Archean or pre-Cambrian age. In the extreme north these are overlain by limestones of Miocene or later age. At one point on the northwest coast a very small area of Jurassic rocks lies on the surface of the coastal plain.The ancient crystalline rocks resemble in many respects the Grenville series of the Canadian Shield. They are largely biotite gneisses, interstratified with which are at least two great beds of white crystalline limestone, often dolomitic, with associated beds of quartzite and of sillimanite-bearing rocks of undoubted sedimentary origin. Charnockite and allied rocks are present also in large amount, especially in the higher parts of the island (Adams 1929).

The main minerals present in fresh rocks are quartz, feldspar, biotite mica, hornblende and hypersthene. Few other minerals are also present as minor components. There are no reactive forms of silica minerals such as opal and chalcedony in these rocks. Hornblende biotite gneiss, biotite gneiss, migmatite and migmatitic gneiss have mica percentages higher than 5% (5%-20%). Mica percentage in charnockite, charnocktic gneiss and granitic gneiss is always less than 5% (U De S Jayawardena and DMS Dissanayake, 2008).

Textural and structural characteristics of metamorphic rocks also have an influence on aggregate strength as well as aggregate production process. The production process also causes to develop new cracks and to open the existing cracks and fractures of the parent rock and reduce the aggregate strength. Mineral content of rocks differ from place to place. Sometimes, even within the same quarry aggregate properties changes due to change in mineral content. Aggregates of gneisses and schist are not identical even with the same mineral composition. Therefore understanding the relationship between all those properties of host rocks and aggregate quality is incomprehensible.

2.2 LAAV of rock Aggregates

Los Angeles Abrasion value indicates the measure of resistance of coarse aggregate to degradation by impact, abrasion and grinding. It is also a measure of strength of the material tested. This test is both an abrasion and impact test and suitable for testing aggregates used in the wearing course (surface dressing), asphalt concrete and other layers. LAAV is important not only for determining suitability of aggregates for a particular uses but to have an idea about the crushing effect and losses during handling and storage of the material itself and crushability of rock types

Los Angeles Abrasion test is suitable for coarse aggregate and applicable for several identified particle size gradations. Selection of particle size range depends on the required size for a particular application.

Loss Angeles Abrasion testing machine is designed to meet the requirement of ASTM C131M-14 (American Standard for Testing Minerals C131) and the test is carried out in accordance with the guidelines provided by the standard.

Loss Angeles Abrasion Value is the percentage of particles passing on 1.7 mm size standard mesh after subjected to rotation in LAAV machine. The machine is designed to meet the required rotation specified in the said standard while the number of rotation is specified in machine instruction manual depending on the particle size range specified.

Table 2-3 Grading of test samples according to the machine instruction manual which follows ASTM C131M-14

Sieve Size (Sq. hole)		Weighting of test samples for grade						
Passing mm	Retained on mm	A	B	C	D	E	F	G
80	63	-	-	-	-	2500	-	-
63	50	-	-	-	-	2500	-	-
50	40	-	-	-	-	5000	5000	-
40	25	1250	-	-	-	-	5000	5000
25	20	1250	-	-	-	-	-	5000
20	12.5	1250	2500	-	-	-	-	-
12.5	10	1250	2500	-	-	-	-	-
10	6.3	-	-	2500	-	-	-	-
6.3	4.75	-	-	2500	-	-	-	-
4.75	2.36	-	-	-	5000	-	-	-

(ASTM, 1994)

Standard steel balls are introduced into the rotation drum of the machine along with the sample to provide impact, grinding and abrasion. Number of steel balls introduced to the drum is also specified based on the particle size range and the weight of the particles used.

Table 2-4 Number of steel balls introduced to LAAV machine according to ASTM C131-14.

Sample Grading	Number of steel balls	Weight of charge (g)
A	12	5000 ± 25
B	11	4584 ±25
C	8	3330 ± 20
D	6	2500 ± 15
E	12	5000 ± 25
F	12	5000 ± 25
G	12	5000 ± 25

(ASTM, 1994)

After specific number of rotation with specified no of steel balls the percentage weight loss of sample is determined as the LAAV value and calculated with the following formula.

$$\text{Loss Angeles Abrasion value} = \frac{(\text{Initial Weight of the sample} - \text{Weight of the sample greater than } 170\mu\text{m})}{\text{Initial weight of the sample}} \times 100$$

This test has been widely used as an indicator of the relative quality or competence of various sources of aggregate having similar mineral compositions. Anyhow the meaning of this test is misinterpreted in Sri Lankan construction industry by mixing different sources of aggregates to meet the required value of the test causing early failures in structures and unexpected decay in road surfaces due to presence of unfit material in the aggregate mixtures.

According to the specifications if LAAV less than 30% is suitable for all mixture, and if it is more than 50% aggregate is unusable in any mixture. Almost all the construction companies test the aggregate properties following the guidelines provided by ICTAD specification prior to and throughout their construction processes. But no one has yet studied the behavior of Los Angeles Abrasion value different varieties of rocks in case of Sri Lankan rock aggregates.

In case of bitumen premix carpet the coarser aggregates should be crushed stone of clean, hard, tough, durable rock of uniform quality. An aggregates mineral composition largely determines its physical characteristics and how it behaves as a pavement material. Therefore, when selecting an aggregate source, knowledge of the quarry rocks and their mineral properties can provide an excellent clue as to the suitability of the resulting aggregate (Cordon 1979).

2.3 Mineralogy of rocks

A wide variety of rock types are suitable for use as aggregates, including hard rocks of metamorphic, igneous and sedimentary origin.

For this one year study the research was narrowed down to high grade metamorphic rocks specially gneissic rocks in Sabaragamuwa Province. Most part of the

Sabaragamuwa province belongs to Highland series and composed of high grade metamorphic rocks derived from sediments and altered by one or more metamorphism and charnokites. The major minerals found are Quartz, feldspar and mica while some tracer minerals such as garnet, silimanite can also be found in some places.

Metamorphic rocks are classified according to their source rock type, structure; microstructure and mineral composition   Mineral composition is a parameter that reflects the proportions of the individual minerals within the rock.
A rock consists of one or more minerals. The physical and mechanical properties are a function of the mineralogical and textural and stuctural characteristics of the rock (Irfan, 1996).

Abrasion resistance is a function of strength, texture and hardness of the rock material where the strength of a rock sample has close relationship with the mineral composition, degree of metamorphism and intensity of micro fractures of its parent rock.

The presence of strong minerals such as quartz, orthoclase and garnet results in high strength of rock mass while the presence of weak minerals such as plagioclase, biotite and muscovite lower the strength of rock masses.

Minerals are chemical compounds; just a few are native elements. The only instrumental technique which identifies the minerals analyzed in a rock sample, or in crystals separated from it, is X-Ray Diffraction. Electron microprobe, X-Ray Fluorescence, Atomic Absorption Spectruscopy and many other analyitical methods only give a chemical composition of minerals, either expressed as weight percent of elements, or oxides, but they don’t identify minerals in a direct way. In such cases exact formula of the mineral interested and the formulas of the other minerals present in the rock should be known with which an approximation can be done with one of the above mentioned test results. The percentage calculation becomes more complex if more mineral compounds are present in the rock specimen to be check.

The microscopic investigation of minerals is the widely used traditional technique for petrographic studies. Not only the rock mineralogy but the textural and structural characteristics of the rock can also be studied by microscopic analysis of thin sections of a particular rock sample. Using photograph of a selected view of microscope, the mineral content of rock sample can be determined manually or with the aid of computer software in respect of the percentage area occupied in the photograph.

The combination of polarizing microscopy along with image analysis makes it possible to determine the mineral composition, as well as the microstructural parameters quantitatively (Heilbronner, 2000; Trčková et al., 2008)

Fully automatic image analysis distinguishes objects from the background according to their colour differences (Ehrlich et al., 1991). This type of system does not identify the minerals itself it can only process the image into different colour intensities and give the percentage area occupied by each colour. Therefore it is not quite a reliable method to identify the minerals having same colour such as quartz and feldspars, which are white at polarized position and white to gray at non-polarized positions.

During semi-automatic image analysis; objects are captured by the operator (Siegesmund et al., 1994; Přikryl, 2006). Whereby the minerals are identified by the person and image is classified manually into different mineral grains, for which clear grain boundaries are a vital factor.

Except above two methods spectroscopic images are manually analyzed in most of the institutes in Sri Lanka applying grid counting technique which is more time consuming and fatigued.

Considering all three methods more precise analysis could be achieved with semi-automatic image analysis. But reliability of the analysis totally depends on how precisely the thin section prepared represents the rock itself and the observers skill to precise identification of mineral grains.

The identification of mineral under microscope needs the knowledge of optical properties of minerals. Some of the basic properties used to identify the major rock forming minerals such as quartz, biotite and feldspars were described below. Table 6 gives the basic propertied used to differentiate the minerals under thin sections for this study.

1. Colour and pleochroism

   Colour and colour intensity are special mineral property. The colour changes when some of the wave lengths are absorbed by the mineral when white light passes through it. If the absorption is outside the visible range mineral appears white to gray colour.

   Minerals having symmetrical crystals are optically isotropic and selective absorptions are the same along all three axes hence the mineral appears with a single colour when the microscopic stage is rotated. The anisotropic minerals have different absorption parallel to three axes. The absorption wavelengths change when the stage is rotated depending on the orientation of the crystals. This phenomenon is called pleochroism.

2. Relief

   Mineral grains appear to be higher or lower than its surrounding because of the refraction and reflection of light at the boundaries.

3. Extinction behavior

   The image of birafringent crystals appears periodic changes between bright and dark images when the stage of the microscope is rotated under polarized light which are called extinction positions. Some minerals appear in different colours (interference colours) at the extinction positions

Figure 2-1 shows the interference colours of minerals under polarized microscope.

4. Twining

   Twining is an optical property due to intergrowth of crystals or deformation of crystals. The lamellar twin (Polysynthetic twin) is used to identify the Plagioclase feldspar.

Figure 2-2 shows the lamellar twining of plagioclase feldspar and Figure 2-3 shows microcline grids in orthoclase feldspars.

Mineral composition reflects the proportions of individual minerals in the rock calculated as total area of individual mineral divided by total area of the rock

$$M = \frac{\Sigma A_{M}}{\Sigma A_{TOT}} \times 100$$

Where M = Mineral content as a percentage

ΣA_M = Area occupied by a particular mineral on thin section view

ΣA_{TOT} = Total area of thin section view

Table 2-5 Basic optical properties of minerals analyzed with this study

Property	Quartz	Plagioclase Feldspar	Orthoclase Feldspar	Biotitic Mica	White Mica
Colour at plain polarized position	White	White to light green	White	Brownish green	white
Colour at crossed polarized position	White – dark grey	White – dark grey	White to dark grey	3rd order birefringence colours	2nd order birefringence colours
Topology and other features	Monomin group	Twin lamellae	Microcline grid	Perfect cleavage	cleavage

Refer Figure 2-1 for 2nd order and 3rd order birefringence colours

Figure 2-2 for Twin lamellae of Plagioclase Feldspar

Figure 2-3 for Microcline grid of K-feldspar

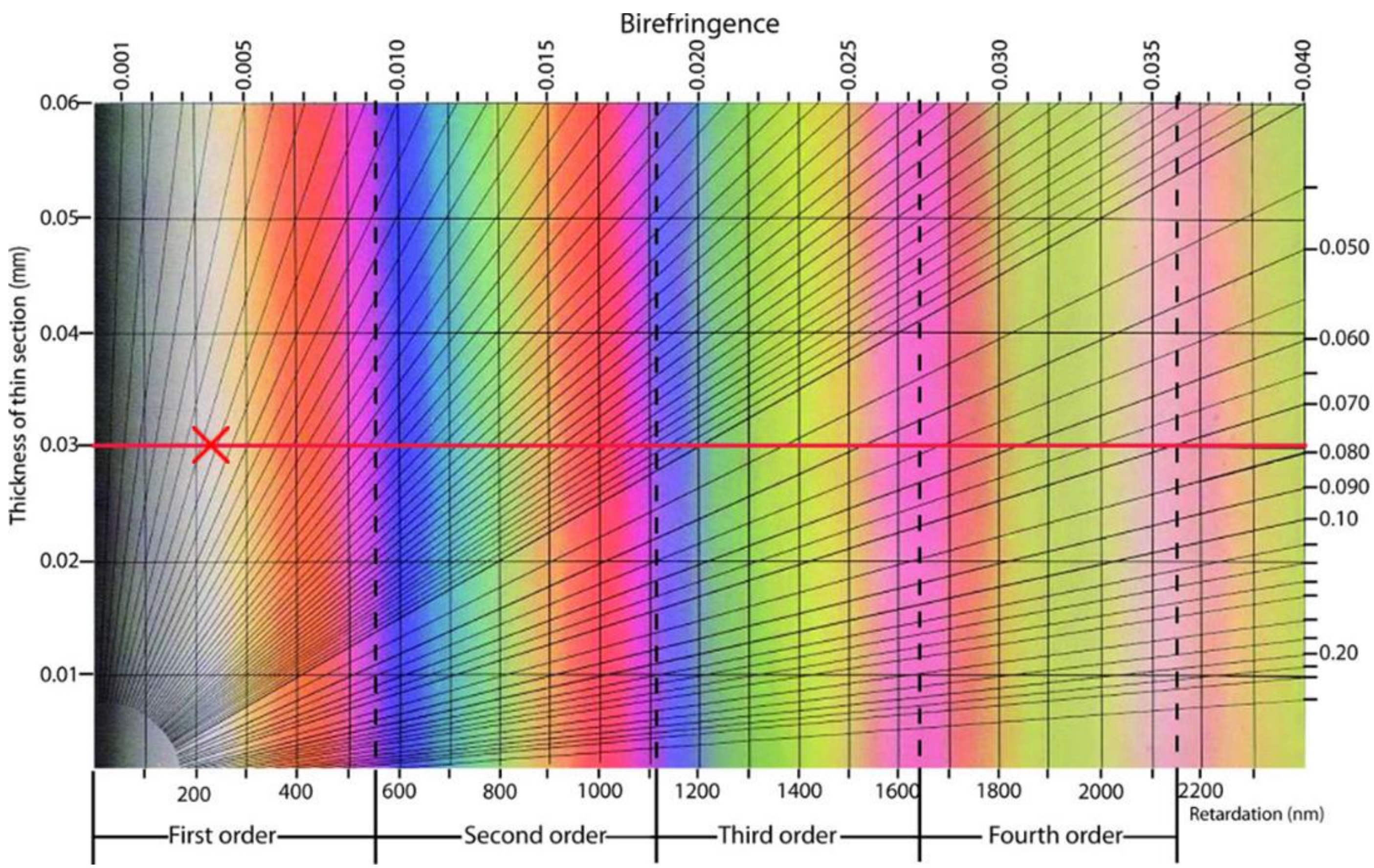


Figure 2-1 Birefringence colours of minerals under microscope

(Stephen A. N., 2014)

