MECHANICAL AND PETROGRAPHIC CHARACTERISTICS OF KAMILA AMPHIBOLITE, DISTRICT SWAT, KHYBER PAKHTUNKHWA, PAKISTAN

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DEPARTMENT OF EARTH AND ENVIRONMENTAL SCIENCES

BAHRIA UNIVERSITY ISLAMABAD

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A thesis submitted in fulfilment of the requirements for the award of the degree of Master of Science (Geology)

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Certificate

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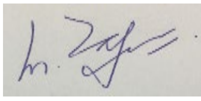
Internal Examiner	Dr. Muhammad Zafar	
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DEDICATION

This thesis is dedicated to my beloved parents and respectable teachers whose prayer and guidance has always been wheels for me that has always helped me to travel in this competitive era.

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ABSTRACT

The current research has focused on the evaluation of mechanical and petrographic traits of Kamila Amphibolite, Swat district, Khyber Pakhtunkhwa, Pakistan. To access the mechanical properties, this study involves Ultra Sonic Pulse Velocity (UPV), Point Load test (PLT), Schmidt Rebound Hammer (SRH) test and Uniaxial Compressive Strength (UCS) test. In the UCS tests, an average strength value of 157.4 MPa was found that is very good for construction application. This indicates high strength (Anon, 1977, 1979, 1981). The point load strength indices (Is) ranged from 2.90 MPa to 16.19 MPa, whereas the corrected indices (Is50) varied from 2.78 MPa to 15.61 MPa, which shows strengths ranging from low to very high. Surface hardness was found to be good in Schmidt Rebound Hammer (SRH) test, as indicated by rebound numbers that averaged 40.50. The UPV values showed the variations in density and elasticity, ranging from 17.13 km/s to 24.93 km/s which shows very high category. The composition was determined by petrographic analysis to consist primarily of amphibole (average 34.9%), plagioclase (25.2%), epidote (12.4%) and quartz (11.4%). It investigated the roles of four essential minerals i.e., amphibole, plagioclase, epidote and quartz. The findings show that there are notable relationships between mechanical properties and plagioclase particularly in the SRH values and UPV tests. Amphibole and epidote show moderate correlation, while quartz continuously displays lower correlations, indicating a smaller influence on the rock's mechanical behaviour. These findings are critical to the advancement of geological study, the best selection of building materials, and the enhancement of resource management techniques.

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CHAPTER 1

INTRODUCTION

1.1 Background

Mechanical characteristics of rocks with similar chemical signatures differ mostly due to changes in their textures and modal mineralogical compositions. The term “texture” refers to the interactions of mineral grains in a rock, as well as their sizes and forms (McPhie, 1993; Bucher and Frey, 1994). The inherent features of rocks, such as texture and mineralogy, can be used to evaluate their engineering properties (Lindqvist et al., 2007).

Most applied rock classification systems in geotechnical and rock engineering are based on mechanical parameters such as uniaxial compressive strength (UCS), tensile strength (TS), Young’s modulus or deformability modulus (E), and Poisson’s ratio (V), and it is thought that these parameters are sufficient to depict the full mechanical response of a rock (Hoek, 1994). However, the viability of a specific rock for usage as a construction material is determined by its constituent minerals. Modal mineral composition, grain size, cement, and grain contact all influence the physical attributes (density, porosity, permeability) and mechanical behavior (strength, deformability, durability, and hardness) of rocks (Meng and Pan, 2007).

Furthermore, the physical and petrographic qualities of sedimentary rocks have a major impact on their mechanical properties (Mosch and Siegesmund, 2007; Sabatakakis et al., 2008; Tandon and Gupta, 2013; Wang et al., 2019). Several studies have suggested the effects of petrographic characteristics on rock stability, and some have shown a link between mineralogical composition and mechanical properties of rocks (e.g. Dincer et al., 2008; Kilic and Teymen, 2008; Liu et al., 2005; Meng and Pan, 2007).

Several research studies on aggregate and limestone conducted in Pakistan have researched mechanical qualities, made engineering assessments, and/or conducted aggregate investigations, and have promoted their usage in building (e.g. Akram et al., 2017; Kamran et al., 2021; Mustafa et al., 2016; Naeem et al., 2014a, 2014b; Naseem et al., 2016; Rehman et al., 2020; Ullah et al., 2020).

Globally, aggregates, primarily composed of natural or crushed rock materials, constitute a significant portion of concrete, accounting for 70% to 80% of its volume in construction. These materials, including limestone, a calcium carbonate-rich sedimentary rock, are vital in the aggregate industry, encompassing gravels, pebbles, cobbles, and crushed rocks. Depending on suitability and transportation costs, igneous and metamorphic rocks like granite and marble, Amphibolite can also serve as construction materials. Aggregates are indispensable in building roads, buildings, railways, water canals, and civil projects, making up over 90% of asphalt pavements and 80% of concrete used in construction. Their durability is paramount, needing to withstand abrasion, crushing, impacting, and disintegration during use, including attrition of surface irregularities and particle splitting. Consequently, geological studies are imperative to evaluate the location, distribution, and characteristics of potential aggregate sources when needed for construction (Shah et al., 2022).

The petrographic and mechanical features of epidote Amphibolite and gabbro-norite rocks of Khagram-Razagram area district Dir, which is part of the Kamila Amphibolite belt showed the mineral composition and textures of these rocks, revealing substantial connections between grain size, alteration degree, and mechanical qualities including compressive and tensile strength. The findings, which are consistent with prior studies on the region's geology, indicate that both rock types are acceptable for usage in construction materials, particularly as dimension stones (Sajid et al., 2009).

Petrography and physico-mechanical properties of the granitic rocks from Kumrat valley are medium to coarse-grained. They are composed mainly of plagioclase, quartz, and orthoclase, with accessory minerals like biotite and muscovite. The study finds that medium-grained granites exhibit higher strength compared to coarse-grained ones. This is reflected in their uniaxial compressive strength, which is greater for medium-grained varieties. The difference in strength is attributed to the finer grain size of the medium-grained granites. Additionally, the rocks' specific gravity, porosity, and water absorption are within acceptable limits. This makes them suitable for construction purposes. The findings suggest that the Kumrat granites meet international standards for construction materials. Their strength is significantly influenced by their texture (Arif et al., 2015).

Textural implications in assessment of physico-mechanical behaviour of metavolcanic rocks from Dir Upper shows that grain size, texture, and mineral alteration all contribute to the increased strength of coarse-grained meta-andesites compared to fine-grained meta-andesites and agglomerates. While the rocks' characteristics are within the acceptable range for engineering uses, their high reactive silica content makes them prone to alkali-silica reactivity in concrete, requiring the use of low-alkali cement or other materials (Yaseen et al., 2020).

1.2 Problem Statement

The Kamila Amphibolite in District Swat, Khyber Pakhtunkhwa, Pakistan, has mechanical and petrographic characteristics that are of geological relevance even though they have not yet been fully investigated. Petrographic characteristics and mechanical properties of Kamila Amphibolite in Khagram-Razagram in district Dir, Khyber Pakhtunkhwa Pakistan was studied by Sajid et al., 2009. Their research missing many mechanical tests like PLT, SRH test and UPV test. This study intends to close the current knowledge gap by addressing the absence of previous investigations and providing essential information into the geological properties and potential use of Kamila Amphibolite in this area.

1.3 Objectives

The objectives of current research work are as follows:

(i). To identify the mechanical characteristics of Kamila Amphibolite.

(ii). To perform the petrographic analysis of Kamila Amphibolite.

(iii). To generate the correlation between mechanical and petrographic properties of Kamila Amphibolite.

1.4 Study Area

The study area (Mingora and Kabal) is in the Swat region of northern Pakistan, between latitude 30° 44’ 00’’ and 34°50’ 00’’ north and longitude 72° 15’ 00’’ to 72° 18’ 00’’ east. Figure 1.1 shows the study area map.

The present study area geologically lies on the northern tip of Indian plate where Precambrian to Mesozoic argillites, quartzite and limestone record a history of shelf deposition interrupted by numerous erosional unconformities (Dipietro, 1993).

Alpurai group is divisible to four formations. The lower part of this group consists of pelites, psammites and Amphibolite while the upper part contains marble, graphite and garnetiferous calc-pelite (Shah et al., 2022).

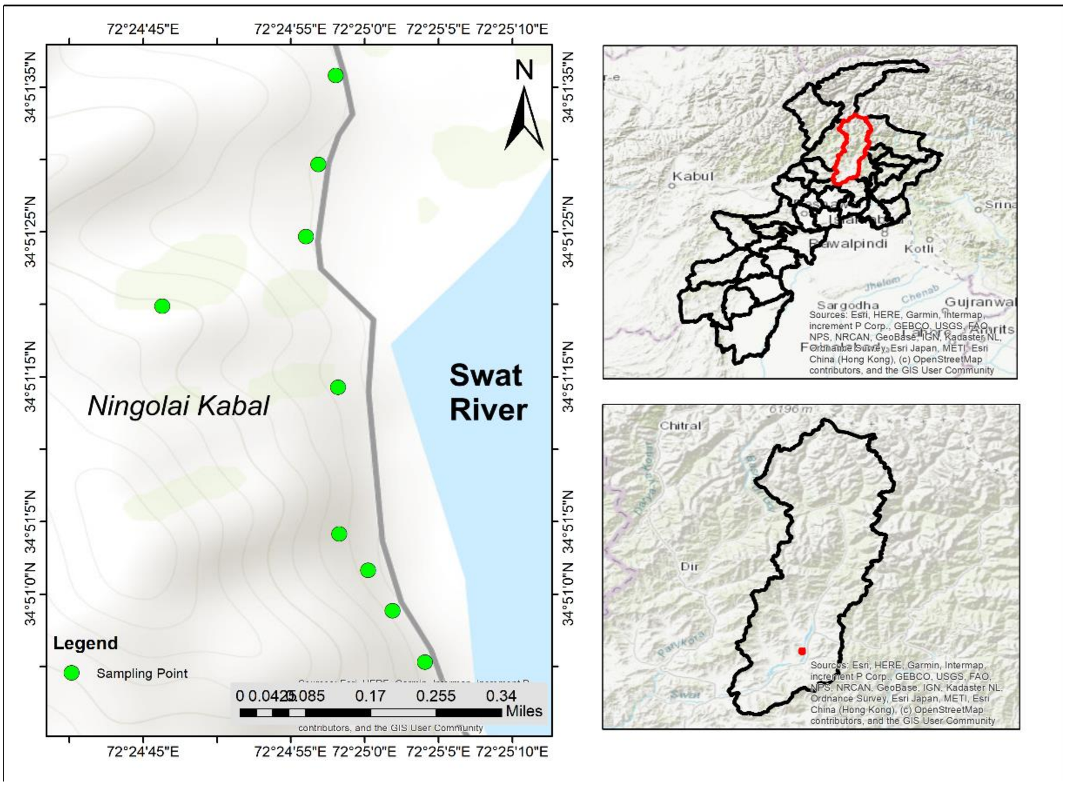


Figure 1.1 Study area map

CHAPTER 2

GENERAL GEOLOGY AND TECTONICS

2.1 Tectonic and Geologic Settings

The area of interest lies within the Kohistan Island arc, a geological formation in northern Pakistan. To the north, this arc is demarcated by the Shyok Suture, also known as the Main Karakoram Thrust. The southern boundary is formed by the Indus Suture, or Main Mantle Thrust. The exposed rocks of Kohistan provide a rare glimpse into the complete structure of an island arc, revealing both its crustal and mantle layers (Tahirkheli et al., 1979). Subsequent research supported the theory that the Kohistan Island Arc was once an oceanic island chain that became thrust over another tectonic plate and tilted upright during the formation of the Himalayas (Jan 1980; Bard et al., 1980; Coward et al., 1982; Khan et al., 1998).

The Main Mantle Thrust (MMT) forms the southern and eastern margins of the Kohistan Island Arc. Geological studies indicate the MMT stretches westward from Afghanistan, traversing through Swat and reaching Babusar. It then curves northward, encircling the Nanga Parbat-Haramosh massif, and eventually connects with the Indus Suture Zone in Ladakh (DiPietro et al., 2000).

