



(RESEARCH ARTICLE)



## Geotechnical and Petrographic Assessment of Kamila Amphibolites from Kuza Drushkhela, Swat (KP), Pakistan: Evaluating Their Feasibility as Concrete Aggregates in Construction Applications

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### Abstract

The growing demand for high-quality, locally available construction materials has intensified interest in evaluating alternative rock sources for aggregate production. This study examines the potential of Kamila Amphibolites, extensively exposed in Kuza Drushkhela of the Matta region, District Swat, Khyber Pakhtunkhwa, Pakistan, for use as coarse aggregates in concrete and other structural applications. The study area lies within the southern portion of the Kohistan Island Arc, a terrain dominated by medium- to high-grade metamorphic rocks. Representative samples, including both aggregate and bulk rock specimens, were systematically collected and subjected to comprehensive petrographic and geotechnical investigations. Petrographic analysis identified Amphibole, Epidote, Hornblende, and Plagioclase as the principal mineral phases, displaying predominantly anhedral to subhedral textures with minor mica and accessory minerals. Engineering evaluation followed ASTM, AASHTO, BS, and National Highway Authority (NHA) standards. The determined properties include specific gravity ( $3.015 \text{ g/cm}^3$ ), water absorption (0.270%), bulk density ( $3.031 \text{ g/cm}^3$ ), soundness (1.022%), flakiness index (12.10%), uniaxial compressive strength (63.83 MPa), and Los Angeles abrasion value (9.84%). These results are within the acceptable range for high-performance construction aggregates. The findings demonstrate that Kamila Amphibolites possess the requisite strength, durability, and physical characteristics, confirming their suitability for concrete manufacturing and large-scale civil engineering works.

**Keywords:** Kamila Amphibolite; Concrete Production; Geotechnical Properties; Kohistan Island Arc; Petrography; Construction aggregates

### 1. Introduction

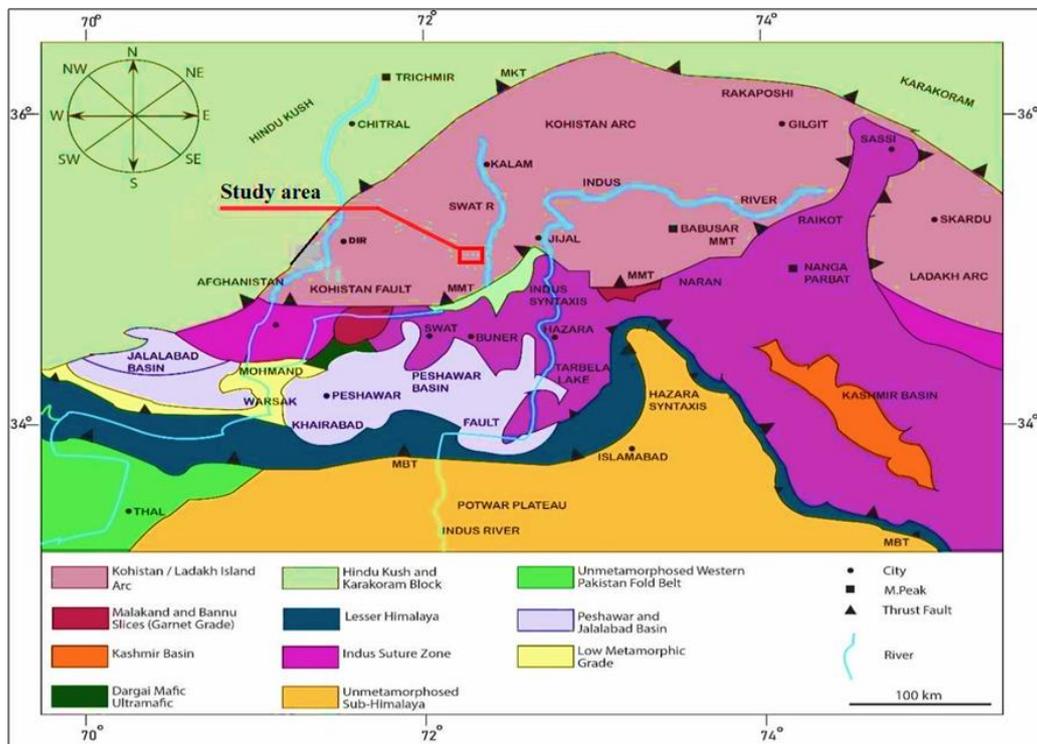
Construction is a cornerstone of national development, encompassing a diverse range of infrastructure projects, including dams, highways, tunnels, bridges, airports, buildings, and power plants. At the core of these endeavors are aggregates, which comprise nearly two-thirds of the total concrete volume and play a critical role in determining its structural strength, workability, durability, and cost-effectiveness (Ashkan, 2014; Ayub et al., 2012). Aggregates are generally classified as coarse or fine based on properties such as particle size, shape, mineralogical composition, surface characteristics, and resistance to crushing and weathering (Langer & Knepper, 1995). Their geological origin—whether igneous, sedimentary, or metamorphic—directly influences their performance in construction materials (Al-Oraimi et al., 2006; Yilmaz et al., 2011). High-quality aggregates enhance concrete's strength, stiffness, and resistance to cracking, whereas aggregates with poor bonding, chemical reactivity, or harmful impurities can lead to early structural deterioration, reducing service life (Ghaezezadeh et al., 2014; Steven et al., 2002). Moreover, sustained performance in