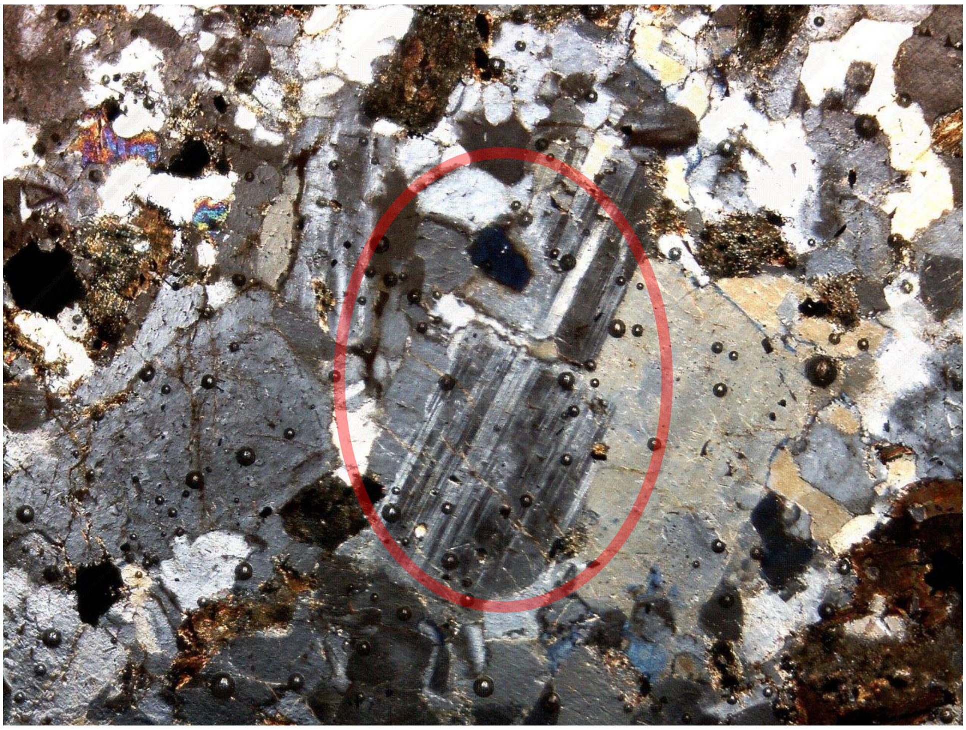


Figure 2-2 Lamellar twining of Plagioclase Feldspar

(Geoscience Research Institute, 2015)

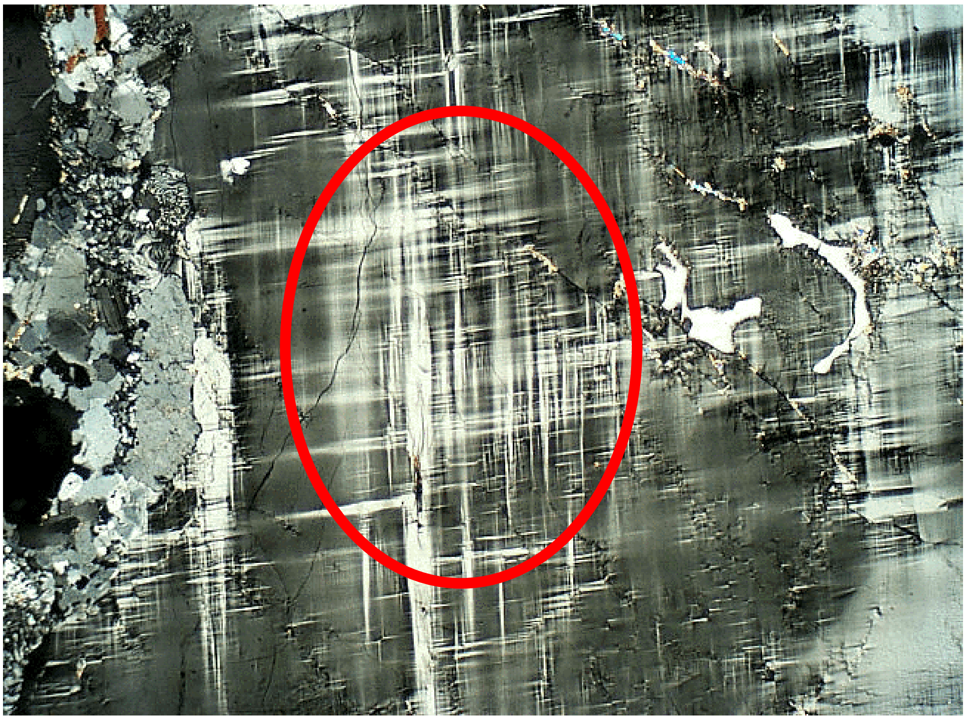


Figure 2-3 Microcline grids in orthoclase feldspar

(Geoscience Research Institute, 2015)

3 METHODOLOGY

3.1 Sample collection & Preparation

Sabaragamuwa Province is selected as the base area for my research because with my past experience through the annual inspection of quarry site for their mining license renewal I have a clear picture about the varieties of rocks found in the area. Almost all the quarries in Sabaragamuwa Province consist of high grade metamorphic rock with different mineral content. For this study I consider some commonly found rocks with different mineral content in Sabaragamuwa province. The location of Sabaragamuwa province which includes both Rathnapura and Kegalle districts is shown by the coloured area of the Sri Lanka map shown in figure 3-1.

Figure 3-1 Map of the study area

Initially about 20 pieces of rock samples were gathered randomly covering the area numbered and location details were recorded out of which 10 samples were selected for further studies. The samples were decided simply by visual observation of those rock pieces depending on their basic mineral content.

Quartz rich as well as feldspar rich rocks are not common in Kegalle District Such rocks are abundantly found in Balangoda, Weligepola and Godakawela areas. One sample rich with quartz is selected from Godakawela area from a quartz mining quarry meanwhile, other sample rich with quartz is selected from waste rock pile of a quarry in Balangoda area.

The details of each sample locations including District, Divisional Secretariat Division and Grama Seva Division and GPS location are given in table 3-1 with their respective smple ID.

Figure 3-2 shows the situation of each sample location plotted on a map with ArcMap 10.1.

Samples were collected from the blasted output of quarries instead of crusher output located in each sampling location selected; especially large rock boulders were collected to ensure the uniformity of the mineral content as well as to minimize the blasting effect. Samples were collected in sample bags and numbered as listed in Table 3.1. About 30-40 kg of each sample was collected and transported to the laboratory be vehicles and special care was given for avoiding the sample mixing.

Samples were sized at the laboratory by hammering and subsequently feeding to laboratory scale jaw crusher. Sample grading B (Refer Table 1-3 on page 13) was selected which should contain 2.5 Kg from 20-12.5 mm size range and 2.5 kg from 12.5-10 mm size range to meet the particle size range of chips (Refer Table 1-6 in page 20) in crusher output which is basically used in asphalt production and surface dressing.

Table 3-1 gives the details of sample locations including District, Divisional Secretariat Division, Grama Seva Division and GPS location.

Table 3-1 Sample Details

Sample ID	Location				Remarks
	District	DS Division	GN Division	GPS	
KE/S1	Kegalle	Dehiowita	Deloluwa	150662E, 194679N	
KE/S2	Kegalle	Dehiowita	Deloluwa	150662E, 194679N	From waste rock file
KE/S3	Kegalle	Ruwanwella	Mahakanda	201322E, 212103N	
KE/S4	Kegalle	Ruwanwella	Mahakanda	201322E, 212103N	
RT/S5	Rathnapura	Godakawela	Masimbula	185410E, 144178N	
KE/S6	Kegalle	Ruwanwella	Mahadeniya	136878E, 201066N	
KE/S7	Kegalle	Mawanella	Thabawita	170292E, 222004N	
KE/S8	Kegalle	Rambukkana	Muwapitiya	160374E, 233521N	
KE/S9	Kegalle	Dehiowita	Welangalla	139686E, 191977N	From waste rock file
RT/S10	Rathnapura	Balangoda	Thelidiriya	196797E, 156056N	From waste rock file

Figure 3-2 shows the sampling locations labled with sample ID.

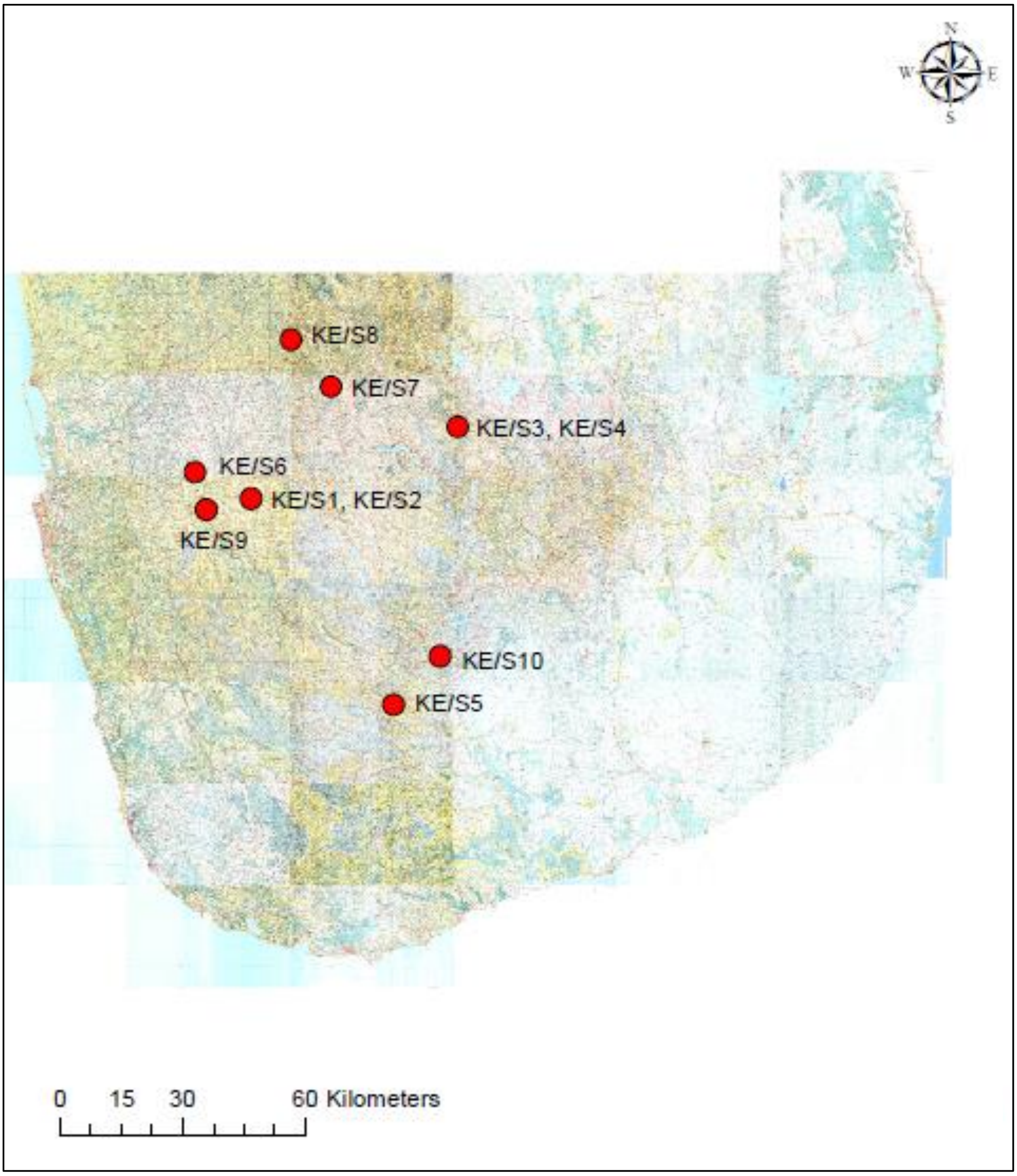


Figure 3-2 Sample Details

3.2 Equipment Used

Loss Angeles Abrasion Value (LAAV) test was carried out with the EKE-458-1 Loss Angeles Abrasion Testing Machine which meets the essential requirements of ASTM 131-14 standards. A photograph of EKE-458-1 machine used for the testing is shown in figure 3-3.

Figure 3-3 EKE-458-1 Loss Angeles Abrasion Testing Machine

Preparation of thin sections for analyzing mineral content was carried out using the instruments shown in figure 3-4 and 3-5.

Figure 3-4 Instrument used for grinding thin section

Figure 3-5 Instrument used for fine grinding and polishing thin sections

The prepared thin sections were analyzed using electronic microscope equipped with AxioCamERc5s shown in Figure 3-6.

Figure 3-6 Electronic Microscope

3.3 Determination of Rock Properties

Loss Angeles Abrasion Value and Relative Density are the major engineering properties determined at the laboratory to accomplish the aim of this study. Amount of major mineral components, quartz, feldspar and mica are determined as a percentage by thin section analysis.

3.3.1 Dry Density

Dry density of each rock samples was determined at the laboratory to have an idea of degree of metamorphism or compaction of rock sample. The test was carried out in accordance with ASTM standard and the basic steps followed are listed below.

1. Three small rock pieces were dried in the oven for 2-3 hours at 105-110^{0}C.
2. Dry weight of the sample was measured using the electronic balance.
3. The buoyancy measuring apparatus was set over the electronic balance and the balance was set to zero.
4. The rock piece was submerged on buoyancy apparatus and the reading on the balance was taken.
5. Relative Dry density was calculated using the following formula.

$$\text{Relative Dry Density} = \frac{m1}{(m1 - m2)} \times \rho_w$$

m1 = dry weight of the sample

m2 = Reading of the balance after submerging the rock piece.

6. Three small rock pieces were tested for dry density and the average value was taken as the dry density of rock sample.

3.3.2 Loss Angeles Abrasion Value

Laboratory test of determining Los Angeles Abrasion Value was carried out following ASTM C 131-14 standard. The basic steps of the test procedure is summarized below.

1. Rock pieces of some quarry sites over the Sabaragamuwa province were collected with the record of their identical location.
2. 10 quarry sites were selected having varying content of quartz, feldspar and biotite by observing the collected rock pieces with magnifying lens.
3. Two large rock pieces of total weight 25-30kg was collected into sample bags

4. The collected rock samples were hammered and crushed to prepare sized sample in the range of 10-20 mm.
5. The crushed samples were sieved using 20mm, 12.5mm and 10mm standard meshes, washed to remove dust and oven dried at 105-110^0 C for 2-3 hours until the sample gained a constant weight.
6. 5kg of sample was weighed and mixed in the following size range.