The Kohistan Island arc's internal oceanic crust can be divided into five distinct geological units (Khan et al., 1997): These units progressively appear as we travel northward, starting from the Indus Suture in the south and reaching the Shyok Suture in the north. The first unit comprises basic and ultramafic cumulates, known as the Jijal ultramafite. The second unit consists of Kamila Amphibolite. The third unit is the Chilas complex, formed by mafic to intermediate plutonic rocks. The fourth unit is the Early bimodal suite, containing intrusive rocks alongside the Gilgit Gneisses. Finally, the northernmost unit is composed of the Chalt volcanics (Petterson and Windley, 1985; Khan et al., 1993).

Asian or Karakoram plate lies to the north of the Main Mantle Thrust (MMT) This plate is dominated by slate formations intruded by the massive Karakoram Batholith and associated igneous rocks. South of the MMT, we encounter rocks belonging to the Indo-Pakistan plate. These rocks are primarily composed of metasedimentary formations ranging from Precambrian to Mesozoic eras, alongside Cambrian granites and gneisses. Further south, in the lower Swat region, the Indian plate exhibits three major rock units. The oldest unit is the Precambrian to Cambrian Manglaur Formation, followed by the Cambrian to Early Ordovician Swat Gneisses. Finally, the youngest unit is the late Paleozoic to early Mesozoic Alpurai Group (DiPietro, 1990; DiPietro et al., 1993). Figure 2.1 shows tectonic map of the study area (Akram et al., 2004)

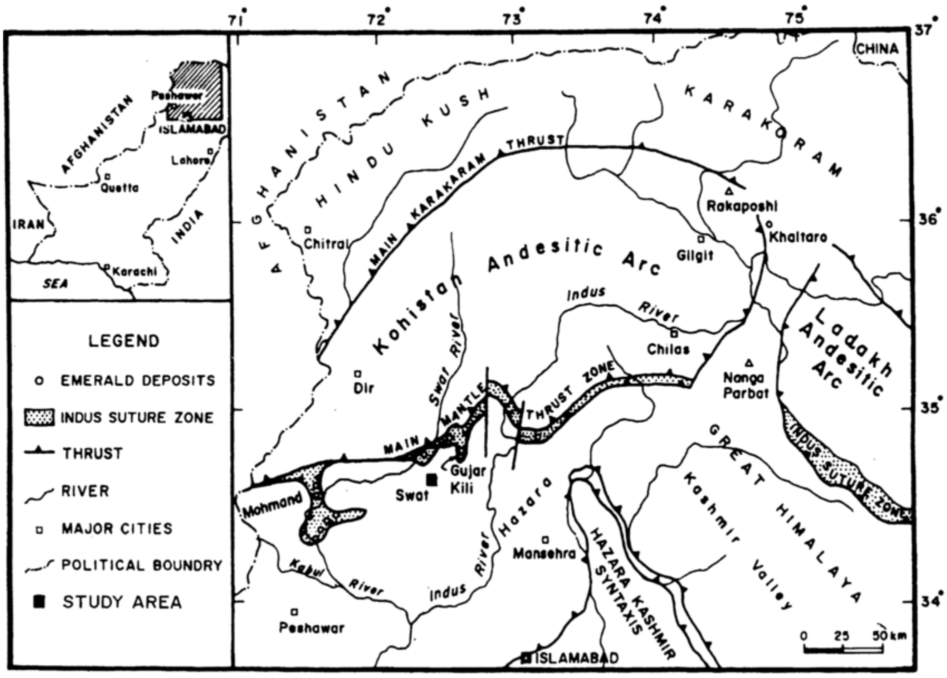


Figure 2.1 Tectonic map of the study area (Akram et al., 2004)

2.2 General Geology of the Study Area

Research on the Kamila Amphibolite has provided a wealth of information on the types and sequences of rocks found there by (Tahirkheli, 1982). The Kamila Amphibolite stretch for roughly 250 kilometers east to west, with a width varying between 10 and 45 kilometers. They typically border the Indus Suture on the north (except when Jijal-like ultramafic rocks intervene) (Jan 1988).

The southern boundary of this unit is either the Indus Suture itself or the Jijal Complex (suggesting an intrusion of Jijal rocks into the Kamila formation). The northern boundary is formed by the Chilas Complex (also hinting at an intrusive relationship with the Kamila Amphibolite) (Khan et al., 1989)

The Kamila Amphibolite are primarily composed of volcanic rocks that have undergone transformation (metavolcanic), dominated by basalts and basaltic andesites. Additionally, they contain rocks formed from solidified magma within the Earth's crust (metaplutonic), including gabbros, norites, and diorites (Treloar et al., 1990, 1996).

This unit has been significantly deformed by a large-scale shear zone within the Earth's crust. However, in less deformed areas (like around Chuprial), remnants of the rocks' original igneous and volcanic features are still visible. These features include layering, contacts between different lava flows, pillow structures, volcanic breccias (fragmented volcanic rock), and hyaloclastites (glassy volcanic fragments) (Dhuime et al., 2009).

Table 2.1 Stratigraphic formations in the study area (Kazmi, 1992)

Formation/Complex	**Location**	**Rock Types**	**Description**
Karora Formation	East	Metasediments	Phyllite, Marble
Kamila Amphibolite	Central	Amphibolite Facies Metamorphic Rocks	Medium- to Coarse-Grained, Dark Color
Chilas Complex	North	Gabbro, Diorite, Ultramafic Rocks	Includes intrusive igneous rocks
Jijal Complex	South	Dunite, Pyroxenite	Ultramafic rocks primarily composed of olivine and pyroxene

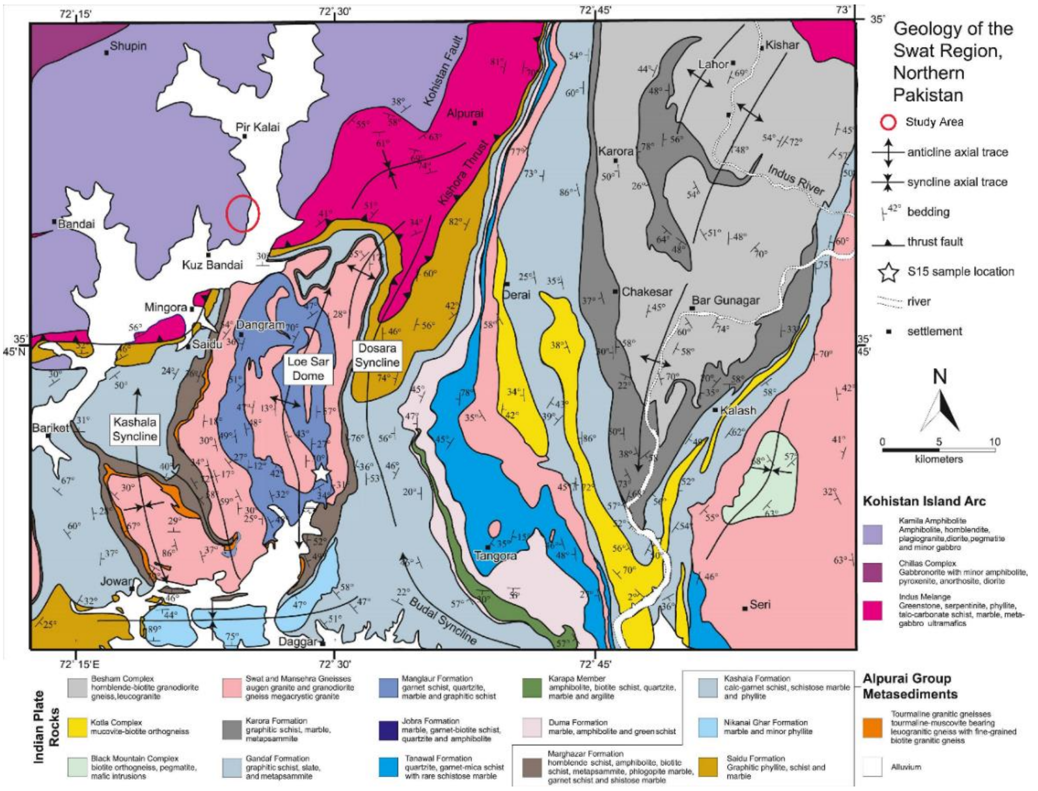


Figure 2.2 Geological map of the study area (Larson et al., 2019)

CHAPTER 3

MATERIAL AND METHODS

3.1 Field Work

For a comprehensive understanding of Amphibolite, fieldwork is an indispensable tool. By directly observing the rock in its natural environment, geologists gain valuable information about its properties that laboratory analysis alone cannot provide. These properties include the rock type (lithology), the size and arrangement of its grains (texture), the thickness of its layers, and the minerals it's composed of (petrology). This firsthand knowledge is critical for selecting the most suitable and representative locations to collect samples, which then form the basis for further investigation in the lab (Fookes & Gilmore, 2000). This research involved both field data collection and laboratory analysis. In the field, we used a geological hammer, Global Positioning System (GPS) unit, measuring tape, and digital camera to document observations. Fieldwork occurred in December 2023, focusing on measuring and collecting samples of the Kamila Amphibolite in Swat, Northern Pakistan.

3.2 Sampling

To assess the physical and mechanical properties of Amphibolite from various zones within the Kamila Amphibolite, ten in-situ rock samples were collected. These bulk samples were subsequently drilled to obtain core specimens for further analysis using uniaxial compressive testing, point load testing, ultrasonic pulse velocity measurement, Schmidt hammer testing, and petrographic thin section analysis. Figure 3.1 show samples collection during field.

Figure 3.1 Samples collections during field work

3.3 Laboratory Testing

The suitability of any rock for engineering projects depends on its geotechnical properties (Auld, 2015; Hoek, 2007). Amphibolite, for instance, can be used as construction materials depending on their grain size, strength, and weathering state (Singh et al., 2011). To evaluate these properties for the Kamila Amphibolite, a series of tests were conducted following established standards like American Society for Testing and Materials (ASTM). The following tests were performed on the collected Amphibolite samples for geotechnical assessment.

3.3.1 Uniaxial compressive strength (ASTM D 2938)

3.3.1.1 Scope

The compressive strength of rock specimens is measured using the Uniaxial Compressive Strength (UCS) test. It is frequently used in geological and engineering applications to assess the mechanical qualities of rock materials. The test establishes the highest axial stress that a piece of rock can bear when compressed uniaxially.

3.3.1.2 Apparatus

Loading machine

An apparatus for loading materials is a press, either mechanical or hydraulic, that can apply a constant load at a predetermined pace. The machine should be able to break the specimen within the specified load range.

Platens

To transfer the stress from the machine to the specimen, use steel plates with hardened faces. The platens should be parallel and level.

Deformation measurement device

A dial gauge or linear variable differential transformer (LVDT) can be used as a deformation measurement tool to quantify axial deformation.

Tools for preparing specimens

A saw, a grinding machine, and further instruments for readying the rock samples.

Alignment fixture

Mechanism to guarantee that the specimen in the loading machine is properly aligned.

Data acquisition system

Data deformation and load recording system.

3.3.1.3 Procedure

Specimen preparation

Accurately cut cylindrical rock specimens with an L/D ratio of 2.5 to 2. Generally, the specimen's diameter should range from 25 to 55 mm. Within 0.02 mm, the specimen's ends should be parallel and flat. Make sure the specimen's sides are flawless and devoid of any obvious flaws or fissures.

Specimen measurement

The specimen's diameter and length should be measured and recorded to the closest 0.1 mm. Calculate the specimen's mass to the closest 0.01 g.

Placing the specimen

The specimen should be placed in the testing machine between the loading platens. Make sure the specimen is correctly positioned and centered to prevent eccentric loading.

Applying load

Along the specimen's axis, apply the force consistently and equally. To achieve failure in five to fifteen minutes, the loading rate needs to be regulated. Loading rates typically fall between 0.5 and 1.0 MPa/s. Throughout the test, keep an eye on the load and deformation.

Recording data

At regular intervals, note the load and the related axial deformation. Load the specimen continuously until it breaks, as evidenced by an abrupt decrease in the applied load.

UCS

Determine the specimen's maximum load (P_max) before to failure. Use this formula to determine the UCS:

UCS = max

UCS = A P max

where A is the specimen's cross-sectional area.

Reporting

The UCS value should be reported to the closest 0.1 MPa. Provide information about the specimen's size, loading rate, and any failure mode observations.