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the presence of a frozen-thaw sequence, chemical reactions, long long-term loading should also be an issue in view of the guaranteed structural resilience and durability. Increasing construction costs and sustainability issues have also increased the need to source high-performance, locally produced aggregates. Nevertheless, there are numerous areas of constraint in which local aggregates are too weak or too short-lived. One of these substances is the Kamila Amphibolite, which belongs to the metamorphic units of Kohistan Island Arc in northern Pakistan. Although in use locally, its engineering potential as fine and coarse aggregate has not received sufficient attention. This study examines geotechnical and engineering characteristics of aggregates at Kamila Amphibolite Quarry site on the Baidara and Bagh Deri Road within the District of Swat, 34.981213 N and longitude 72.429547 E. This analysis is critical in estimating whether it will be appropriate for the concrete and road base and civil infrastructure products. There is a need to critically analyze the physical attributes and functionality of aggregate mining under the specified environment, laws, and economic policies to promote viable and sustainable utilization of the resource (Langer et al., 2003).

### 1.1. Regional Geology and Tectonic Evolution

The study area, Kuza Drushkhela village, lies just south of the Main Mantle Thrust (MMT) along the southern margin of the Kohistan Island Arc (KIA) in Swat District, northern Pakistan. This region represents a key tectonic suture where the Indian Plate collided with and overrode the Kohistan Arc, marking the closure of the Neo-Tethys Ocean and subsequent Himalayan orogeny (DiPietro, 1991; Searle, 1999). The Kamila Amphibolite Unit (KAU), composed of metavolcanic and metasedimentary rocks, reflects a complex history of tectonothermal events (Khan et al., 2013). Bounded to the north by the MMT and to the south by the Indian Plate basement, the unit extends east-west and is subdivided into four belts: Babusar, Niat, Jal, and Sumal. Mineralogical assemblages, including hornblende, actinolite, plagioclase, epidote, and garnet, indicate high-grade metamorphism (Treloar et al., 2000). These features highlight the KAU's significance in understanding arc crust formation, Neo-Tethyan subduction, and Himalayan tectonic evolution.



**Figure 1** Geological map of the North-Western Himalayas, showing the study area marked by a red rectangle (Modified after Ahmad et al. (2003))

## 2. Methodological Framework

### 2.1. Petrographic and Geotechnical Analysis

Complete geological field research was done in the Kamila Amphibolite area in order to estimate the petrographic and geotechnical properties of the rock formation. Representative samples were systematically gathered according to apparent differences in color, surface texture, and on the basis of noticeable geology variations of the surface. Six

samples were chosen to be analyzed by petrographic analysis. The mineralogical composition, the texture, and the metamorphic features of the sample were studied under a polarizing microscope by the means of employing thin sections at the Petrographic Laboratory, Bacha Khan University, Charsadda. The samples have been obtained in five sets in order to be evaluated geotechnically. They were tested at the national center of excellence in geology (NCEG), university of Peshawar using the ASTM and BS standard methods. Among tests conducted were specific gravity and water of absorption (ASTM C127128), soundness (ASTM C88) bulk density (ASTM C29), flakiness and elongation index (BS 812 Part 105), Los Angeles abrasion resistance (ASTM C131), porosity (ASTM C97) and unconfined compressive strength (ASTM D7012). Field records included field lithological records, structural records and weathering records. The combination between observation related to field, petrographic and engineering test outcomes in construing the relationships among macro-structural geology and micro-scale rock properties that influence strengths and durability. The elucidating methodological researcher presents handy facts regarding Kamilla amphibolite engineering feasibility.