Particle size	Amount
20-12.5mm	2.5kg
12.5-10mm	2.5kg

7. The prepared sample was introduced into the cylinder of the testing machine after cleaning it and 12 standard steel balls were added.
8. The cylinder of the LAAV machine was rotated for 500 revolutions at the specified speed.
9. The rotated sample was discharged from the cylinder completely and sieved with 1.7mm standard sieve.
10. The retained sample was washed and oven dried for 2-3 hours at 105-110^{0}C and weighed.
11. Los Angeles Abrasion Value is calculated with the following formula.

$$\text{LAAV} = \frac{\text{M1} - \text{M2}}{\text{M1}} \times 100$$

M1 = Original weight introduced into the cylinder

M2 = Weight of particles retained on 1.7mm sieve

12. Three samples were tested from each rock sample and the average value was taken as the LAAV of the sample.

3.3.3 Thin Section Analysis

Thin sections of each sample were prepared at the laboratories. The prepared thin sections were analyzed for major textural and structural features and mineral content. The major steps followed are mentioned below.

1. Thin section of each mineral specimen was observed under polarizing microscope for remarkable difference in grain size, amount of cracks and fractures present.
2. Photographs of microscopic views were taken with the camera attached to the electronic microscope.
3. Without changing the position of view all mineral grains in that particular view was identified at polarized and non-polarized positions and by rotating the stage of the microscope.
4. The photographs of each view were uploaded to AutoCAD software and mineral grains were drawn into separate layers.
5. The area percentage occupied by each mineral is calculated and assumed represents the volume percentage occupied by each mineral.
6. Three views from one thin section were analyzed in same procedure and average content of each mineral was determined

4 RESULTS

All numerical values obtained at laboratory tests and the calculated values of each engineering property and average values of them are tabulated below under sub heading of each property.

4.1 Dry Density

Table 4-1 shows the test results of dry weight, buoyancy meter reading and calculated values of relative dry density of each rock sample.

Table 4-1 Determination of Relative Dry Density

Sample ID	Sub sample	Dry Weight (g)	Buoyancy Reading (g)	Relative Dry Density	Average Relative Dry Density
KE/S1	1	21.0	8.1	2.59	2.63
	2	11.5	4.3	2.67	
	3	4.5	1.7	2.64	
KE/S2	1	33.5	12.0	2.79	2.78
	2	12.0	4.3	2.79	
	3	8.0	2.9	2.75	
KE/S3	1	11.5	4.0	2.875	2.82
	2	10.5	3.9	2.69	
	3	7.5	2.6	2.88	
KE/S4	1	9.5	3.5	2.71	2.71
	2	10.0	3.7	2.7	
	3	9.0	3.3	2.73	
RT/S5	1	29.5	10.0	2.95	2.74
	2	19.5	7.6	2.56	
	3	19.0	7.2	2.71	
KE/S6	1	8.0	3.3	2.42	2.44
	2	11.0	4.6	2.39	
	3	6.0	2.4	2.5	

KE/S7	1	5.5	1.9	2.89	2.73
	2	7.0	2.6	2.69	
	3	6.0	2.3	2.61	
KE/S8	1	6.0	2.0	2.87	2.92
	2	5.0	1.7	2.94	
	3	8.0	2.7	2.96	
KE/S9	1	15.5	5.7	2.74	2.74
	2	18	6.9	2.6	
	3	12	4.1	2.9	
RT/S10	1	12.5	4.46	2.8	2.76
	2	16	6.15	2.6	
	3	10.5	3.7	2.82	

4.2 Los Angeles Abrasion Value

Table 4-2 gives the laboratory test results and determination of LAAV of each rock sample.

Table 4-2 Determination of LAAV

Sample ID	Weight Retained (g)			LAAV %			Average LAAV %
	S1	S2	S3	S1	S2	S3	
KE/S1	2621	2626	2620	47.58	47.48	47.6	47.55
KE/S2	2701	2667	2662	45.98	46.66	46.76	46.47
KE/S3	2810	3025	2925	43.8	39.5	41.5	41.6
KE/S4	2453.5	2450	2455	50.94	51.0	50.9	50.94
RT/S5	2684	2742	2723	46.32	44.96	45.54	34.20
KE/S6	Omitted due to low relative density						
KE/S7	2625	2506	2580	47.5	49.88	48.4	48.59
KE/S8	2600	2630	2550	58.0	47.4	49.0	48.13
KE/S9	2900	2825	2975	42	43.5	40.5	42
RT/S10	2275	2100	2375	54.5	58	52.5	55

4.3 Mineral Content

Percentage of quartz, feldspar and mica content of each rock sample was listed in table 4-3. The relevant microscopic views and the separated layers of mineral grains with AutoCad software are attached as appendix A.

Table 4-3 Percentage of mineral content in rock samples

Sample ID	% Quartz Content	% Feldspar Content	% Mica Content	% Other Mineral Content
KE/S1	67.7	29.2	2.8	0.5
KE/S2	68.8	11.0	19.0	0
KE/S3	36.0	50.7	11.9	1
KE/S4	75.4	20.1	4.5	0.5
RT/S5	99	0.5	0.5	0
KE/S7	45.8	47.8	6.4	0.5
KE/S8	63.2	2.3	34.5	1
KE/S9	41.5	40.9	16.6	3.3
RT/S10	11.0	76.3	11.9	1

4.4 Summary of Test Results

Summary of laboratory test results are given in table 4-4 for easy reference.

Table 4-4 Summary of Test Results

Sample ID	Specific Dry Density	LAAV %	% Quartz Content	% Feldspar Content	% Mica Content
KE/S1	2.63	47.55	67.7	29.2	2.8
KE/S2	2.78	46.47	68.8	11.0	19.0
KE/S3	2.82	41.6	36.0	50.7	11.9
KE/S4	2.71	50.94	75.4	20.1	4.5
RT/S5	2.74	34.20	99	0.5	0.5
KE/S6	2.4	Omitted due to low relative density			
KE/S7	2.73	48.59	45.8	47.8	6.4
KE/S8	2.92	58.13	63.2	2.3	34.5
KE/S9	2.74	42	41.5	40.9	16.6
RT/S10	2.76	55	11.0	76.3	11.9

5 DISCUSSION

Foremost aim of this piece of study was to examine and develop any relationship between quartz content and LAAV of rock aggregates and also to analyze the other basic rock forming minerals such as feldspar and mica to look for any relation to LAAV. While carrying out practical work, the other influencing factors were kept constant or negligible as much as possible.

5.1 Quartz Content Vs. LAAV

Figure 5-1 shows the first, second and third order regression lines fit for the plotted data of % LAAV against the % of quartz content in rock samples.

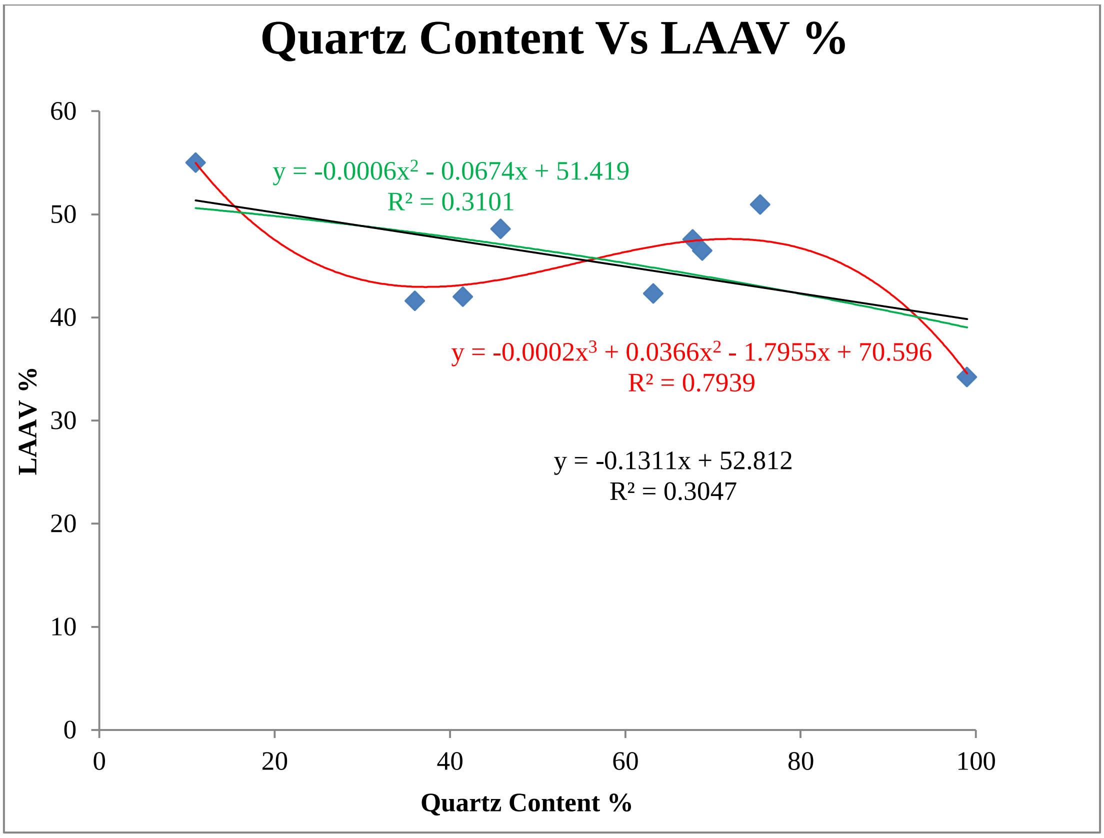


Figure 5-1 Quartz Content Vs. LAAV

The best relationship observed by regression analysis of quartz content and LAAV is the third order polynomial relationship shown in red colour in figure 5-1.

The coefficient of determination or R^2 for this relationship is 0.7952 which says that 79.92% of analyzed data fits the proposed regression line. This relationship need to be improved by carrying more laboratory testing of different samples.

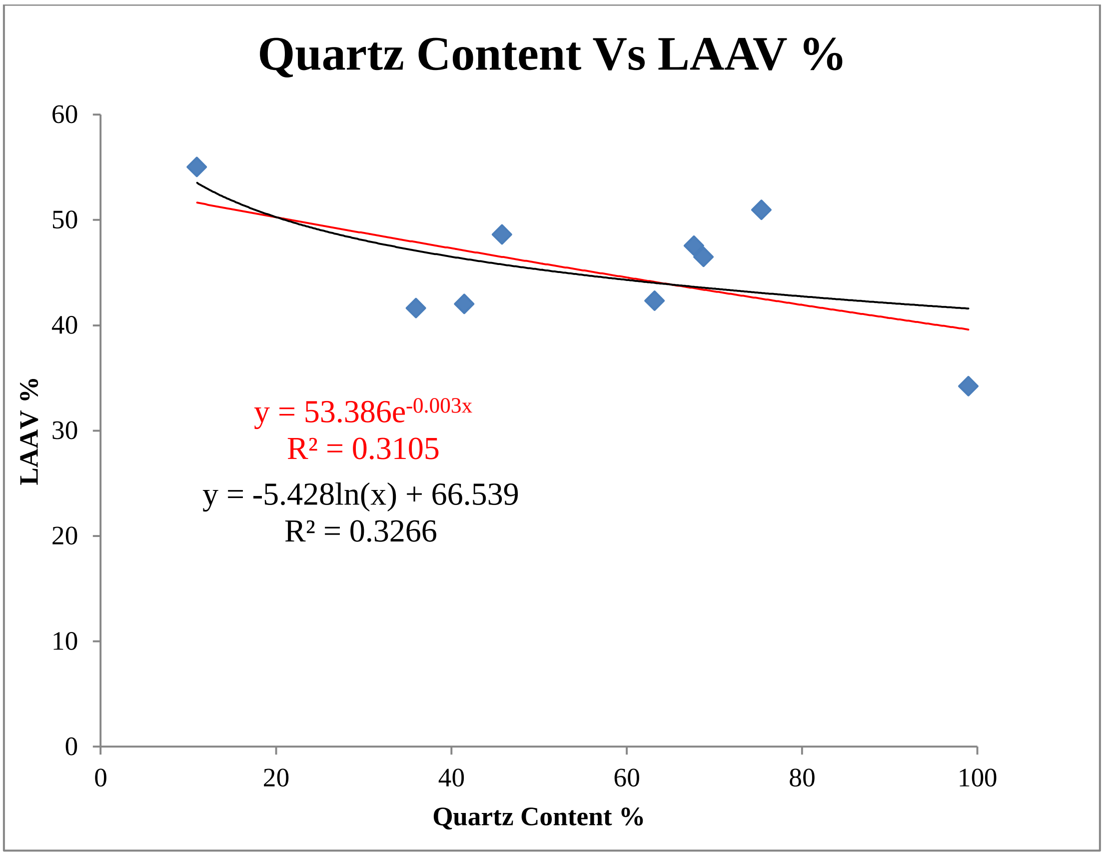


Figure 5-2 Quartz Content Vs. LAAV

Figure 5-2 shows the exponential and logarithmic curves best fit with the results of quartz content vsLAAV. Exponential function is shown in red colour while logarithmic function is shown in black. The two curves do not fit for the data.

5.2 Feldspar Content Vs. LAAV

Figure 5-2 shows the best fit curves of first, second and third order polynomials in black yellow and red colours respectively for the graph of LAAV vs Feldspar content. The curves in blue and yellow colours show the proposed exponential and logarithmic curves respectively. The coefficient of determination reveals that there is no precise relationship between feldspar content and LAAV.