Uniaxial compressive strength (UCS) is a popular method for evaluating a rock sample’s strength. This test simulates how a rock would behave under compressional stress in a single direction (uniaxial). To perform the UCS test, core samples are extracted from larger rock pieces using a core drilling machine (Çelik, 2017). These core samples, typically cubic, cylindrical, or prismatic in shape (Siegesmund and Dürrast, 2014), are then loaded in a compression testing machine until failure occurs.

Figure 3.2 Unconfined compressive strength test (sample 1)

Figure 3.3 Samples after UCS test

3.3.2 Point load test (ASTM 5731-16)

3.3.2.1 Scope

To find a rock specimen's Point Load Strength Index, use the Point Load Test (PLT). The uniaxial compressive strength of rocks can be quickly and affordably estimated using this index. Because it requires little sample preparation and may be conducted on uneven rock fragments, it is frequently utilized for both laboratory and field testing.

3.3.2.2 Apparatus

Point load test machine

A device that applies a concentrated load on a rock specimen by means of two hydraulically or manually driven conical platens.

Loading mechanism

A loading frame equipped with a pressure gauge or load cell to measure the applied load.

Specimen preparation tools

Equipment for cutting and shaping rock samples, like a saw or hammer

Calipers

To measure the dimensions of the specimen

3.3.2.3 Procedure

Specimen selection and preparation

A representative specimen of the rock mass under study should be chosen. Specimens might take the form of irregular lumps, chunks, or cores. Prepare cylindrical samples for core specimens that have a length-to-diameter ratio (L/D) of 0.3 to 1.0. Make sure the load application area for block or irregular specimens is between 30 and 85 mm.

Specimen measurement

Take a measurement and note the specimen's dimensions. Measure the minimal cross-sectional area (W) at the planned load application places for irregular shapes. Determine the separation between the sites where the load is applied (D).

Placing the specimen

Insert the specimen between the point load test machine's conical platens. Make sure the area with the smallest cross-sectional area receives the given load.

Applying load

Apply the weight consistently and continuously. As the specimen splits, increase the load until it fails. At failure, note the maximum load (P).

Calculating point load strength index

Calculate the Point Load Strength Index (Is(50)) using the formula:

Is(50)= P/D2

where PPP is the maximum load and DDD is the distance between the load application points.

Normalize the value to a standard diameter of 50 mm:

Is(50)=Is·(50D)0.45

I_s(50) = I_s * (D / 50)^0.45

Reporting

The Point Load Strength Index (Is(50)) should be reported to the closest 0.1 MPa. Provide information about the specimen's dimensions, kind (core, block, or irregular), and any observations you have about the failure mechanism.

Amphibolite, metamorphic rocks derived from igneous precursors, exhibit significant strength anisotropy due to their foliated structure. This directional dependence of mechanical properties is a crucial factor when evaluating their response to stress. Studies, such as one by Gomes et al (2014) investigating Amphibolite from Baixada Santista, Brazil, highlight this effect. Their research found a substantial difference in point load strength index (Is50) depending on the loading direction relative to the foliation. Samples loaded parallel to the foliation displayed an Is50 value of 2.44 MPa, while those loaded perpendicularly reached 5.41 MPa, representing a strength increase of over 120% . This research emphasizes the importance of considering foliation orientation during point load testing of Amphibolite to obtain accurate and representative strength data.

Figure 3.4 Point load test (sample 1)

Figure 3.5 Sample 1 after point load test

3.3.3 Schmidt rebound hammer (ASTM D5873-14)

3.3.3.1 Scope

The strength and hardness properties of rock or concrete surfaces can be quickly and non-destructively measured with the Schmidt Hammer test. It is used to calculate the in situ compressive strength of rock material in geotechnical and civil engineering.

3.3.3.2 Apparatus

Schmidt rebound hammer

A hammer that is spring-loaded and has a specific energy level, usually 2.207 Nm.

Calibration anvil

A well-calibrated steel anvil is utilized to verify the Schmidt Hammer's calibration.

Grinding stone

To make uneven or rough surfaces smooth before testing.

Measuring tape/device

To record the positions of test points.

Recording sheet/device

In order to record the rebound values and determine the average.

3.3.3.3 Procedure

Preparation

Make sure the surface being tested is smooth and clean. If the surface needs to be prepared, use the grinding stone. Using the calibration anvil, verify the Schmidt Hammer's calibration.

Testing

To test a surface, hold the Schmidt rebound hammer perpendicular to the surface. When the hammer hits the surface, apply pressure on it. Note the rebound value that appears on the scale of the hammer. For every test location, record at least 10 readings in order to allow for variability. The distance between the readings should be at least 25 mm. To determine the mean rebound number, take the lowest and highest rebound numbers out of the equation and average the remaining values.

Data interpretation

To determine the material's compressive strength, use the mean rebound number. This can be accomplished by using empirical correlations between rebound numbers and compressive strength values for particular types of rock.

Calibration and maintenance

Using the calibration anvil, check and calibrate the Schmidt Hammer on a regular basis. For maintenance and calibration procedures, adhere to the manufacturer's recommendations.

Among indirect methods for rock strength evaluation, the Schmidt hammer (Hr) is a popular tool. Developed in 1948 (Katz, 2000), Schmidt hammers come in various types, with two main categories being N-type and L-type. Both are widely used for rock hardness determination.

The key difference between these hammers lies in their impact energy. The L-type hammer delivers a lower impact energy of 0.735 Nm, while the N-type packs a stronger punch at 2.207 Nm. This distinction makes the L-type more suitable for rock testing, as suggested by Gotkan (2015), while the N-type finds applications in concrete testing due to its higher impact force.

Amphibolite, metamorphic rocks with a foliated structure, present unique challenges in strength assessment. The Schmidt Hammer (SH), a popular tool for estimating rock strength, can be affected by the inherent variability in texture and composition of these rocks. While it offers a rapid and non-destructive method, the SRH primarily measures surface hardness, which may not directly translate to the deeper strength of the rock mass.

To obtain a more comprehensive understanding of amphibolite strength, a multi-method approach is recommended. This can involve combining the SRH with established techniques like the Point Load Test (PLT). The PLT provides a direct measure of rock strength by inducing a controlled fracture through a sample. By utilizing both methods, researchers can capture both surface hardness and internal strength characteristics.

Furthermore, considering the foliation orientation during testing is crucial. Studies have shown that Amphibolite loaded perpendicular to the foliation exhibit higher strength compared to those loaded parallel. This emphasizes the importance of understanding the rock’s structure for accurate strength assessment.

Figure 3.6 Performing Schmidt rebound hammer test (Sample 7)

3.3.4 Ultrasonic pulse velocity (ASTM C597)

3.3.4.1 Scope

Ultrasonic pulse velocity (UPV) in rock specimens can be measured according to the method described in ASTM D7012-14 standard. By measuring how long it takes an ultrasonic pulse to pass through a sample of rock, this test can determine its quality and integrity. UPV is a non-destructive technique that can provide details about the mechanical characteristics of rock samples, including their homogeneity, density, and elasticity.

3.3.4.2 Apparatus

Ultrasonic pulse generator and receiver

High-frequency (usually 50 kHz to 1 MHz) pulses can be generated and received.

Transducers

Crystals known as piezoelectrics change mechanical vibrations from electrical signals and vice versa. Pulses are received by one type and transmitted by another.

Amplifier

Enhances the received signal for accurate time measurement.

Timing device

A high-precision timer is used to calculate the difference in time between sent and received pulses. Microseconds should be the desired level of accuracy.

Coupling medium

A material, such as grease or petroleum jelly, to guarantee that transducers and the rock surface have good acoustic contact.

Rock specimens

Prepared using the dimensions and shapes—usually cylindrical or prismatic—specified in the standard.

3.3.4.3 Procedure

Specimen preparation

To ensure maximum contact with the transducers, make sure the rock specimens are prepared with smooth, flat, and parallel surfaces. Accurately measure and document the specimens' dimensions.

Calibration

Calibrate the ultrasonic pulse velocity equipment with a reference material whose parameters are known.

Coupling

Connect the transducers and the specimen by applying the coupling medium to their contact surfaces.

Positioning

Transducers should be positioned on opposing ends of the specimen. To prevent any movement throughout the test, make sure they are positioned securely and in alignment.

Pulse transmission

Transducers should be positioned on opposing ends of the specimen. To prevent any movement throughout the test, make sure they are positioned securely and in alignment.

Time measurement

Create an ultrasonic pulse, then permit it to pass through the sample. The transducer on the other side receives the pulse.

Calculation

Calculate how long it takes the pulse to pass through the specimen. This is known as the transit time.

Calculate the ultrasonic pulse velocity (V) using the formula

V=L/T

Where:

- The pulse velocity is V (m/s).
- L is the specimen's length (in millimetres).
- T stands for travel time (s).

Repeat measurements

To guarantee precision and uniformity, measure each specimen more than once. Three measurements are usually obtained and averaged.

Data recording

Note the pulse velocity, specimen size, and any other relevant data.

Ultrasonic pulse velocity (UPV) is another non-destructive and indirect method of gaining traction for assessing the uniaxial compressive strength (UCS) of rocks. Studies by Chary et al (2006), Yilmaz et al (2014), and Jiang et al (2020) all explored the use of UPV for estimating rock strength. These studies consistently observed a correlation between UPV and rock strength, with higher UPV values indicating greater strength and vice versa. This suggests that UPV can be a valuable tool for indirectly evaluating rock strength.

With a six-decade history, the ultrasonic pulse velocity method has become a standard tool for assessing concrete health. This non-destructive approach extends beyond surface inspection. It excels at detecting concealed cracks, cavities, and other internal flaws that may jeopardise structural integrity. The method's adaptability includes the ability to monitor the impact of environmental concerns. Engineers can acquire significant insights into how concrete reacts to aggressive chemicals and the harmful effects of freeze-thaw cycles by measuring the velocity of ultrasonic waves through it. This method is also valuable in the field of rock analysis, providing a tool to evaluate the strength of rock cores recovered from a structure or geological formation.

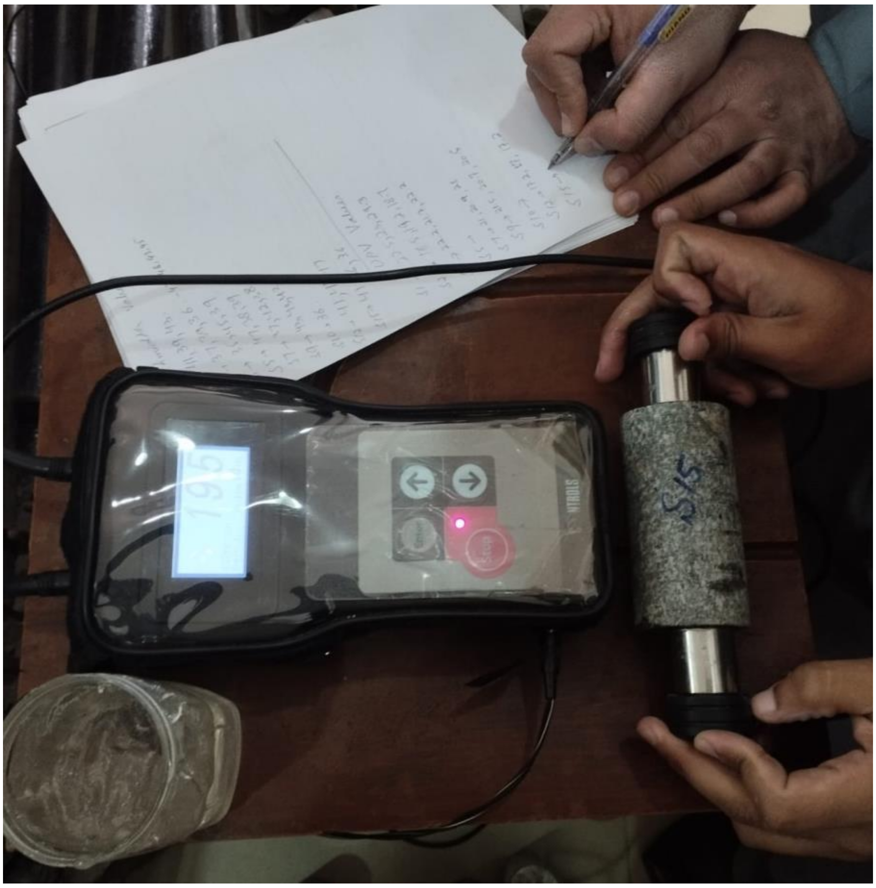


Figure 3.7 Ultrasonic pulse velocity test

3.3.5 Petrography of Kamila Amphibolite

3.3.5.1 Petrographic procedure

Sample collection

Gather representative samples of fresh rock. Record the location, the field observations, and the geological context.