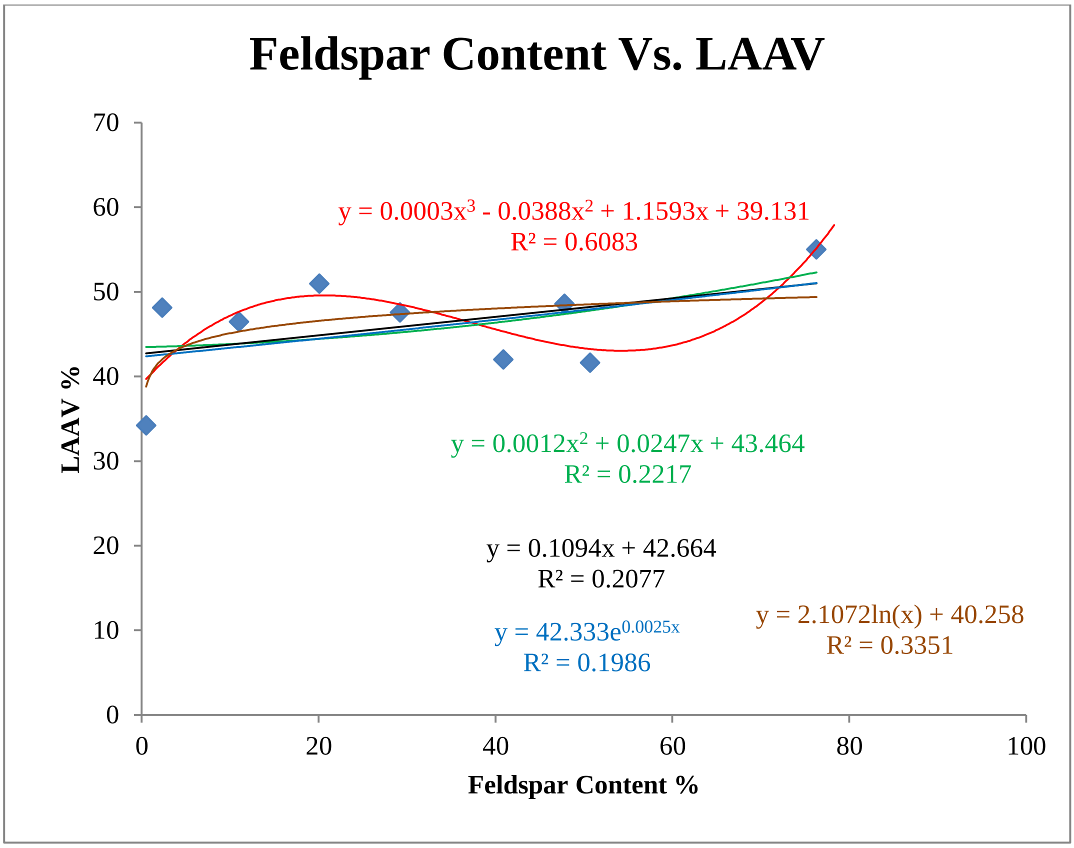


Figure 5-3 Feldspar Content Vs. LAAV

Developing a relationship between feldspar content and LAAV is unsuccessful because presence of orthoclase feldspar causes for higher strength while plagioclase feldspar reduces the strength of the sample. Sample KE/S3 and KE/S9 consists of orthoclase feldspar in which the LAAV is relatively higher than the other samples. In case of KE/S10 feldspars are plagioclase and has lower LAAV value than KE/S3 and KE/S9those which have approximately same feldspar content.

5.3 Mica Content Vs. LAAV

The same relationships are studied for mica content and LAAV as well. Figure 5-4 shows the relevant curves for polynomial, exponential and logarithmic functions. The first, second and third order polynomials are shown in black, red and green colours while exponential and logarithmic functions are shown in brown and blue colours respectively.

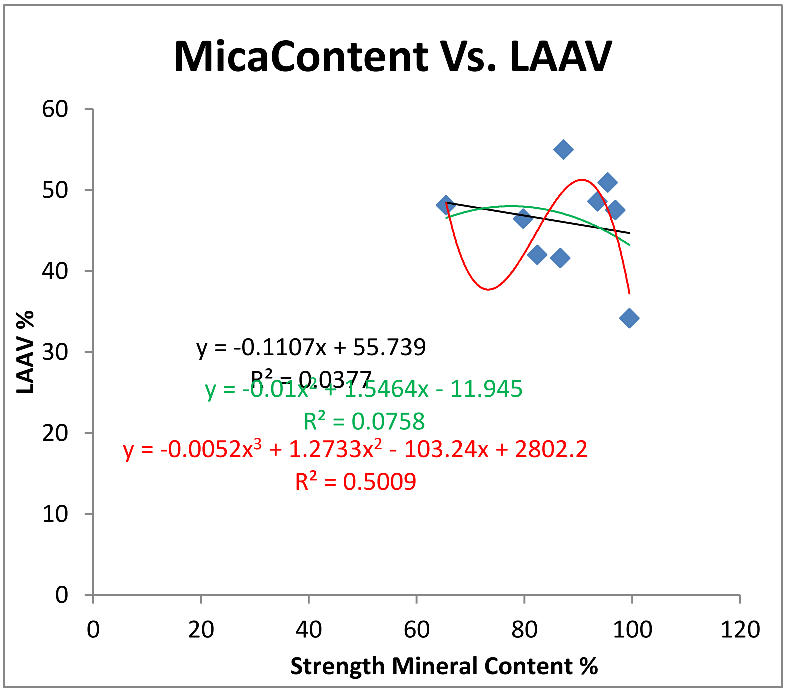


Figure 5-4 Mica Content vs. LAAV

When mica is scattered over the sample as pockets the strength reduces. If mica is dispersed with quartz the sample has higher strength. Sample KE/S8 has mica scattered as pockets where by higher LAAV than other samples.

5.4 Relative Dry Density Vs. LAAV

Out of the ten samples selected, one sample which had sample identity as KE/S6 had to be rejected due to lower value of relative density. The relative density observed for the sample was 2.4.

Dry density is a physical property influenced by the specific gravity of the composition minerals and the degree of compaction of the minerals. Metamorphic rocks are well compacted and have specific gravity between 2.5 to 2.8. The degree of metamorphism or compaction can be kept equal by selecting rock samples within this density range.

I studied any relationship between Relative Dry Density and LAAV which is shown in figure 5-5.

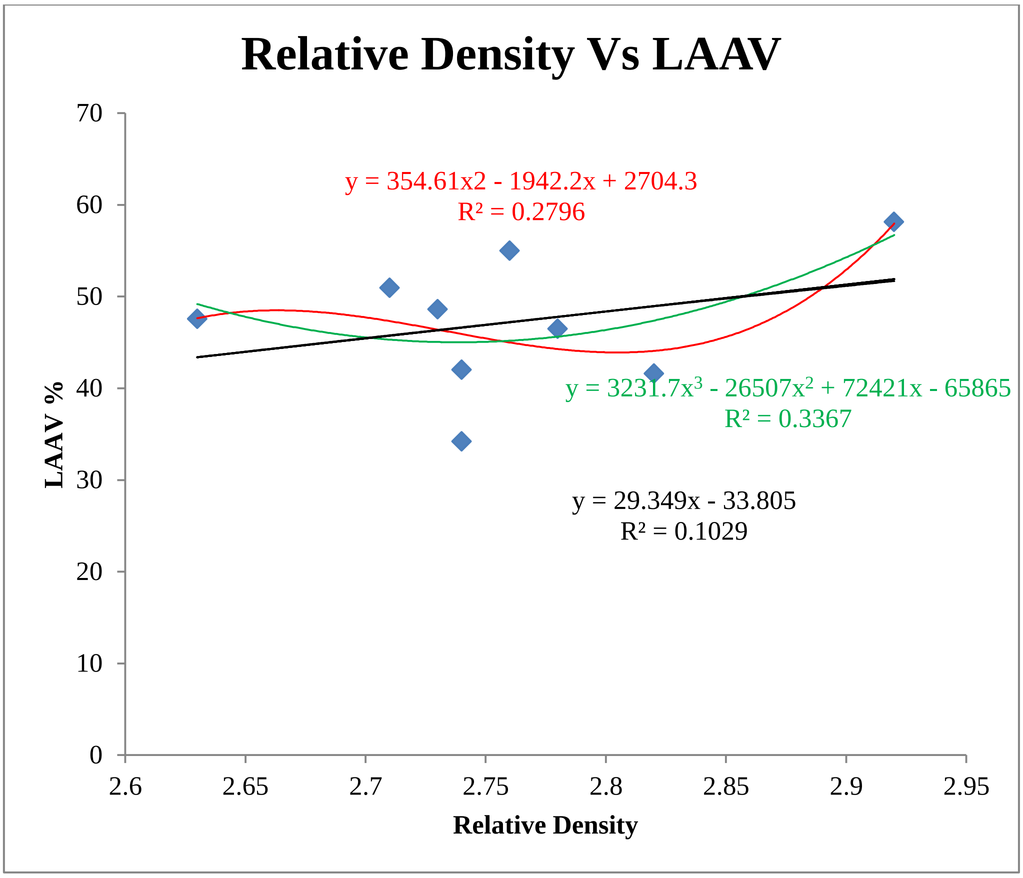


Figure 5-5 Relative Dry Density Vs. LAAV

By simply observing the data points it is visible there is a data gap in between10 - 30% and 80 – 90% of quartz content. If more data is fed in between these ranges would definitely improve the relationship.

The observed data gap is basically due to poor sample selection. If test samples were selected based on thin section analysis data a good representative sample set would be obtained. But due to extreme difficulties in preparing thin sections the test samples were selected based on visual observation of the sample.

Most of the data falls in between 50 and 40 in the graph. That means more rock samples have their LAAV value in between 50—40%.

According to ICTAD Sri Lanka the LAAV of aggregate suitable for wearing course should be less than 40% while for the base course is less than 50%. The regression line lies almost over the 40% line of LAAV. Above 95% of quarts should be presents to have LAAV lower than 40%according to the regression analysis. It leaves bit confusion and need further clarification with more samples tested at the laboratory.

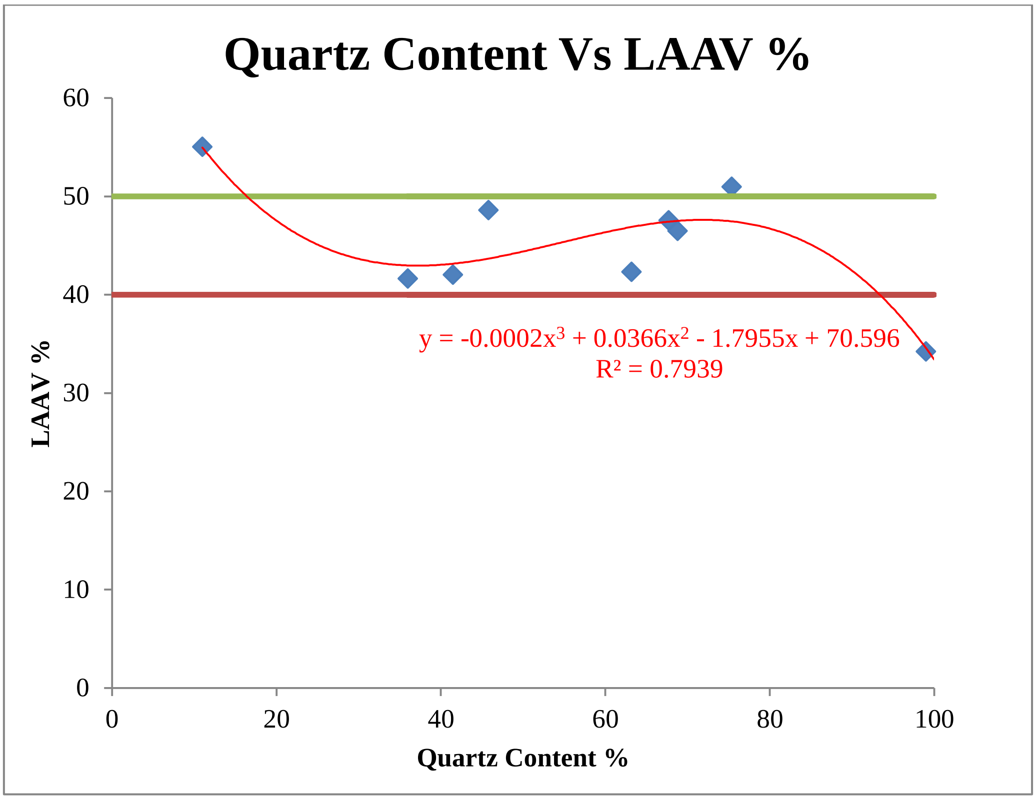


Figure 5-6 Optimum Mineral Content

Therefore special care should be taken while selecting aggregates for wearing course because majority represents LAAV above 40%.

5.5 Limitations

Los Angeles Abrasion Value or any other strength factor of aggregates is not only related to its mineral content. It depends on various other factors as described in my first chapter. For this work I tried to control the effect of other factors as possible. But achieving complete success in this regard is impossible.

The effect of internal cracks developed during blasting process, micro fractures and cracks opened during hammering and crushing on LAAV is assumed to be uniform.

Quarry sites having visible structural features such as joints, fractures which causes for rock weathering is obviously omitted while selecting sample locations. Dry density is influenced by the specific gravity of the composition minerals and the degree of compaction of the minerals. Metamorphic rocks are well compacted and have specific gravity between 2.5 to 2.8. Dry density of rock samples were measured to verify the degree of compaction or in other words the degree of metamorphism of selected rock samples do not have much variation .

The following petrographic factors have been revealed as the most important ones for LAAV of rock aggregates: the size of crystals, the form, arrangement and dimensions ratio of crystals and the presence of micro fractures in parent rock. Thin sections are to be carefully analyzed with polarizing microscope for remarkable variations in above factors and the unsound samples to be omitted to use in developing relationship.

Restraining to the aim of this study only the relationship between major rock forming minerals; quartz, feldspar and mica are concerned. But the content of some unsound minerals in parent rock may also have influence on LAAV of rock aggregates which need further studies.

The Atomic Absorption Spectroscopy is incapable of identifying minerals except single elements with which the mineral content could be calculated if the exact formulae of each mineral present in the rock sample are known. It is almost impossible with various rock types. Therefore I had to go for the thin section analysis, which is the only available technique left.

The petrographic analysis of thin sections for determining mineral content is wholly personnel dependent. Colour and colour intensity changes with the thickness of the mineral section where hindering of mineral grains results. The standard thickness of a section should be 2-3 microns. Maintenance of this technique depends on the petrography’s skill and experience.

At the beginning it was decided to analyze the microscopic image of thin section with some image classifying software like Arc GIS. On midway it was realized that the grains of same mineral are classified into different colour intensities depending on their orientation due to pleocrhoism. Even in the same grain different colour intensities are found and are identified as different mineral. Considering the fact semi-automatic classification using AutoCAD software was decided to be carry out for this study. The microscopic view was mineral vise separated into different layers manually and the area percentage of each layer objects was calculated and assumed to be represents the actual volume percentage occupied by the minerals.

In order to have more precise reading for mineralogical composition of a rock sample, general practice is to analyze thin sections prepared at three sections of a sample. Anyhow, because of the limited time period available for the project and considering the extreme difficulties of preparing thins sections, one thin section was prepared and analyzed.

5.6 Field Guide

A field guide for aggregates was developed with the test results which may be useful to the engineers and other technical persons to quickly check the suitability of aggregates used at construction sites. This field guide can be further developed by including other important engineering properties related to the aggregates such as Aggregate Impact Value, Aggregate crushing value, 10% fines value and polished stone value.

This field guide can be used for following purposes at field works.

1. To study the possibility of predicting LAAV of rock aggregates by visual comparison with the field guide.
2. To study possibility of comparing samples of aggregate from new sources with samples of aggregate from one or more sources, for which test data or performance records are available.

Small part of the field guide was given in figure 5-7 on the next page for your understanding and the complete field guide is attached as Appendix B of this report for your references.