Sample preparation

Cutting:

Cut sample rocks into small pieces (about 1 by 2 inches).

Mounting:

Use epoxy resin to attach the sample to a glass slide.

Grinding:

Grind to a 0.03 mm thickness.

Polishing:

To make sure the surface is smooth, polish.

Microscopic analysis

A polarizing light microscope should be used. Examine the minerals, grain size, shape, arrangement, and texture.

Mineral identification

Use the Becke line approach for the Refractive Index. Identify interference colors in birefringence. Rotate the stage to find the extinction angle. Document patterns of cleavage and fracture

Interpretation

Group rocks according to the texture and makeup of their minerals. Examine the history and mechanisms of geology. Observations and interpretations should be recorded using drawings or images.

Reporting

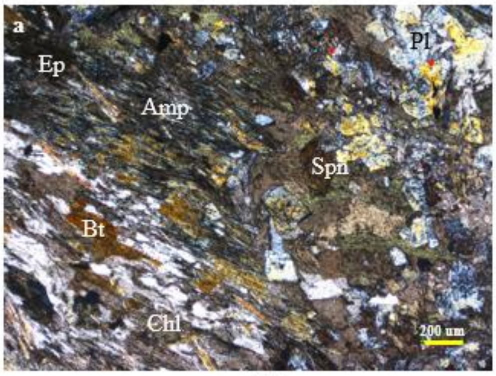
Provide a summary of the results that cover the texture, categorization, and mineralogy. Add photomicrographs of the main characteristics. Relate data to other geological information.

Table 3. 1 Petrographic analysis showing mineralogical composition of all amphibolite samples in percentage (%)

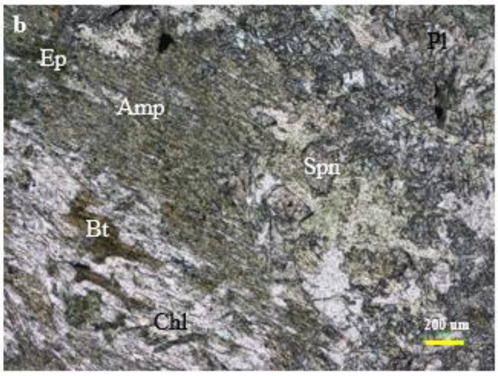
Sample	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10
Amphibole	54	22	45	15	37	38	41	22	45	50
Plagioclase	23	40	20	39	20	29	18	40	23	20
Epidote	8	18	15	20	18	10	12	14	12	9
Quartz	5	14	14	14	15	6	16	13	10	7
Chlorite	3	4	2	4		7	5	3	4	3
Clinopyroxene			2	1				1	1	1
Sphene	2	1	1	3	4	4	3	4	2	4
Biotite	4			2	3	3	3	1	1	3
Muscovite	1	1	1	2	2	2	2	2	2	2
Apatite	Tr	Tr	Tr		1	1	Tr			1
	100	100	100	100	100	100	100	100	100	100

Table 3.1 provided lists the mineralogical composition of ten Amphibolite samples (S-1 to S-10). Each row represents a different mineral, and each column represents the percentage of that mineral in a specific sample. The minerals listed include amphibole, plagioclase, epidote, quartz, chlorite, clinopyroxene, sphene, biotite, muscovite and apatite. Tr shows trace amount of the mineral.

The following images show petrography of each sample of the Kamila Amphibolite.

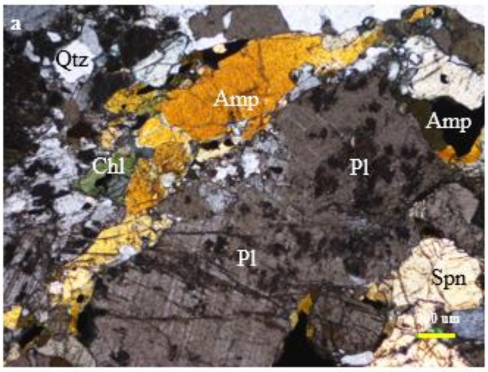


Cross light

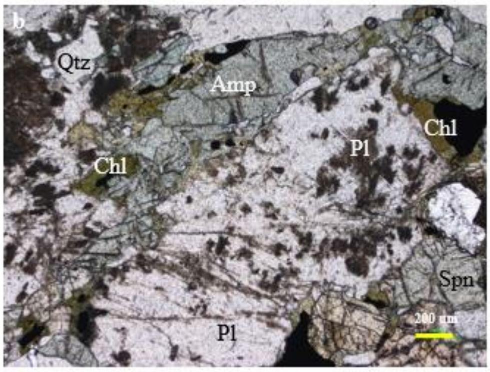


Plane light

Sample 1

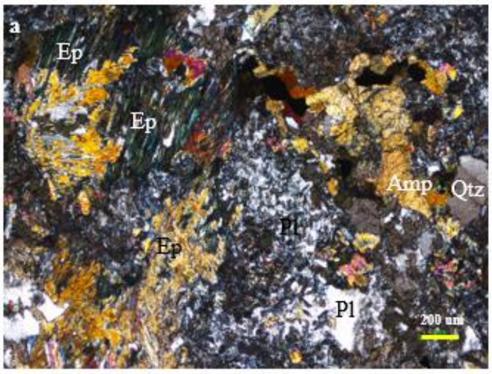


Cross light

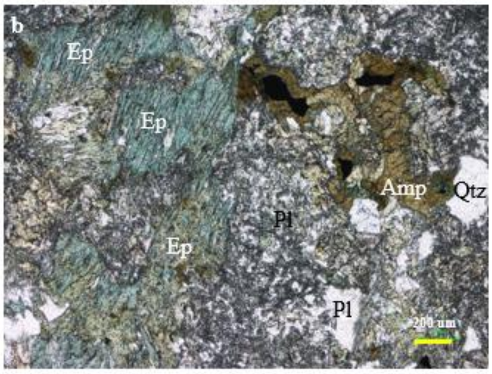


Plane light

Sample 2

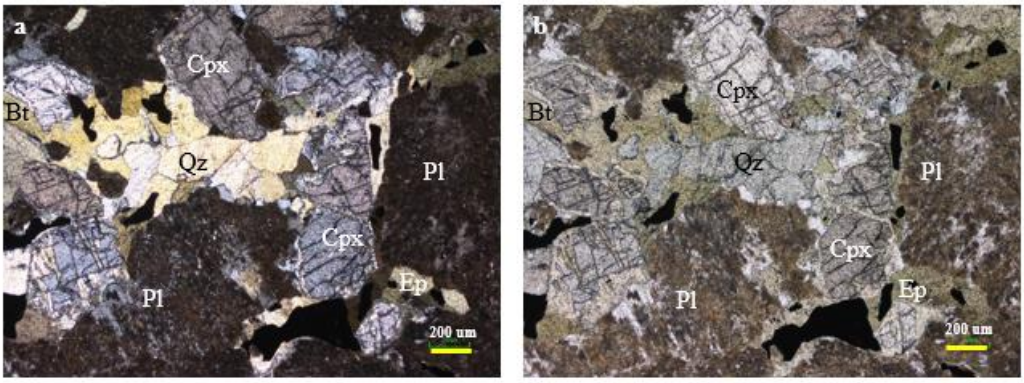


Cross light



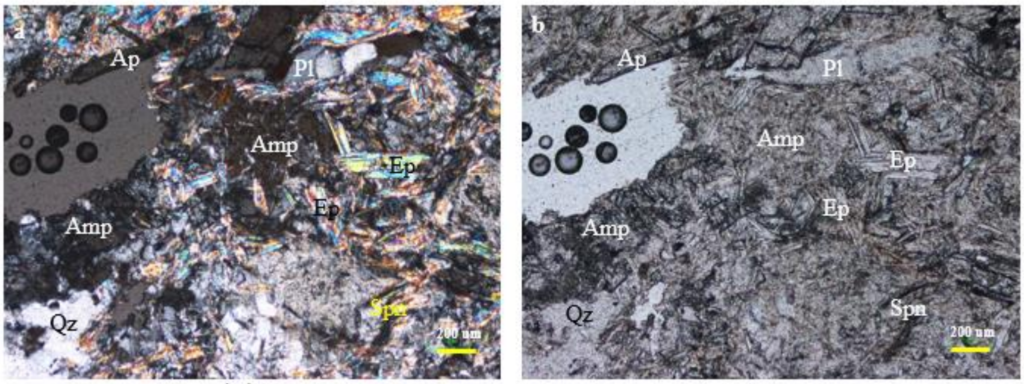
Plane light

Sample 3



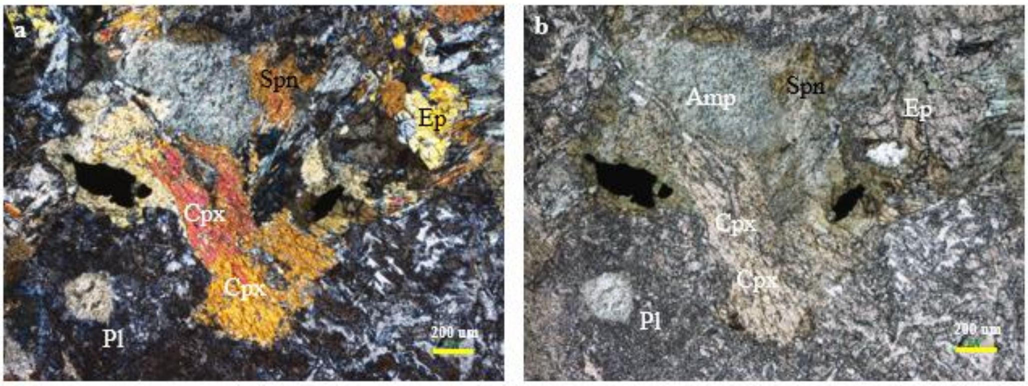
Cross light Plane light

Sample 4



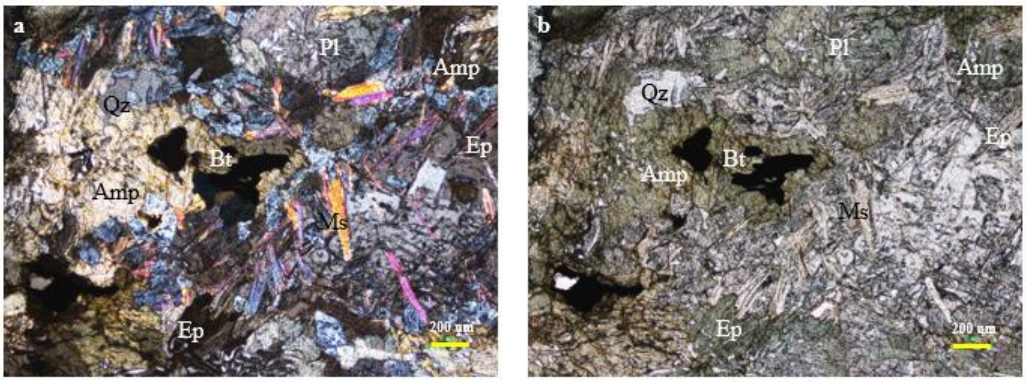
Cross light Plane light

Sample 5



Cross light Plane light

Sample 6



Cross light Plane light

Sample 7

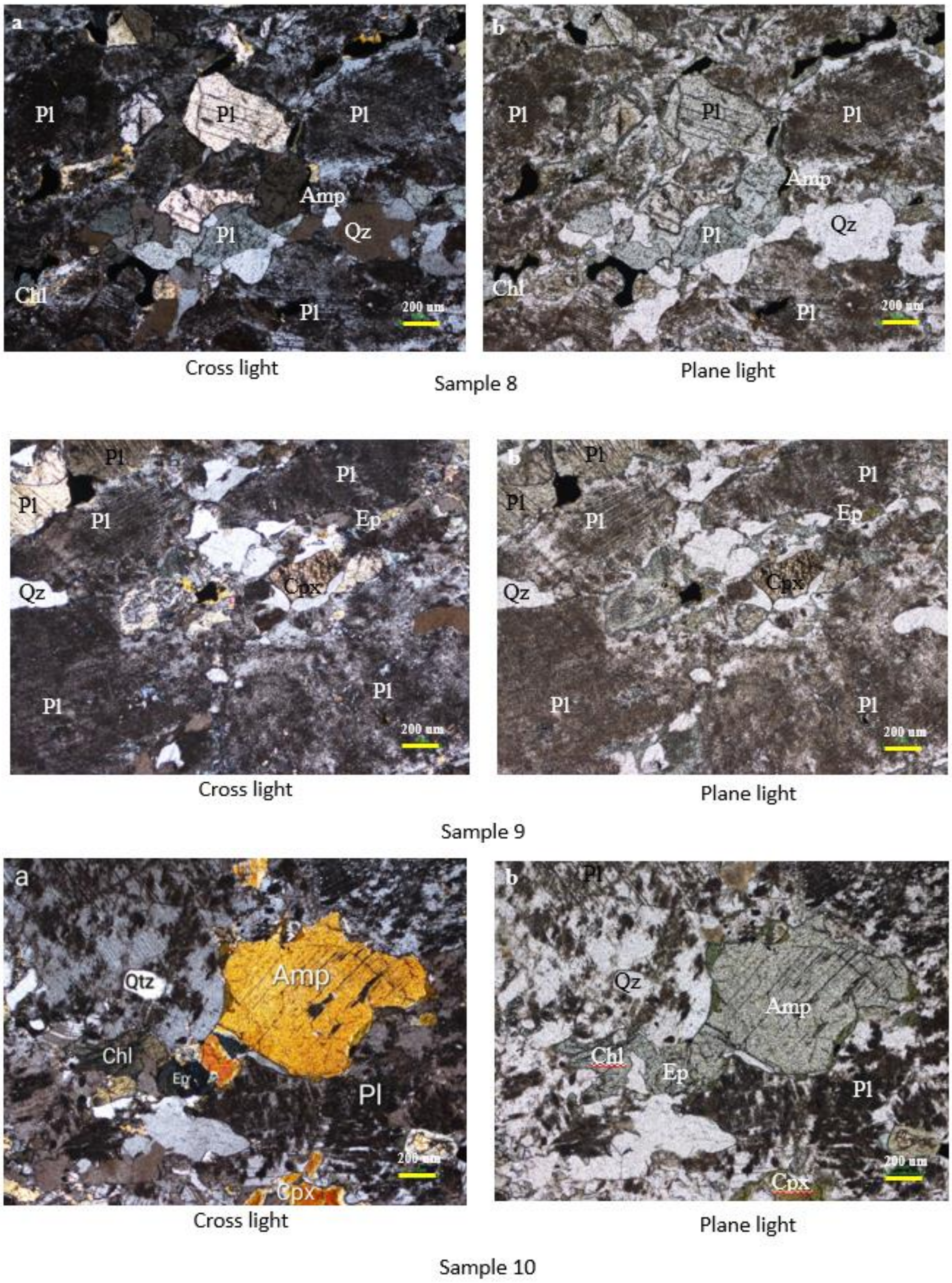


Figure 3.8 Petrographic images of sample 1-10

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Scope and Importance of The Study

This study looks at the mineral composition and physio mechanical properties of Amphibolite rock. Through a variety of tests, it analyses important minerals and how they affect strength, offering important information about the behaviour and creation of the rock. The results are applicable in both academic and practical contexts because of this understanding, which is critical for geological research, resource management, construction material selection, and future scientific studies.

4.2 Unconfined Compressive Strength (ASTM D 2938)

As per standard specifications (ASTM D4543) the cylindrical cores were extracted and prepared from the collected field samples and subjected to UCS test. Subjecting the rock cores in UCS test machine and applying uniaxial load till its failure have revealed the peak compressive strength of rock core samples (Table 4.1). The peak compressive strength values were compared with the classification charts proposed by ISRM and IAEG. The comparison indicated that the samples belongs to very strong category.

Table 4.1 IAEG and ISRM classification of rock on the basis of strength.

IAEG (Anon, 1979)		**ISRM (Anon, 1981)**	
Strength (MPa)	**classification**	**Strength (MPa)**	**classification**
<15	Weak	<6	Very low
15-50	Moderately strong	20-Oct	Low
50-120	Strong	20-60	Moderate
120-230	Very strong	60-200	High
>230	Extremely strong	>200	Very high

Table 4.2 UCS values of all samples

Sample Number	Area(mm)^2	Load (KN)	Strength (MPa)
S1	2366	372.7	158
S2	2366	446.7	189
S3	2366	419.2	177
S4	2366	424	179
S5	2366	426.9	180
S6	2366	403.1	170
S7	2366	151.7	64
S8	2366	370.9	157
S9	2366	337.8	143
S10	2366	372	157

4.3 Point Load Test (ASTM D5731-16)

Table 4.3 Point load test values

Sample Number	Axial						
	W =(Dia)mm	D=(Length) mm	A	De	P	Is	Is50
S1	54.9	31.9	1749.7	47.21	9.71	4.36	4.25
S2	54.9	31.2	1710.7	46.68	9.88	4.53	4.40
S3	54.9	29.5	1619.6	45.42	5.99	2.90	2.78
S4	54.9	32.8	1800.7	47.89	7.26	3.16	3.10
S5	54.9	29.6	1625.0	45.50	8.68	4.19	4.02
S6	54.9	30.4	1669.0	46.11	34.42	16.19	15.61
S7	54.9	30.1	1652.49	45.8812	24.99	11.871	11.420
S8	54.9	30.5	1674.45	46.185	29.36	13.764	13.281
S9	54.9	30.7	1685.43	46.3362	23.32	10.861	10.495
S10	54.9	29.5	1619.55	45.4216	17.5	8.4822	8.1235

The table 4.3 summarizes sample diameter (W), sample length (D), area (A), equivalent core diameter (De), applied load (P), point load strength index (Is), and corrected point load strength index (Is50) are displayed in the point load test (PLT) results for the Kamila Amphibolite samples (S1 to S10).

4.3.1 Sample dimensions

Every sample has a 54.9 mm diameter and a length that varies from 29.5 mm to

32.8 mm.

4.3.2 Applied load (P)

The load fluctuated between 5.99 kN (S3) and 34.42 kN (S6), suggesting that the sample strength was not constant.

4.3.3 Point load strength index (Is)

The values varied from 16.19 MPa (S6) to 2.90 MPa (S3).

4.3.4 Corrected point load strength index (Is50)

The corrected values ranged between 2.78 MPa (S3) lowest to 15.61 MPa (S6) highest. The mechanical strength of the Kamila Amphibolite samples varies significantly, as indicated by the point load strength indices (Is and Is50), with S6 exhibiting the highest strength and S3 the lowest. Understanding the mechanical characteristics of Kamila Amphibolite in engineering applications depends on these results.

Table 4.4 Standard values of resistance to point load test (Carol, 2008; Garnica et. al, 1997, garrido et al, 2010)

Is(50) (MPa)	**Resistance to point load**
< 0.03	Extremely low
0.03-0.1	Very low
0.1-0.3	Low
0.3-1.0	Moderate
1.0-3.0	Medium
3.0-10.0	High
> 10.0	Very high

4.4 Ultrasonic Pulse Velocity (ASTM C597)

The outcomes of ultrasonic pulse velocity measurements on ten samples of Kamila Amphibolite are shown in this table. A non-destructive method of measuring the speed at which sound waves pass through a piece of rock is the ultrasonic pulse velocity test. The density, elasticity, and integrity of the rock all affect the velocity.

A transducer sends a sonic pulse through the rock sample in this test, and a second transducer picks up the signal that is received. The ultrasonic pulse velocity is then determined by measuring the length of time it takes for a sound wave to pass through the sample.

Since each sample has the same area, it can be determined that variations in UPV are caused by the characteristics of the material. The variation in rock quality is indicated by the UPV values, which vary from 17.13 km/s (S8) to 24.93 km/s (S1). S8 has the lowest UPV, indicating a lesser density, while S1 has the greatest, indicating the best quality. Throughout all samples, the average UPV is 20.30 km/s. Better rock quality appropriate for demanding applications is indicated by higher UPV values; lower values indicate possible flaws. An evaluation of Amphibolite's appropriateness for different engineering and construction applications is facilitated by an understanding of these UPV values.

Table 4.5 Results of ultrasonic pulse velocity test

Sample Number	Area(mm)^2	Avg. UPV Value
S1	2366	24.93
S2	2366	18.8
S3	2366	22.03
S4	2366	17.83
S5	2366	21
S6	2366	20.9
S7	2366	21.03
S8	2366	17.13
S9	2366	19.36
S10	2366	20

Table 4.6 Description of UPV of rocks (Anon 1979).

S.no.	V (m/s)	Description
1	<2500	Very low
2	2500-3500	Low
3	3500-4000	Moderate
4	4000-5000	High
5	>5000	Very high

4.5 Schmidt Rebound Hammer (ASTM D5873-14)

A non-destructive method for determining a material's rebound hardness is the

Schmidt Hammer test. The material's moisture content, surface condition, compressive strength, and other characteristics all affect the rebound value.

In order to determine the rebound distance of a mass that is spring-loaded, a hammer is used to strike the surface of the rock sample. Next, a Schmidt Hammer rebound number is calculated using this distance. Each sample's rebound number is shown in the table.

The Schmidt hardness values for ten Amphibolite samples, each measuring 2366 mm^2, are displayed in the table below. The strength of the rock can be determined by measuring its hardness, which is determined through the Schmidt Hammer Test.

As each sample has the same area, variations in Schmidt values can only result from variations in the material. Rock hardness varies, as indicated by the values, which vary from 33 (S7) to 46 (S2). The surfaces S2 and S7 have the highest and lowest values, respectively, indicating the hardest and softest surfaces. For all samples combined, the average Schmidt value is roughly 40.5. Better rock strength is indicated by higher Schmidt values, which qualifies it for more demanding applications. Knowing these characteristics makes it easier to determine whether Amphibolite is appropriate for a variety of engineering and construction uses.

Table 4.7 Schmidt rebound hammer test results

Sample Number	**Area$(mm)^2$**	**Avg. Schmidt Value**
S1	2366	41
S2	2366	46
S3	2366	40
S4	2366	41
S5	2366	39
S6	2366	43
S7	2366	33
S8	2366	43
S9	2366	39
S10	2366	40

4.6 Regression Analysis

Regression analysis is a statistical method used to predict the values of single or more dependent variants from a group of independent variable values. Being part of the work, multiples linear regression models have also been carried out for the prediction of mechanical behaviour of these rocks.

Significant insights into the correlations between mineral composition and rock strength characteristics can be gained by performing a regression analysis of the R2 values for each mineral tested against different mechanical properties. Four important minerals were analysed: quartz, amphibole, plagioclase, and epidote. The analysis was conducted in connection to four tests: Schmidt hardness, Uniaxial Compressive Strength (UCS), Point Load Test (PLT), and Ultrasonic Pulse Velocity (UPV).