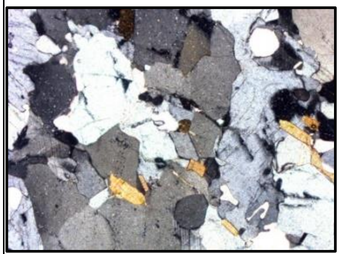
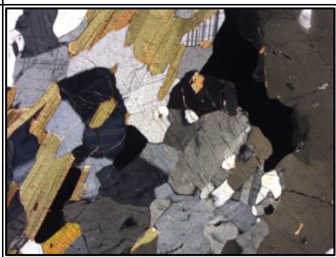
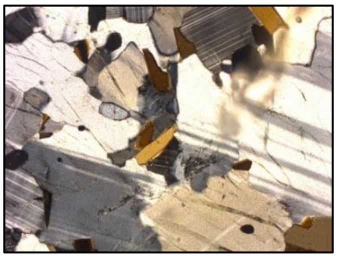
No	Photograph	Microscopic View	Engineering Properties	Mineral Content %
1			LAAV % = 47.55 Relative Dry Density=2.63	Quartz = 68 Feldspar = 19 Mica = 3
2			LAAV % = 46.47 Relative Dry Density=2.78	Quartz = 71 Feldspar = 10 Mica =19
3			LAAV % = 41.6 Relative Dry Density=2.82	Quartz =36 Feldspar = 51 Mica =12

Figure 5-7 Example of Field Guide for Rock Aggregates

6 CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

1) Los Angeles Abrasion value of most of the rock varieties found in Sabaragamuwa province is in between 40-50%.
2) The regression line fit for the relationship between Los Angeles Abrasion Value and Quartz Content is a third order polynomial.
3) The best fit line for the test data is $y = -0.0002x^3 + 0.0366x^2 - 1.7955x + 70.596$ with coefficient of determination equals 0.7939.
4) A reasonable relationship was not found on feldspar and mica content with LAAV.
5) A small field guide was developed with which the LAAV of basic rock types in Sabaragamuwa province could be predicted.

6.2 Recommendations

1) The observed relationship between quartz content and LAAV needs to be further developed and proved with more laboratory testing of samples.
2) The field guide for aggregates found in Sabaragamuwa Province need to be further developed with other important aggregate properties such as aggregate impact value, aggregate crushing value, 10% fines value and polished stone value.

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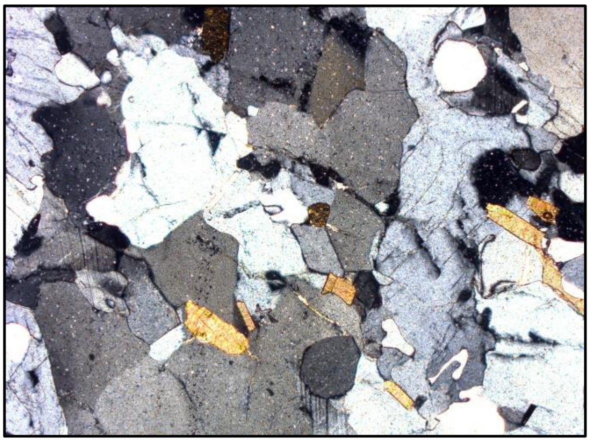
Appendix A

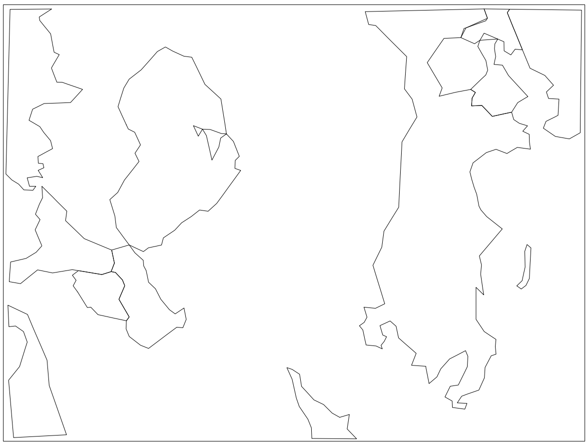
Analysis of Mineral Content with AutoCad Software.

Sample ID : KE/S1 (View 1)

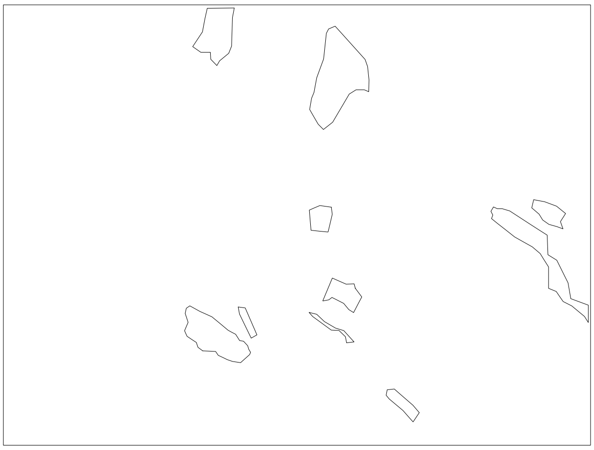
Microscopic View KE/S1-1



Feldspar Grains: KE/S1-1



Mica Grains: KE/S1-1



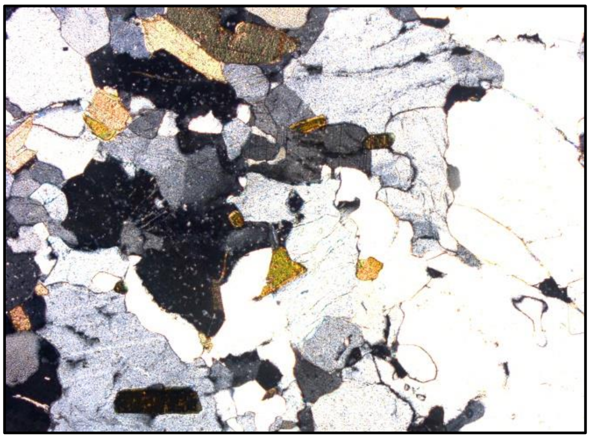
Area percentage of Feldspar= 32%

Area percentage of Quartz = 65.07%

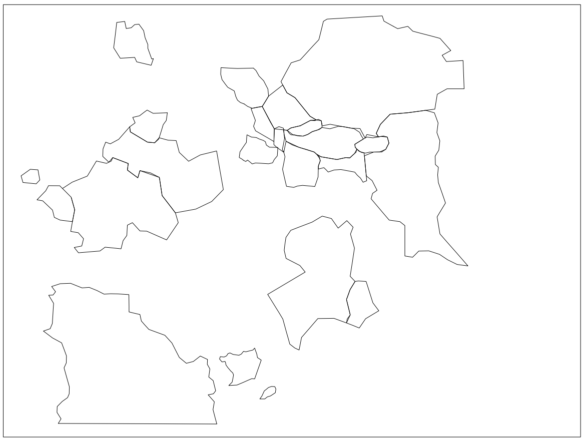
Area percentage of Mica = 2.2%

Sample ID :   KE/S1(View 2)

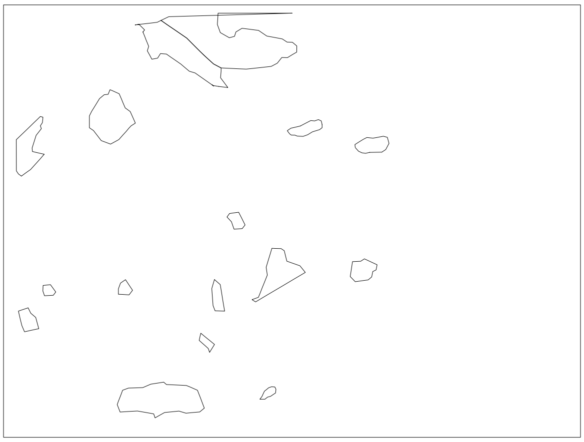
Microscopic View KE/S1-2



Feldspar Grains: KE/S1-2



Mica Grains: KE/S1-2



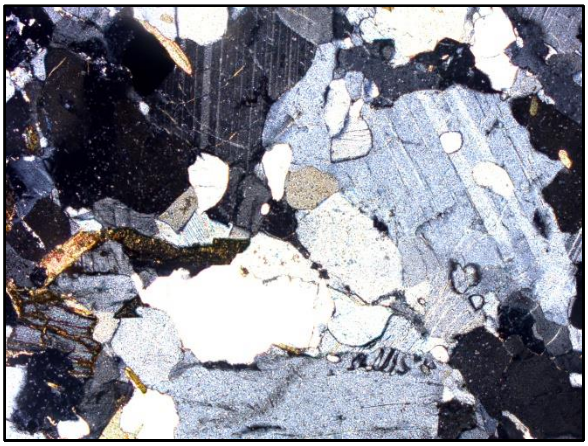
Area percentage of Feldspar=31.69%

Area percentage of Mica = 3.2%

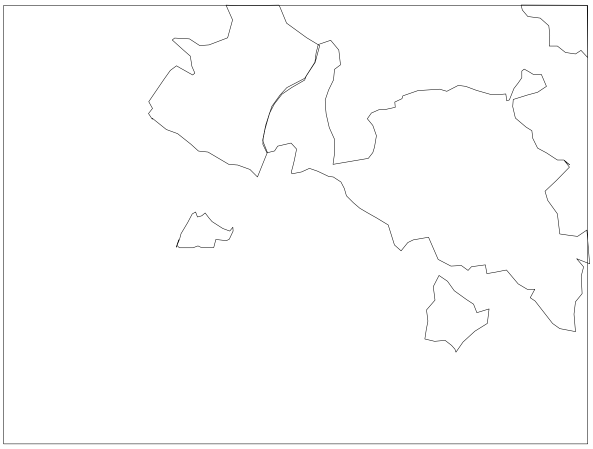
Area percentage of Quartz = 65.11%

Sample ID : KE/S1 (View 3)

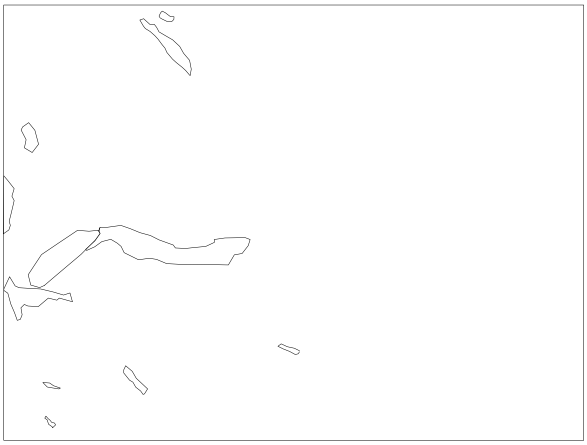
Microscopic View : KE/S1-3



Feldspar Grains: KE/S1-3



Mica Grains: KE/S1-3



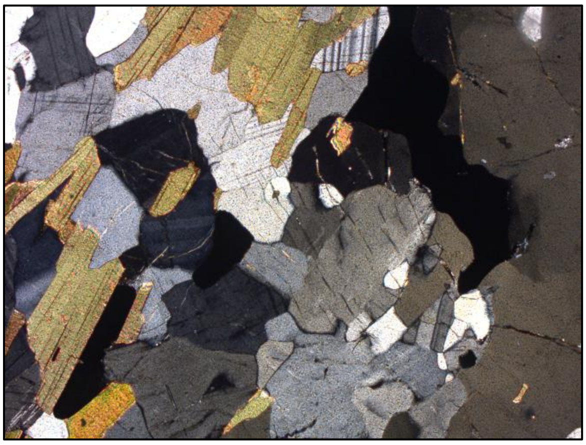
Area percentage of Feldspar= 23.85%

Area percentage of Mica = 3.0%

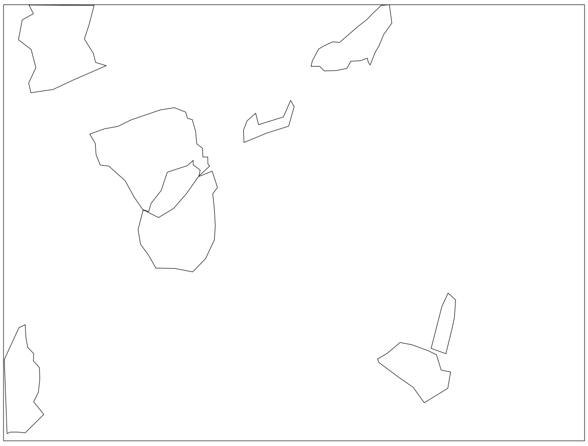
Area percentage of Quartz = 73%

Sample ID :   KE/S2 (View 1)

Microscopic View : KE/S2-1



Feldspar Grains: KE/S2-1



Mica Grains: KE/S2-1

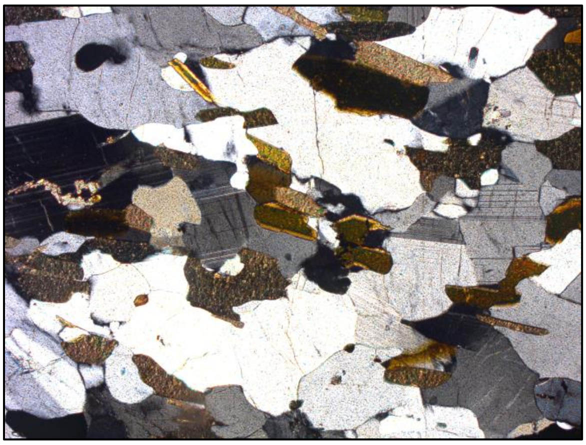
Area percentage of Feldspar= 10.05%

Area percentage of Mica = 27.65%

Area percentage of Quartz= 62.3%

Sample ID : KE/S2 (View 2)

Microscopic View : KE/S2-2



Feldspar Grains: KE/S2-2

Mica Grains: KE/S2-2

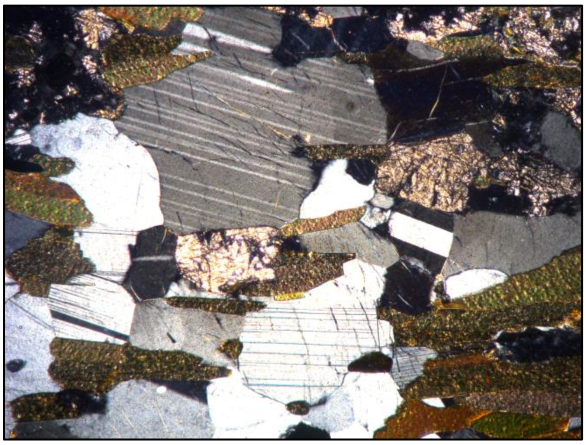
Area percentage of Feldspar=14.86%

Area percentage of Mica =10.27%

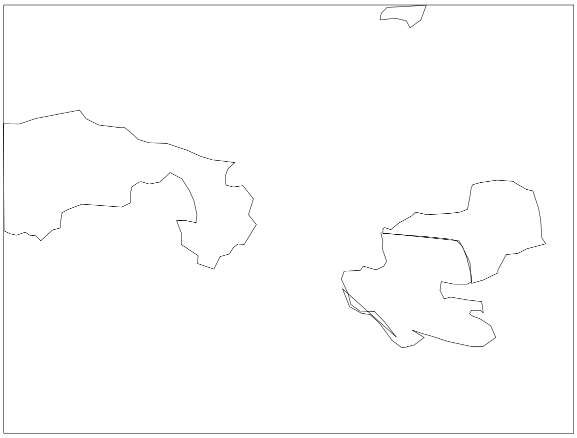
Area percentage of Quartz= 74.87%

Sample ID : KE/S2 (View 3)