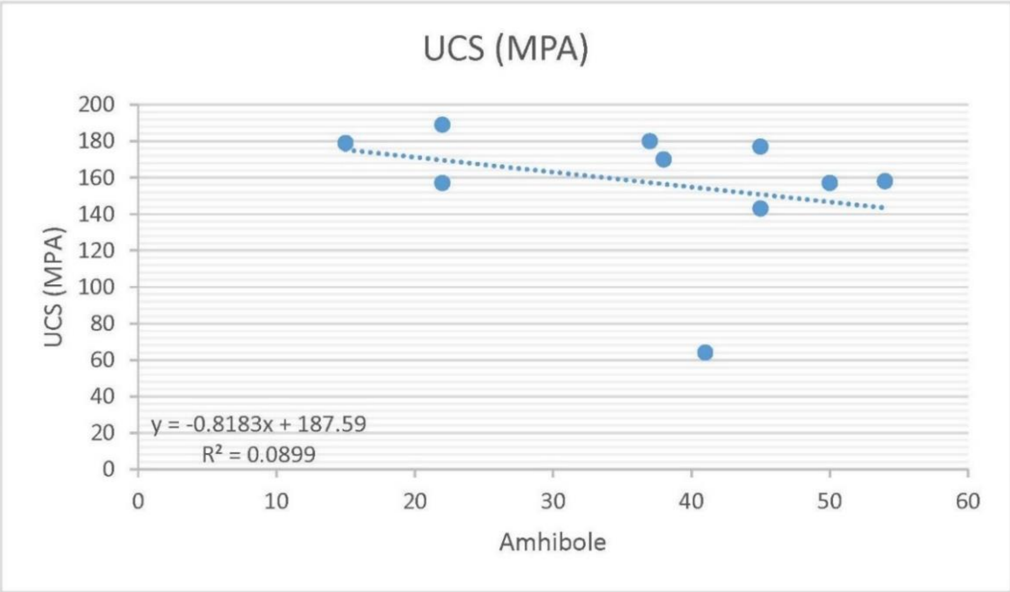


Figure 4.1 Regression analysis of UCS (MPa) versus amphibole (%)

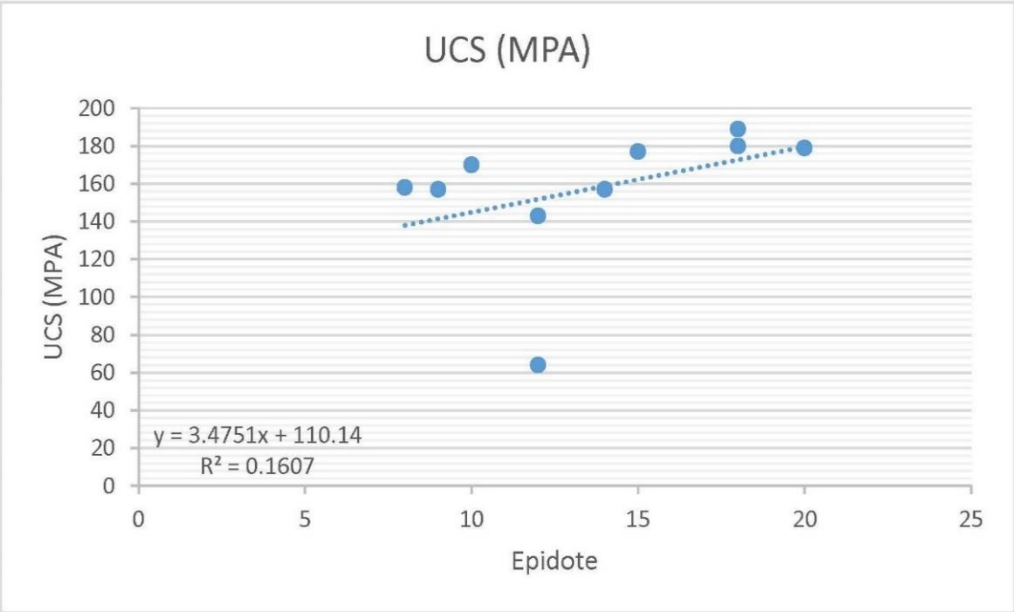


Figure 4.2 Regression analysis of UCS (MPa) versus epidote (%)

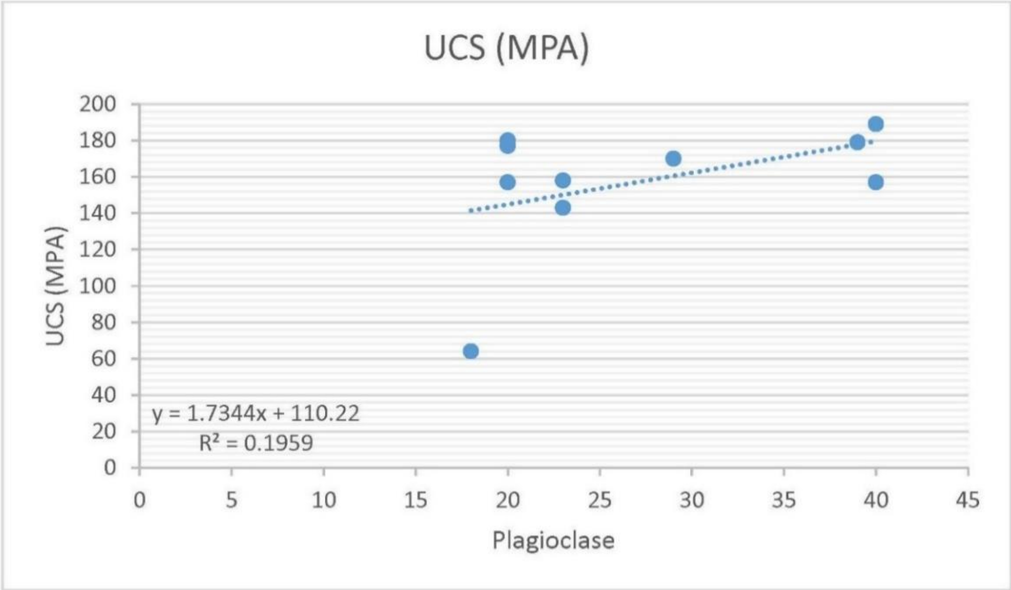


Figure 4.3 Regression analysis of UCS (MPa) versus plagioclase (%)

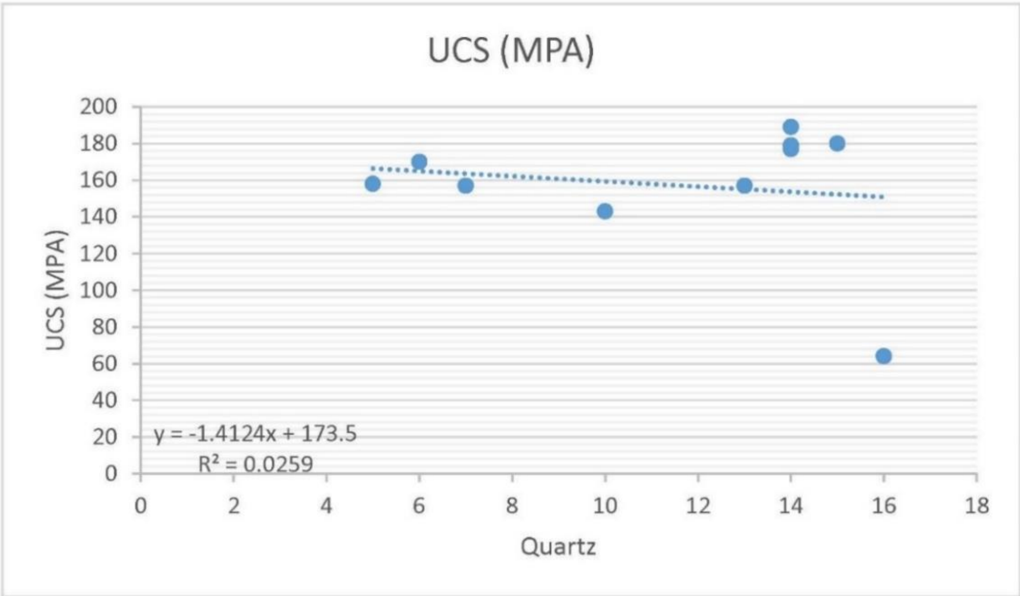


Figure 4.4 Regression analysis of UCS (MPa) versus quartz (%)

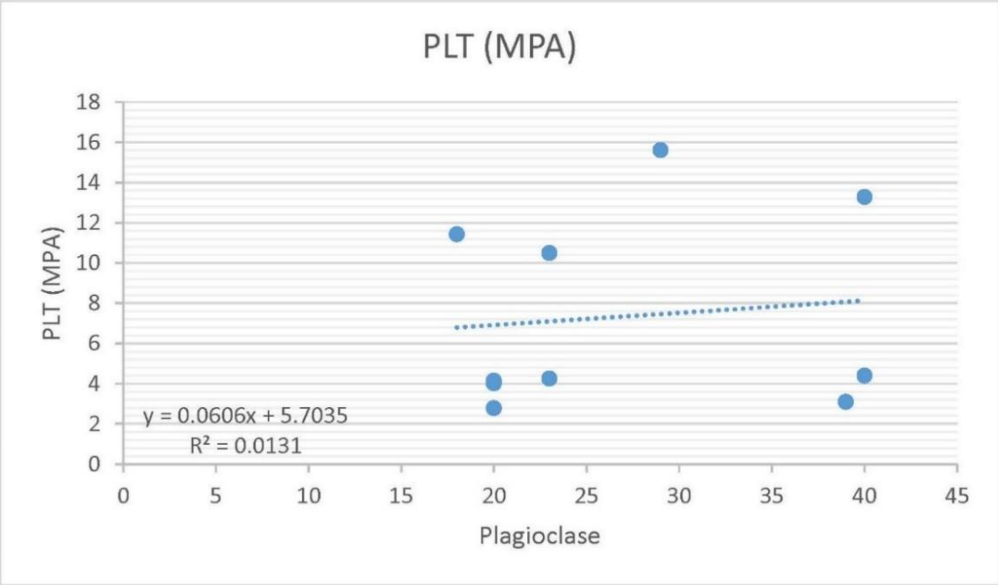


Figure 4.5 Regression analysis of PLT (MPa) versus plagioclase (%)

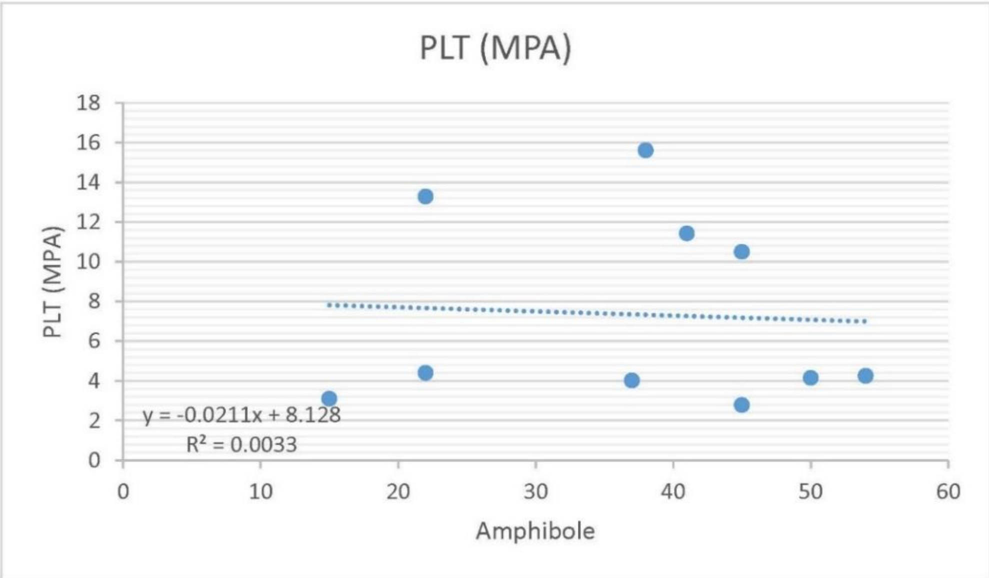


Figure 4.6 Regression analysis of PLT (MPa) versus amphibole (%)

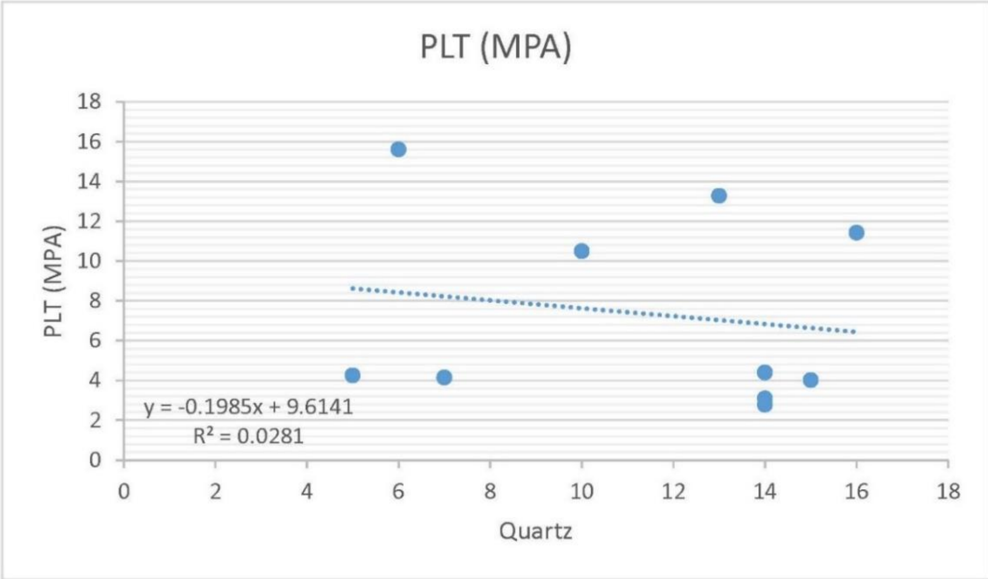


Figure 4.7 Regression analysis of PLT (MPa) versus quartz (%)

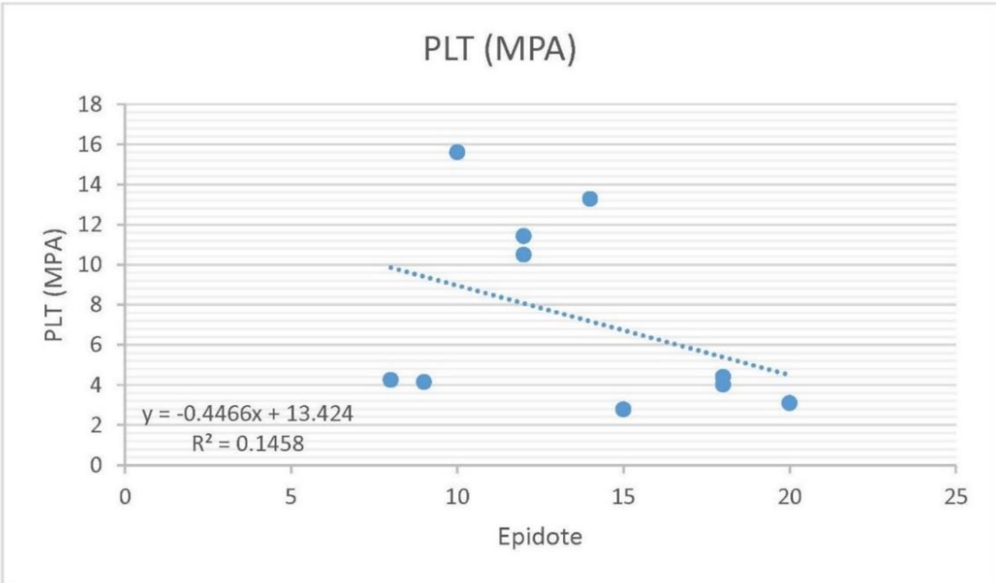


Figure 4.8 Regression analysis of PLT (MPa) versus epidote (%)

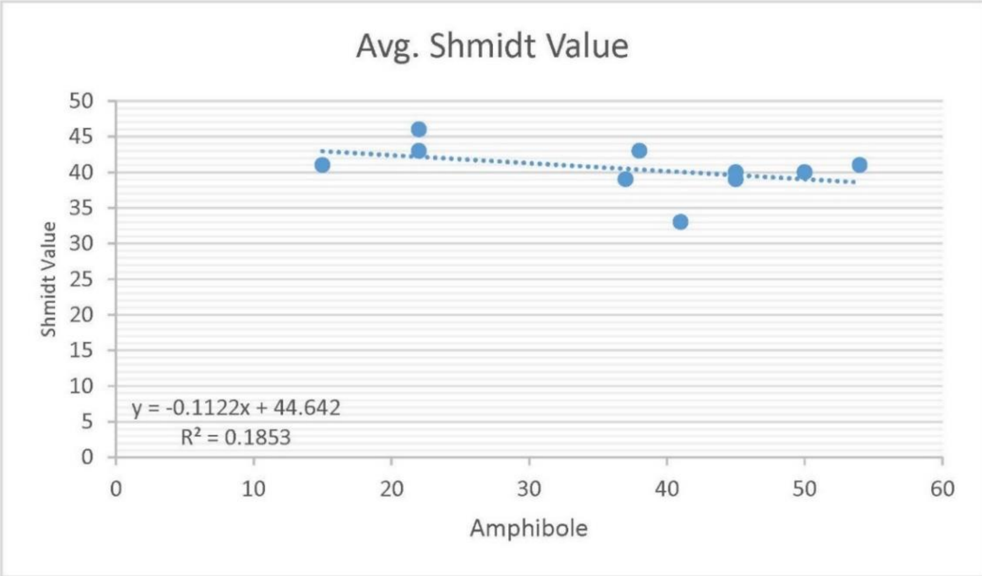


Figure 4.9 Regression analysis of average schmidt rebound hammer value versus amphibole (%)

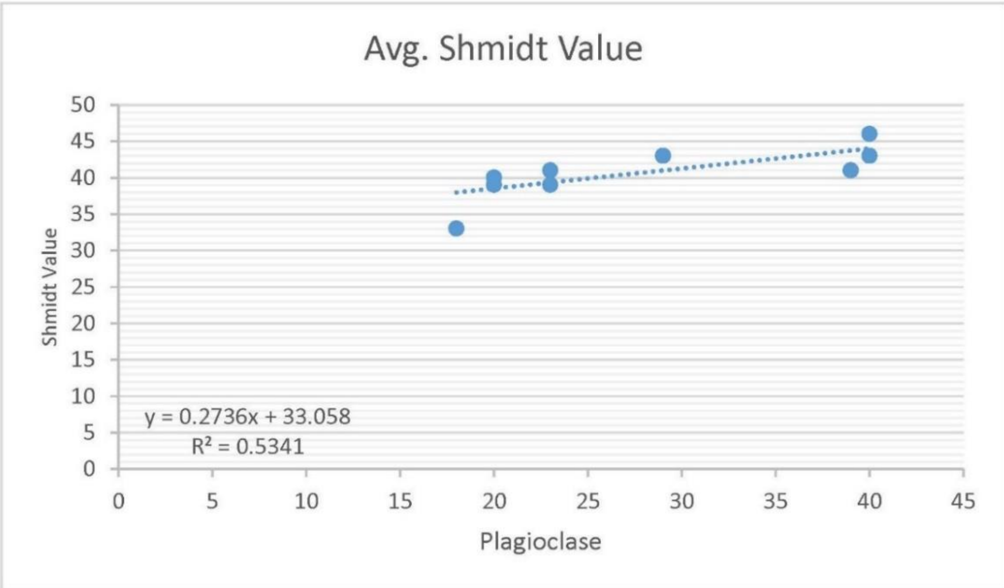


Figure 4.10 Regression analysis of average schmidt rebound hammer value versus plagioclase (%)

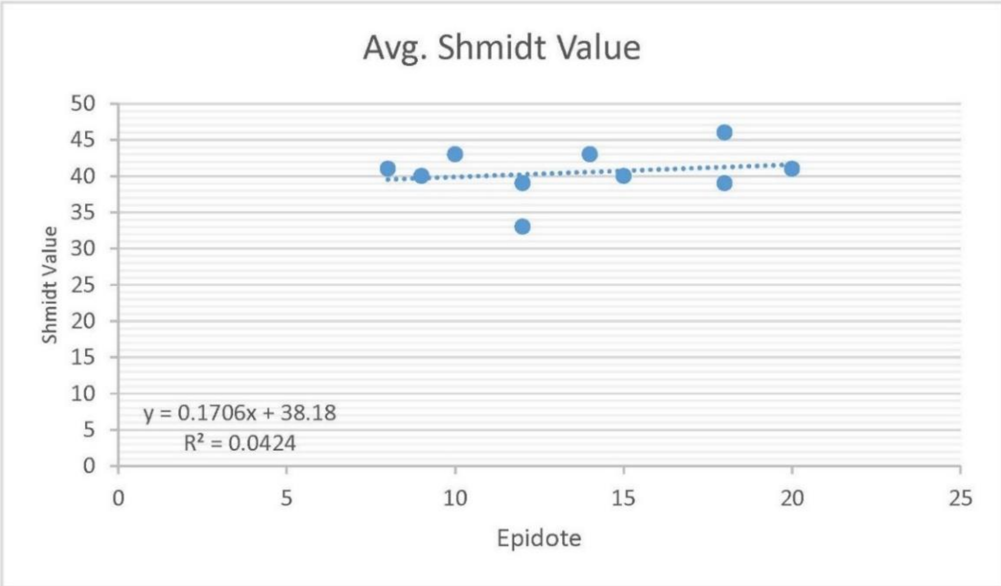


Figure 4.11 Regression analysis of average schmidt rebound hammer value versus epidote (%)

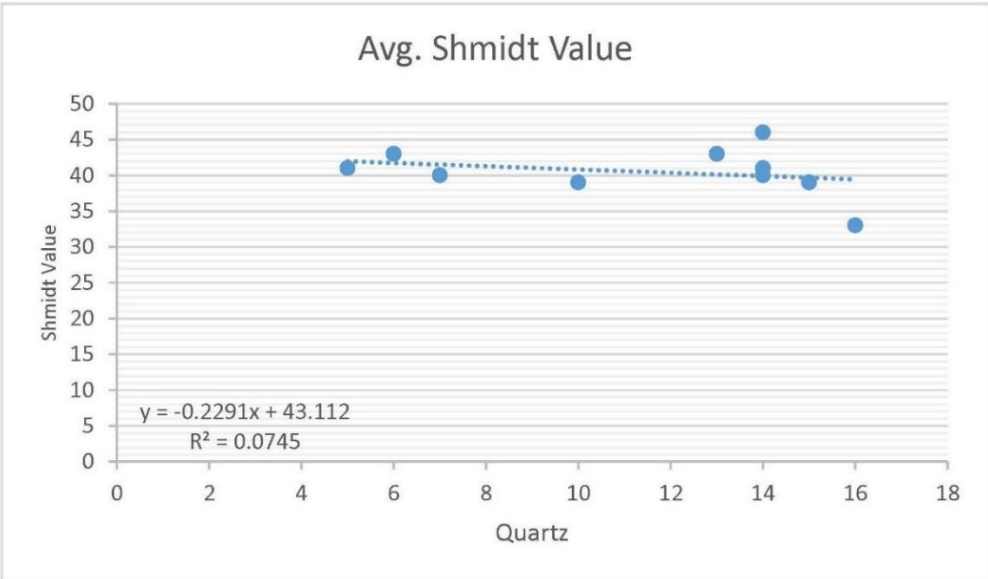


Figure 4.12 Regression analysis of average schmidt rebound hammer value versus quartz (%)

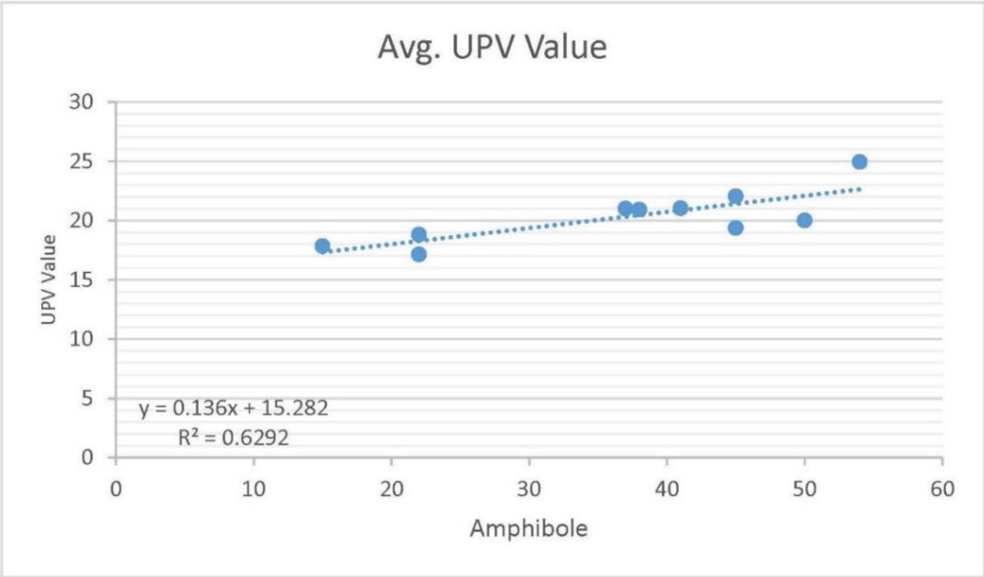


Figure 4.13 Regression analysis of average UPV versus amphibole (%)