Microscopic View: KE/S2-3



Quartz grains KE/S2-3



Mica Grains: KE/S2-3

Area percentage of Feldspar = 76%

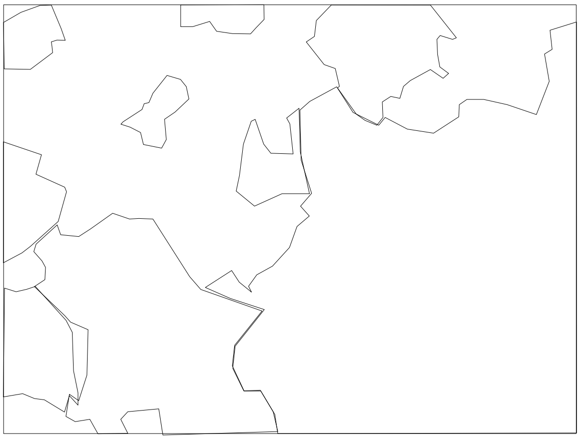
Area percentage of Mica = 10.1%

Area percentage of Quartz= 13.9%a

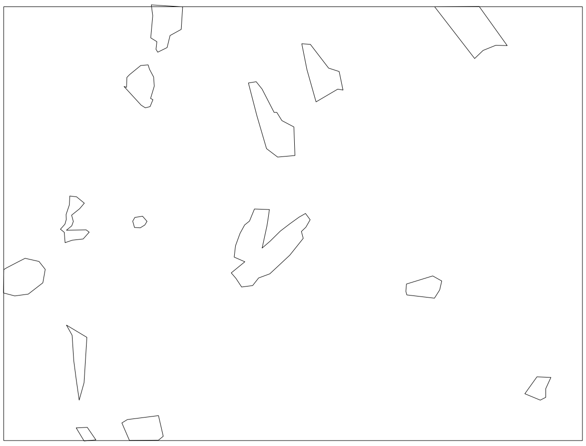
Sample ID : KE/S3 (View 1)

Microscopic View : KE/S3-1

Feldspar Grains: KE/S3-1



Mica Grains: KE/S3-1



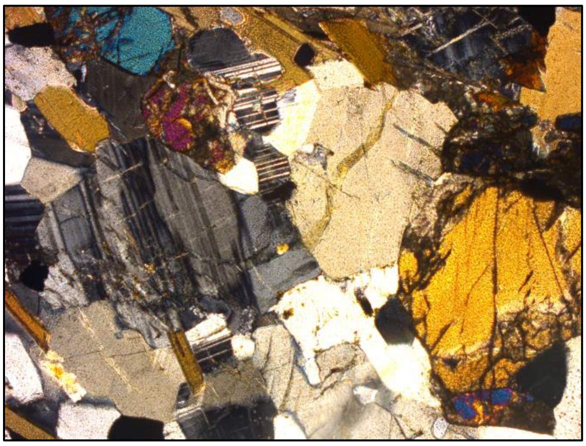
Area percentage of Feldspar = 67.78%

Area percentage of Mica = 5.59%

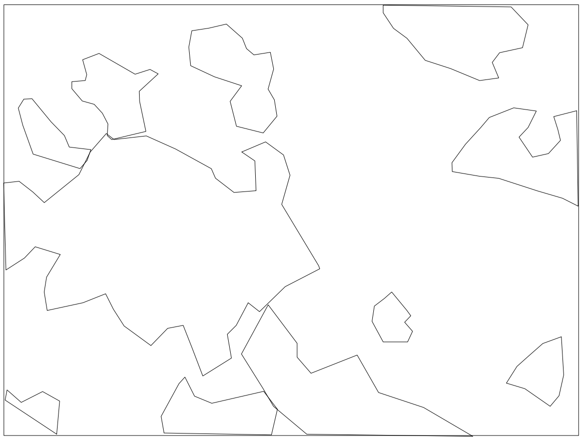
Area percentage of Quartz= 26.63%

Sample ID : KE/S3 (View 2)

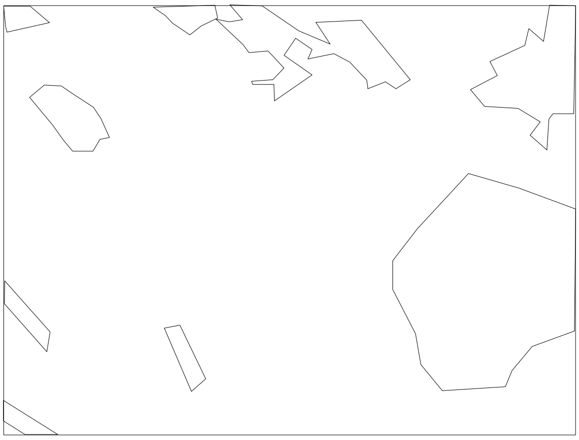
Microscopic View : KE/S3-2



Feldspar Grains: KE/S3-2



Mica Grains: KE/S3-2



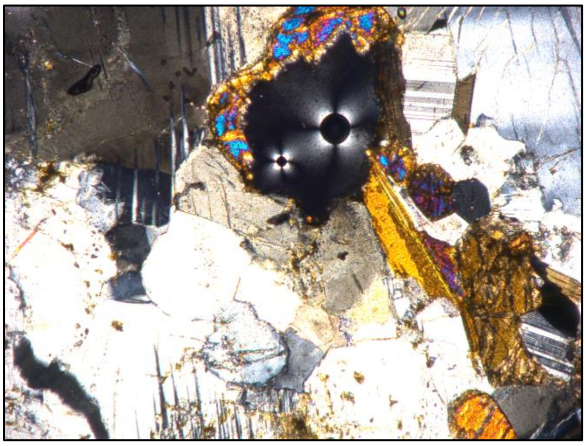
Area percentage of Feldspar = 36.01%

Area percentage of Mica = 20.86%

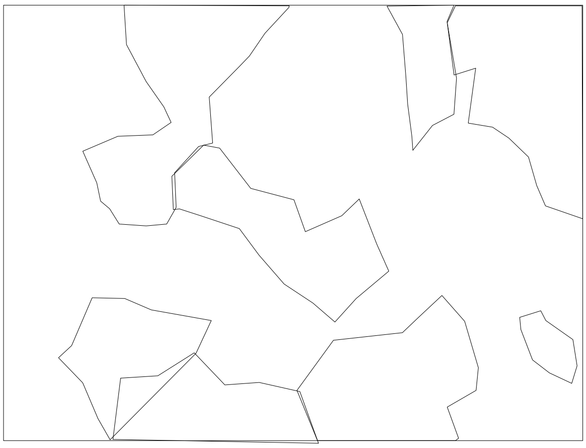
Area percentage of Quartz= 40.12%

Sample ID : KE/S3 (View 3)

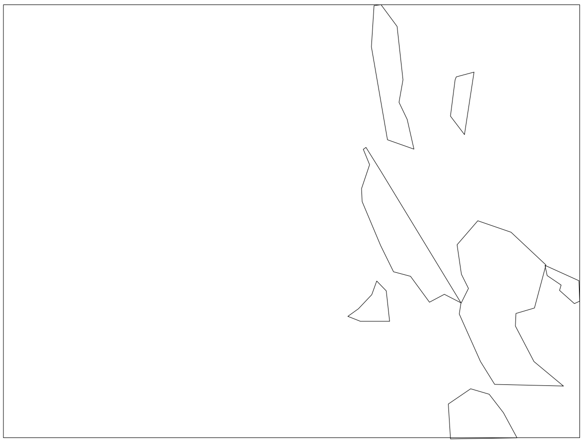
Microscopic View : KE/S3-3



Feldspar Grains: KE/S3-3



Mica Grains: KE/S3-3



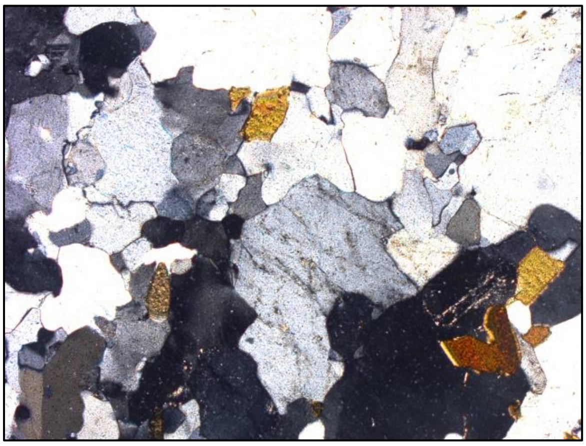
Area percentage of Quartz = 41.36%

Area percentage of Mica = 9.22%

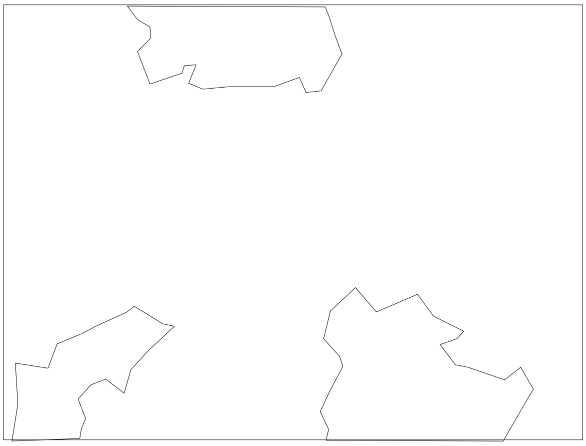
Area percentage of Feldspar=48.3%

Sample ID : KE/S4 (View 1)

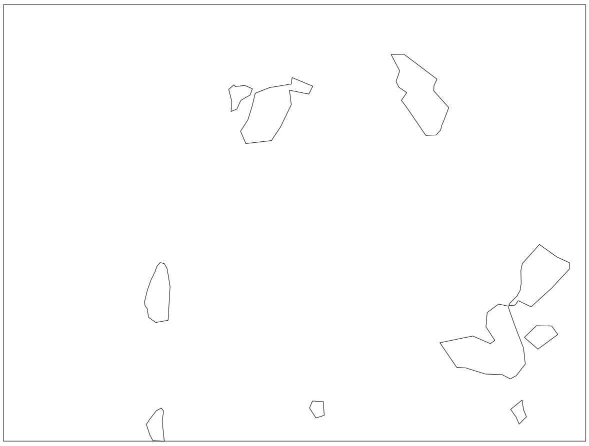
Microscopic View : KE/S4-1



Feldspar Grains: KE/S4-1



Mica Grains: KE/S4-1



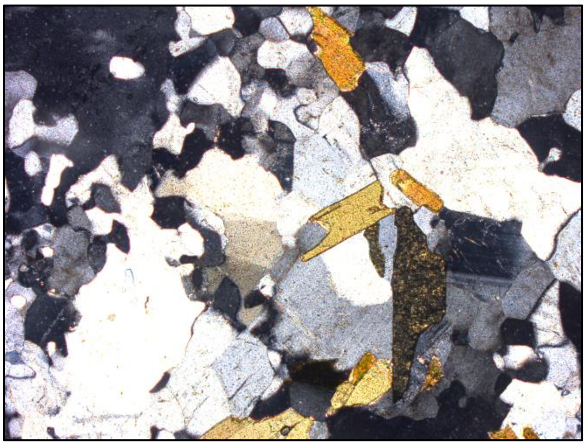
Area percentage of Feldspar =18.32%

Area percentage of Mica = 4.91%

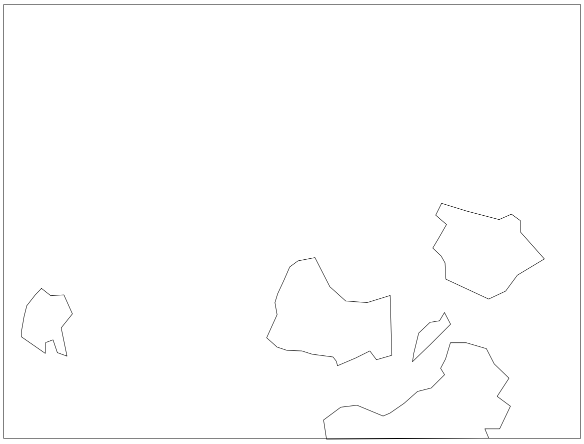
Area percentage of Quartz= 76.77%

Sample ID : KE/S4 (View 2)

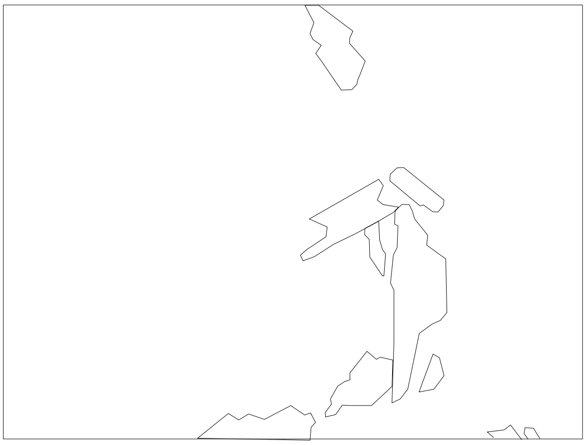
Microscopic View : KE/S4-2



Feldspar Grains: KE/S4-2



Mica Grains: KE/S4-2



Area percentage of Feldspar = 10.74%

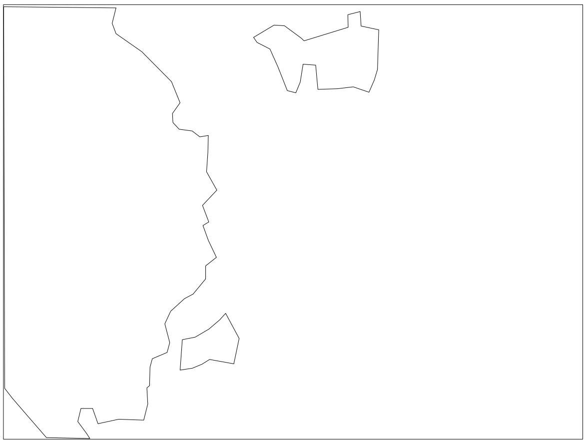
Area percentage of Mica = 7.62%

Area percentage of Quartz= 81.64%

Sample ID : KE/S4 (View 3)