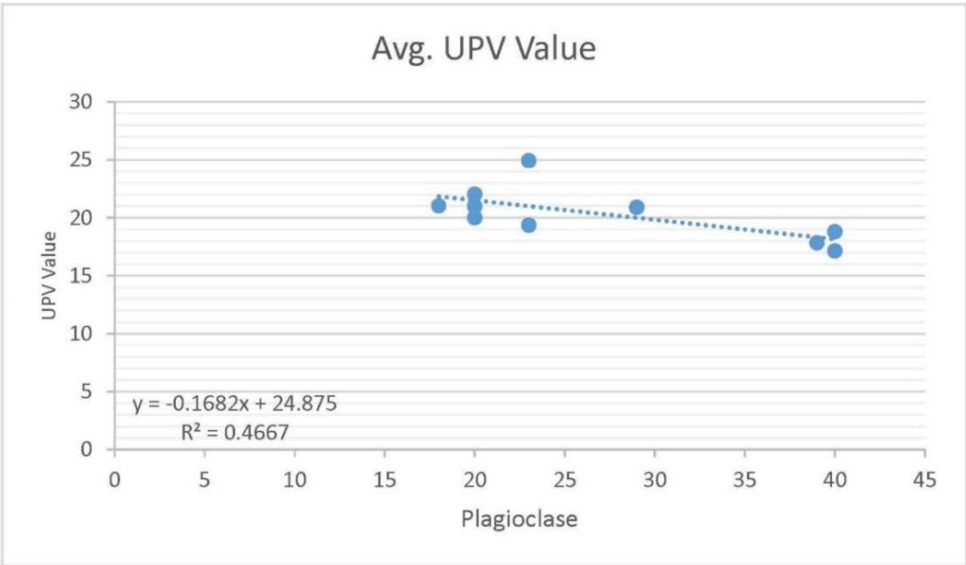


Figure 4.14 Regression analysis of average UPV versus plagioclase (%)

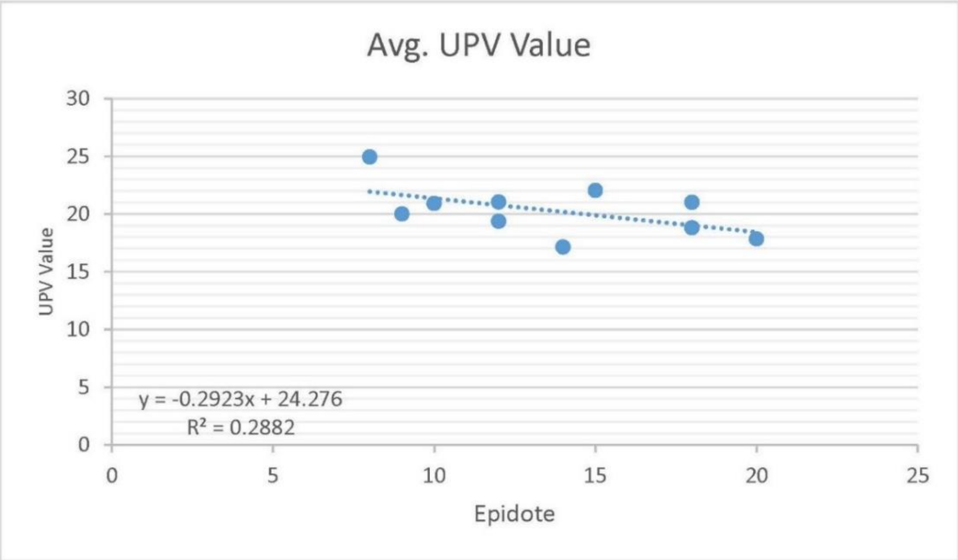


Figure 4.15 Regression analysis of average UPV versus epidote (%)

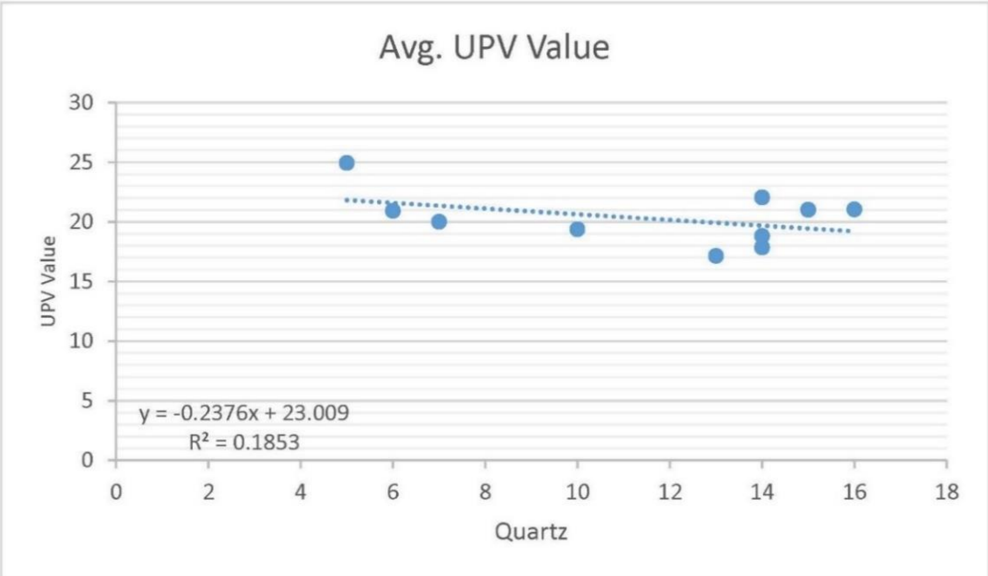


Figure 4.16 Regression analysis of average UPV versus quartz (%)

plagioclase has the greatest R^2 value for UCS (MPA) at 0.1959, followed by Epidote at 0.1607, suggesting a reasonable association with rock strength. The R2 values for Quartz and Amphibole are significantly lower, at 0.0259 and 0.0899, respectively, indicating weaker relationships (Fig. 4.1– 4.4).

Quartz exhibited R^2 value of 0.0281, Amphibole 0.0033, Plagioclase 0.0131, and Epidote 0.1458 in the PLT (MPA). This shows that all minerals showed poor relationships, with the strongest correlation found in epidote (Fig. 4.5 – 4.8).

Plagioclase had a reasonably significant correlation ($R^2 = 0.5341$) for the Schmidt hardness test. Following Amphibole with a correlation of 0.1853, Quartz and Epidote showed significantly lower correlations of 0.0745 and 0.0424, respectively (Fig. 4.9 – 4.12).

Amphibole has the highest R^2 value in the UPV test, at 0.6292, suggesting a strong relationship between the mineral and ultrasonic pulse velocity. R^2 of 0.4667 for plagioclase indicated a noteworthy association as well. The moderate association between Epidote and Quartz was indicated by their respective R^2 values of 0.2882 and 0.1853 (Fig. 4.13 – 4.16).

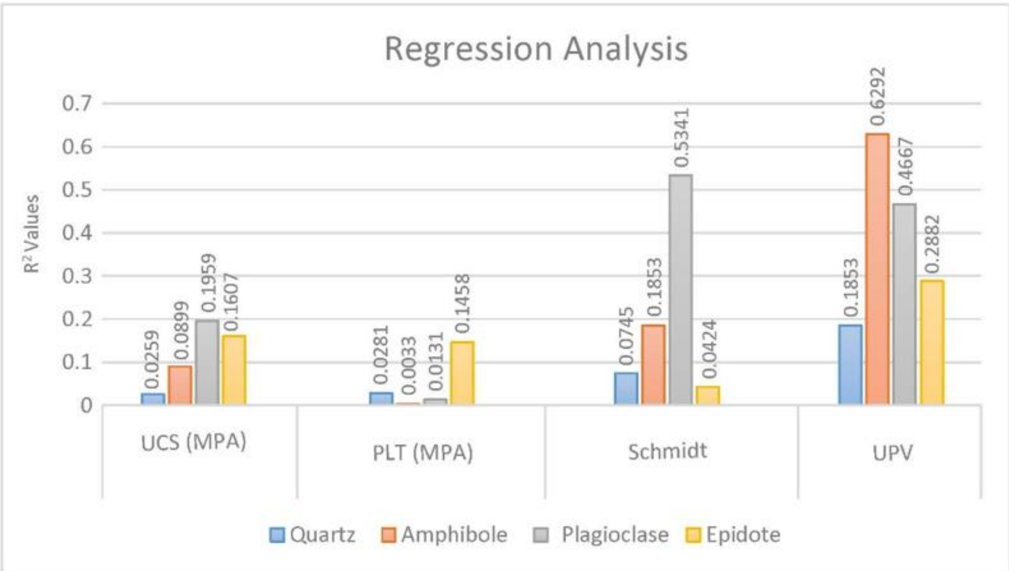


Figure 4.17 Summary of all the regression analysis

According to these results, there is a general stronger link between Plagioclase and mechanical qualities, especially in the Schmidt hardness and UPV tests. Amphibole and Epidote show moderate correlation while Quartz, on the other hand, continuously shows lower correlations in all tests, suggesting that it would have less of an impact on the mechanical properties than the other minerals. Predicting the performance of rocks in many geological applications requires a thorough understanding of the various ways that minerals contribute to the mechanical behaviour of rocks, that's what this analysis delivers (Fig. 4.17).

4.7 Conclusions

4.7.1 Mechanical strength

According to IAEG standards, the UCS test on Kamila Amphibolite samples shows that the majority have high compressive strengths, ranging from 143 MPa to 189 MPa, designating them as "very strong". The overall results validate the strong nature of the rock and its suitability for applications that demand long-lasting materials, despite considerable fluctuation, with one sample exhibiting much lower strength.

The Point Load Test results showed considerable strength variation. The applied loads varied between 5.99 kN and 34.42 kN, whereas the point load strength indices (Is) varied from 2.90 MPa to 16.19 MPa. According to the corrected indices (Is50), Sample S6 had the highest strength and Sample S3 the lowest, with a range of 2.78 MPa to 15.61 MPa. According to these findings, the rock has a high to medium resistance to point loads, indicating that it is suitable for structural uses.

The Ultrasonic Pulse Velocity (UPV) test ranged from 17.13 km/s to 24.93 km/s. Higher UPV values, like those for Sample S1, indicate superior rock quality, whereas lower values, like those for Sample S8, indicate probably flaws. Higher values often indicate better suitability for engineering applications; the average UPV was 20.30 km/s.

Schnidt Rebound values range from 33 (S7) to 46 (S2), with an average of 40.5, according to the Schmidt Hammer test results for the Kamila Amphibolite samples. These variances represent changes in the hardness of the material; greater values indicate tougher rock appropriate for demanding applications. This information is useful in determining whether Amphibolite is suitable for usage in engineering and construction.

4.7.2 Petrographic characteristics

Based on the petrographic examination, the mineral composition was found to be primarily composed of amphibole (averaging 34.9%), plagioclase (2 .2%), epidote (12.4%) and quartz (11.4%). These mineral components give the rock its exceptional strength and longevity, which makes it a dependable building material.

4.7.3 Regression analysis

According to regression analysis, the mechanical properties of Kamila Amphibolite are most closely correlated with plagioclase, particularly in the Schmidt hardness, and UPV tests. Amphibole and Epidote are moderately effective while Quartz has lesser influence on the mechanical properties of the rock.

4.8 Recommendations

4.8.1 Structural applications

Kamila Amphibolite is a very ideal material for structural applications due to its high UCS values and significant point load strengths. For essential applications, give priority to samples with high Schmidt Hammer and UPV values to ensure the dependability and durability of the rock.

4.8.2 Quality control

Along with UCS and PLT, soundness and bulk density test can be carried out for quality assessment.

4.8.3 Mineral considerations

Use samples with higher concentrations of amphibole and plagioclase, as these minerals have a strong association with mechanical strength. Reduce the influence of weaker minerals in vital applications, such as quartz.

4.8.4 Further testing

For future investigation, go for extra testing i.e, alkali aggregate reaction, sulfate soundness, bulk specific gravity, water absorption etc to identify and resolve any underlying problems that might be affecting performance.

4.8.5 Application suitability

Tasks that call for strong materials. If samples exhibit take advantage of the rock's toughness and longevity for engineering and building significant strength changes, exercise caution and carefully assess the intended use cases for these samples.

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