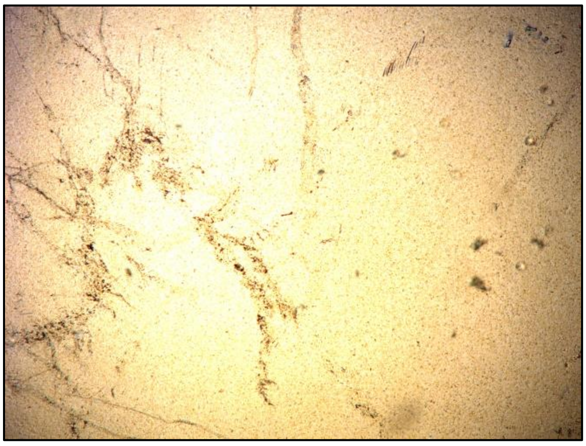
Microscopic View : KE/S4-3

Feldspar Grains: KE/S4-3



Sample ID : KE/S5 (View 1)

Microscopic View : KE/S5-1



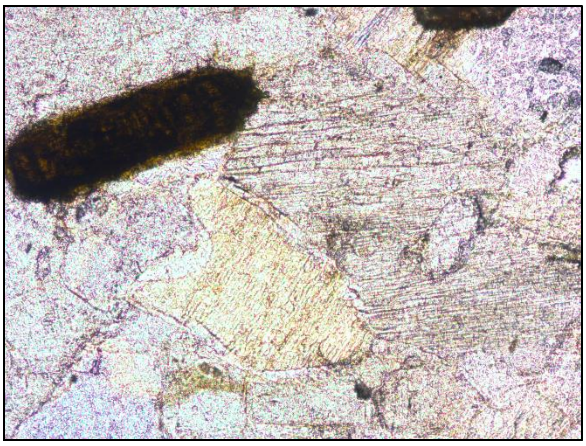
Area percentage of Quartz = 99%

Area percentage of Mica =0.5%

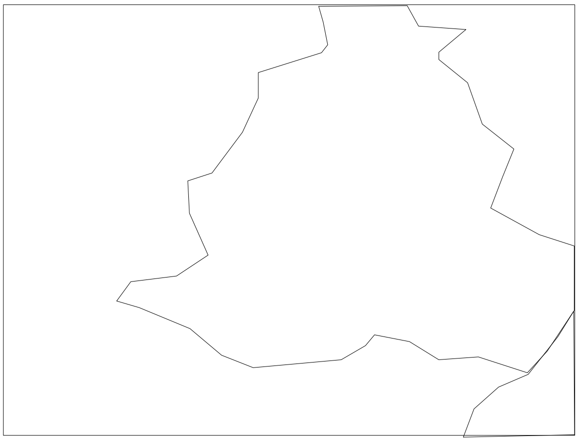
Area percentage of Feldspar=0.5 %

Sample ID : KE/S7 (View 1)

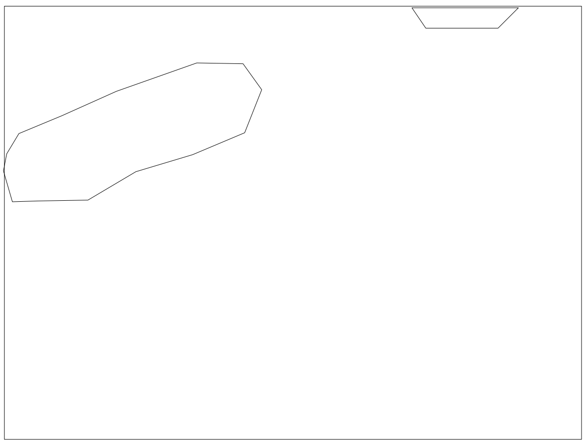
Microscopic View : KE/S7-1



Feldspar Grains: KE/S7-1



Mica Grains: KE/S7-1



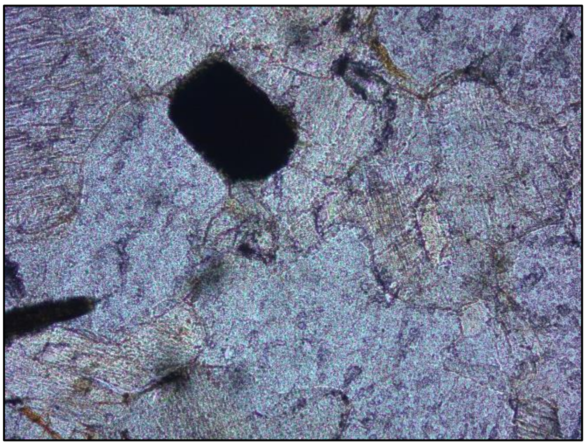
Area percentage of Feldspar = 43.45%

Area percentage of Mica = 8.95%

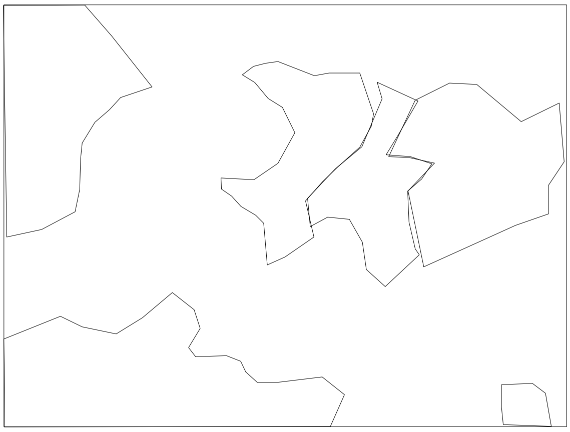
Area percentage of Quartz=47.6%

Sample ID : KE/S7 (View 2)

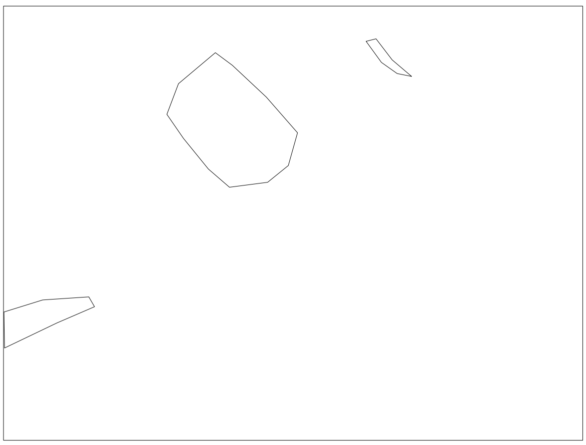
Microscopic View : KE/S7-2



Feldspar Grains: KE/S7-2



Mica Grains: KE/S7-2



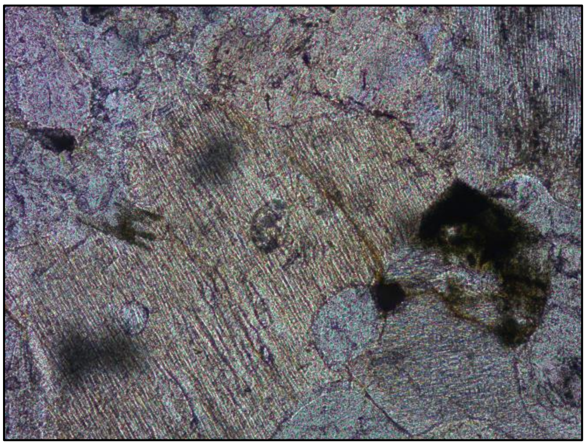
Area percentage of Feldspar =40.66%

Area percentage of Mica = 5.35%

Area percentage of Quartz =53.99%

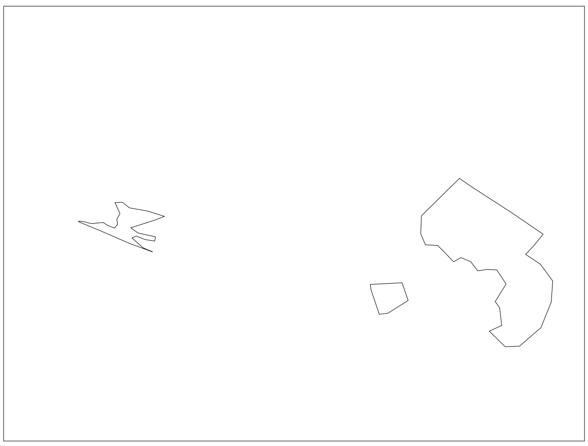
Sample ID : KE/S7 (View 3)

Microscopic View : KE/S7-3



Feldspar Grains: KE/S7-3

Mica Grains: KE/S7-3



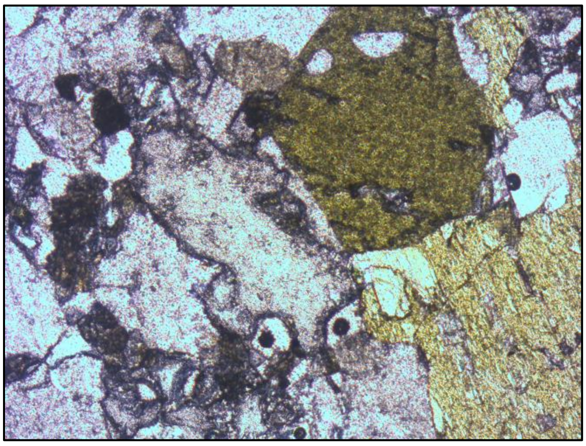
Area percentage of Feldspar = 59.4%

Area percentage of Mica = 4.94%

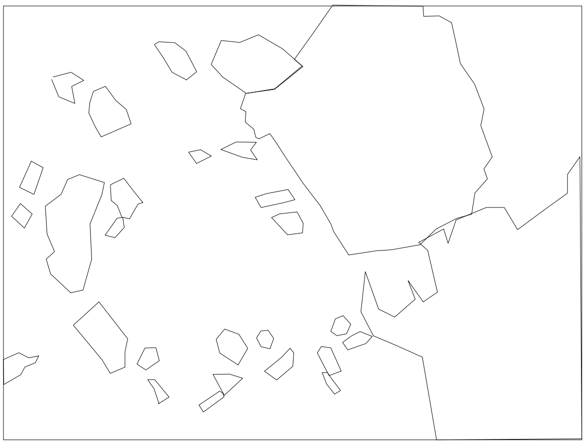
Area percentage of Quartz = 35.66%

Sample ID : KE/S8 (View 1)

Microscopic View : KE/S8-1



Mica Grains: KE/S8-1



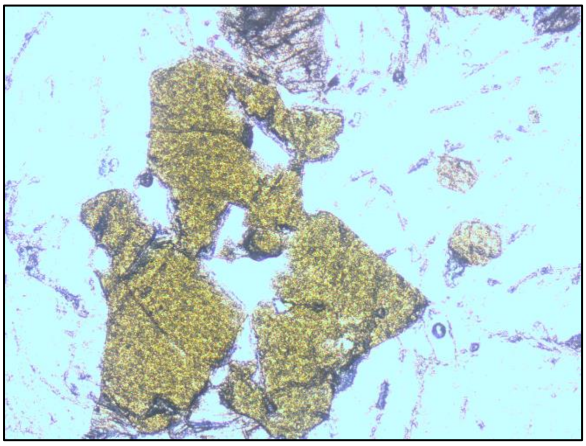
Area percentage of Quartz = 58.6%

Area percentage of Mica = 39.4%

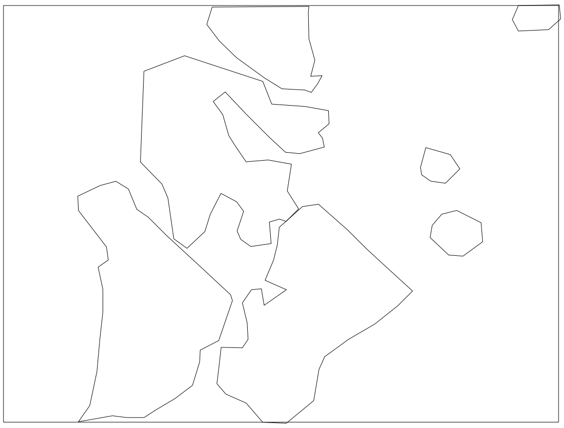
Area percentage of Feldspar= 2%

Sample ID : KE/S8 (View 2)

Microscopic View : KE/S8-2



Mica Grains: KE/S8-2



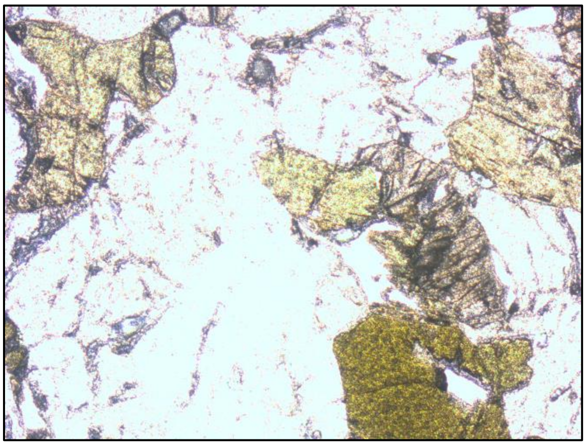
Area percentage of Quartz = 66.12%

Area percentage of Mica = 31.88%

Area percentage of Feldspar= 2%

Sample ID : KE/S8 (View 3)

Microscopic View : KE/S8-3



Mica Grains: KE/S8-3

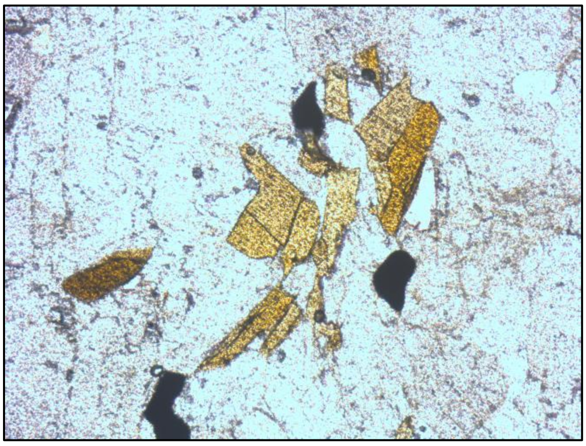
Area percentage of Quartz = 65.00%

Area percentage of Mica = 32.24%

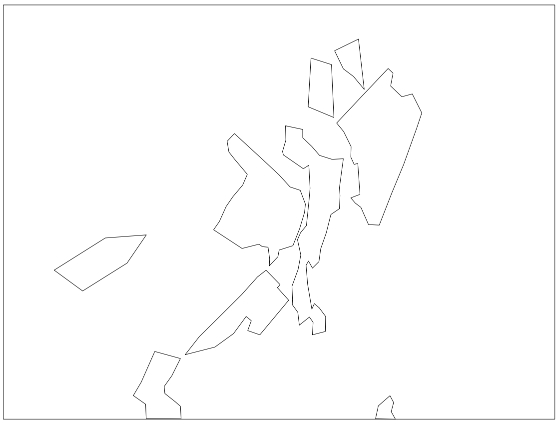
Area percentage of Feldspar= 2.76%

Sample ID : KE/S9 (View 1)

Microscopic View : KE/S9-1



Mica Grains: KE/S9-1



Feldspar Grains: KE/S9-1

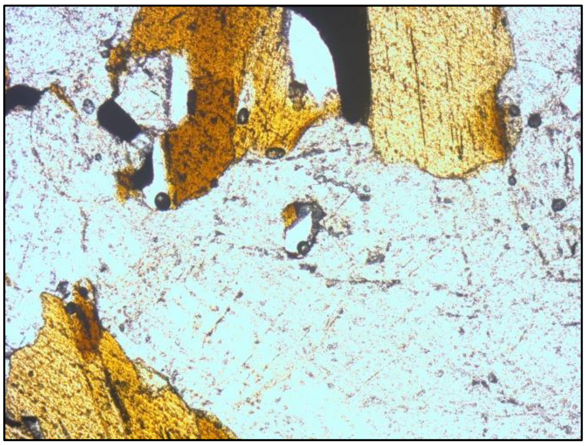
Area percentage of Quartz= 42.28%

Area percentage of Mica =11.8%

Area percentage of Feldspar= 45.6%

Sample ID : KE/S9 (View 2)

Microscopic View : KE/S9-2



Mica Grains: KE/S9-2

Feldspar Grains: KE/S9-2

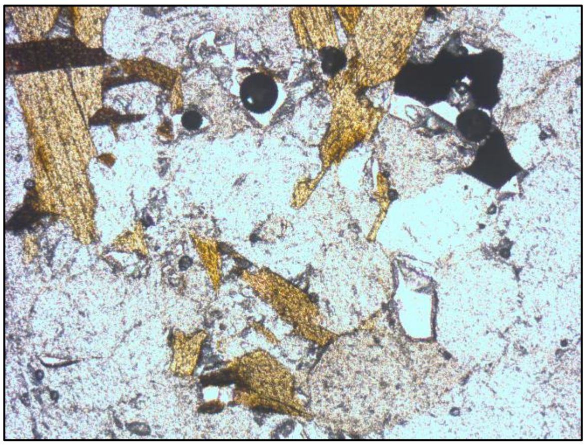
Area percentage of Quartz = 44%

Area percentage of Mica = 20.6%

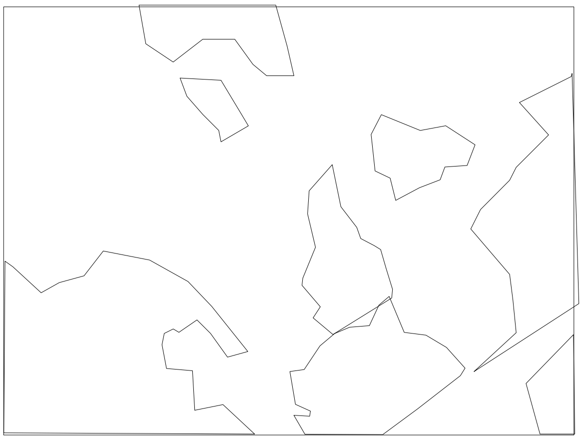
Area percentage of Feldspar= 34%

Sample ID : KE/S9 (View 3)

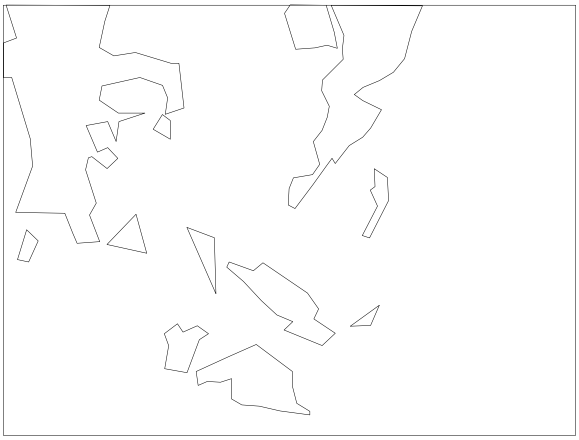
Microscopic View : KE/S9-3



Feldspar Grains: KE/S9-3



Mica Grains: KE/S9-3



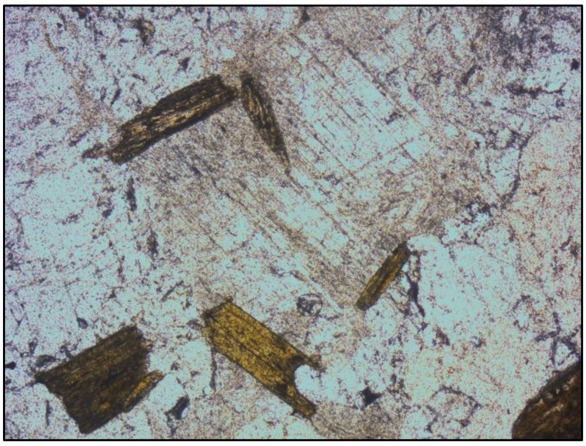
Area percentage of Quartz = 38.2%

Area percentage of Mica =17.54 %

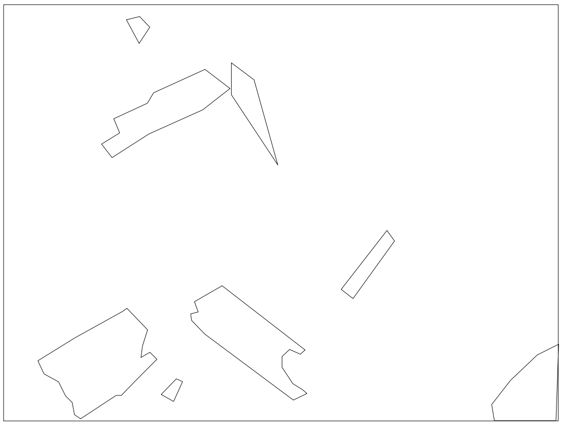
Area percentage of Feldspar= 43.18%

Sample ID : KE/S10 (View 1)

Microscopic View : KE/S10-1



Mica Grains: KE/S10-1



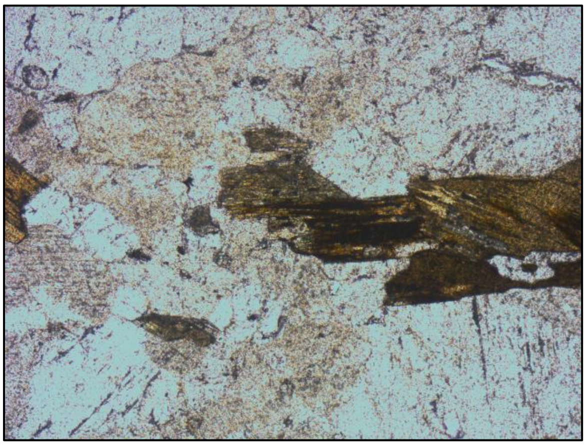
Area percentage of Feldspar = 78.9%

Area percentage of Mica = 9.8%

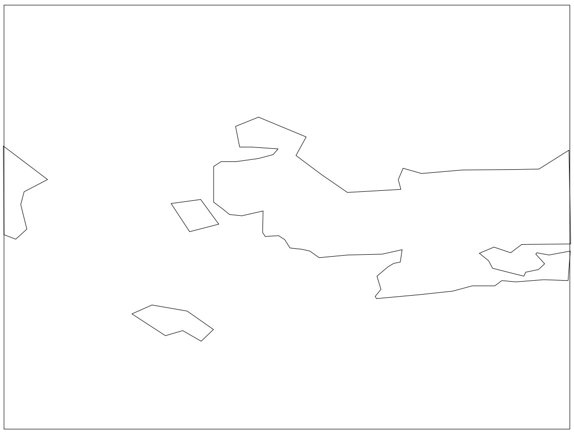
Area percentage of Quartz= 9.2%

Sample ID : KE/S10 (View 2)

Microscopic View : KE/S10-2



Mica Grains: KE/S10-2



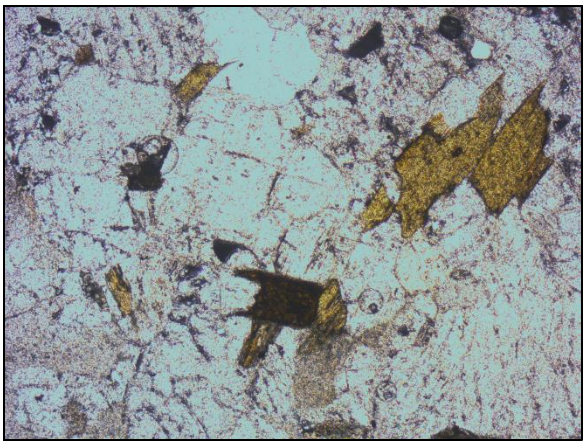
Area percentage of Quartz = 10%

Area percentage of Mica = 15.9%

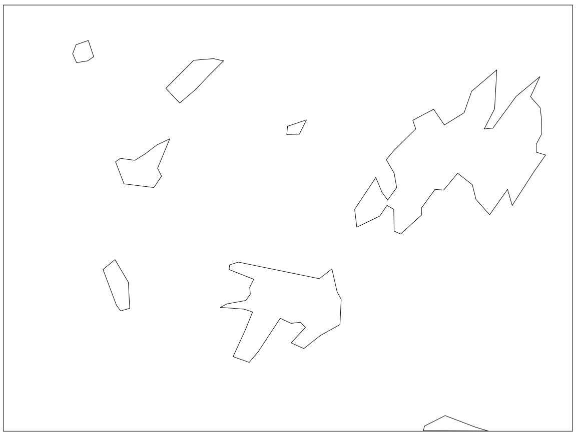
Area percentage of Feldspar= 74.1%

Sample ID : KE/S10 (View 3)

Microscopic View : KE/S10-3



Mica Grains: KE/S10-3



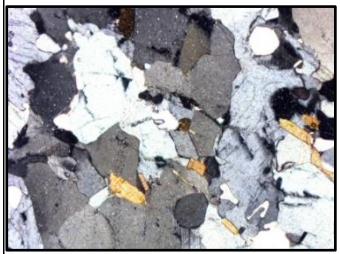
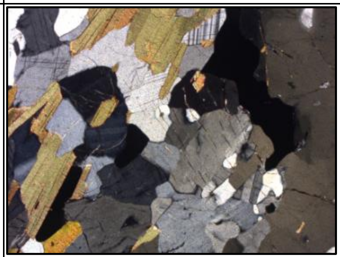
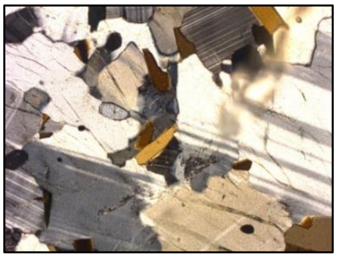
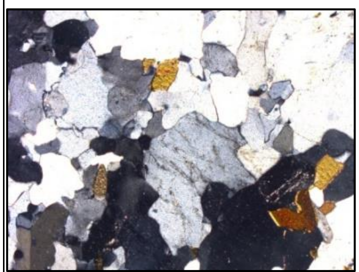
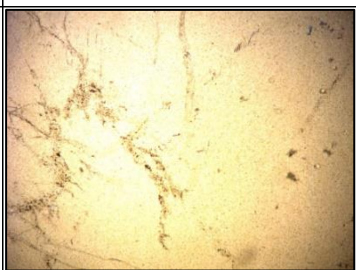
Area percentage of Feldspar = 76%

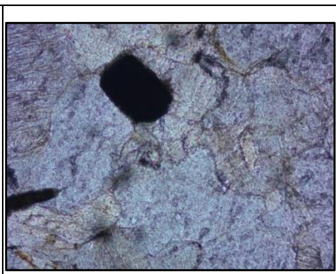
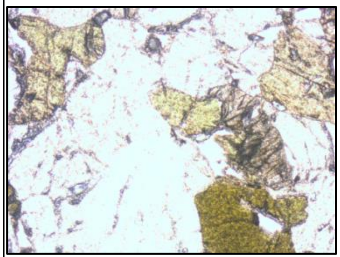
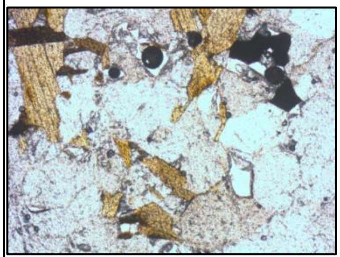
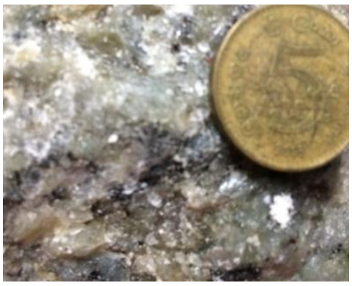
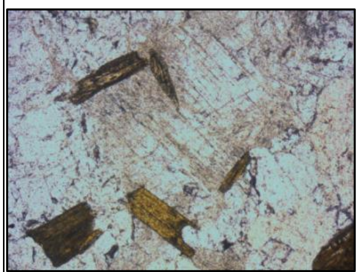
Area percentage of Mica = 10.1%

Area percentage of Quartz= 13.9%

Appendix B

Field guide for engineering properties of rocks based on their mineralogy

No	Photograph	Microscopic View	Engineering Properties	Mineral Content %
1			LAAV % = 47.55 Relative Dry Density=2.63	Quartz = 68 Feldspar = 19 Mica = 3
2			LAAV % = 46.47 Relative Dry Density=2.78	Quartz = 71 Feldspar = 10 Mica =19
3			LAAV % = 41.6 Relative Dry Density=2.82	Quartz =36 Feldspar = 51 Mica =12
4			LAAV % = 50.94 Relative Dry Density=2.71	Quartz = 75 Feldspar = 20 Mica =4.5
5			LAAV % = 34.2 Relative Dry Density=2.74	Quartz = 99 Feldspar = 0.5 Mica =0.5

6			LAAV % = 48.59 Relative Dry Density=2.73	Quartz = 46 Feldspar = 48 Mica =5.5
7			LAAV % = 48.13 Relative Dry Density=2.92	Quartz = 63 Feldspar = 8 Mica =34
8			LAAV % = 42 Relative Dry Density=2.74	Quartz = 39 Feldspar = 41 Mica =16.7
9			LAAV % = 55 Relative Dry Density=2.76	Quartz =4 Feldspar =84 Mica =12