## 2.2. Field Observations

The field studies carried out at Kamila geological site revealed it possessed medium and coarse- textures, interlocking minerals, distinct foliation and dark green to black hues. Mineral assemblage and textural characters pointed at medium- and high-grade metamorphism. Structural evidence including folds, fractures, shear zones, and mineral veins had provided evidence of the tectonic and metamorphic history. Secondary mineral growth and discoloration were other effects of weathering that created a geological kind of rock.



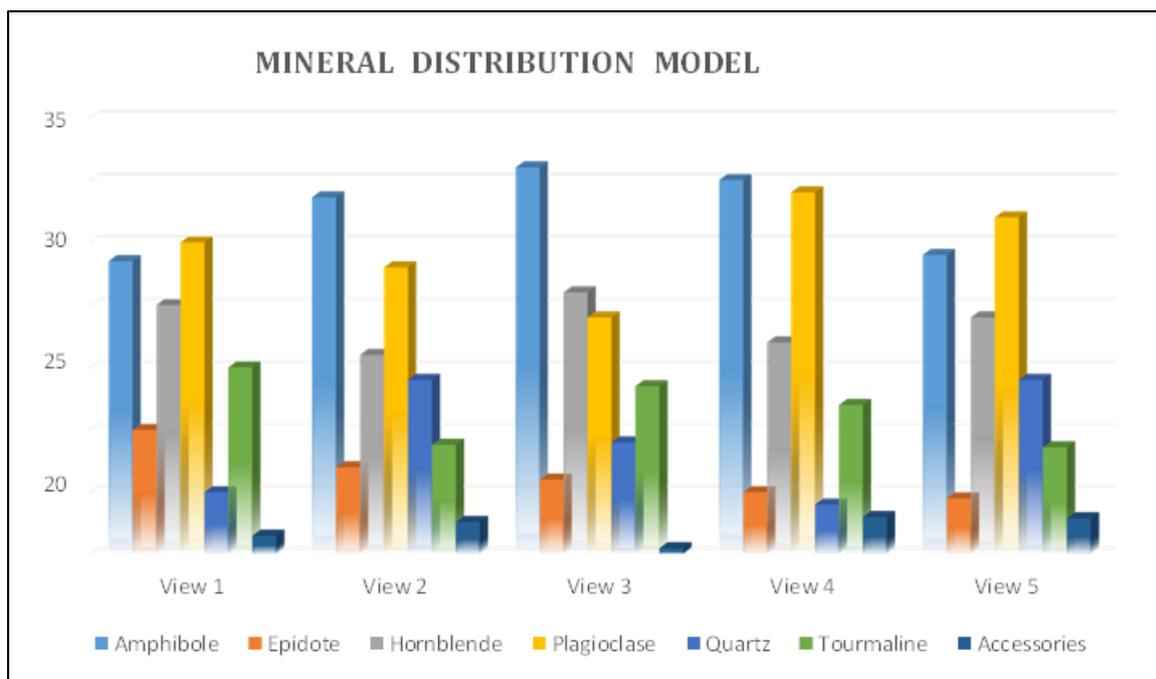
**Figure 2** Field photographs showing different features of the Kamila amphibolite: (a) angular fragments produced by mechanical weathering, (b) fresh blocks displaying massive texture, (c) quarry exposure with a fresh amphibolite face, (d) weathered slope exposing foliated layers, (e) banded amphibolite with prominent foliation (hammer for scale), and (f) angular boulders accumulated at the slope base

### 3. Petrographic Observations

Thin section photo results (a to f) indicate the petrographic constituents present in a medium refined metamorphic rock that begins with hornblende (Hbl), plagioclase (Plg), amphibole (Amp), biotite (Bt), epidote (Ep), quartz (Qtz), muscovite (Ms flakes) and the accessory mineral anthophyllite (Ath). The most common mineral phases are amphibole, epidote, hornblende, and plagioclase (anthophyllites, feldspar, and other dilute phases are found as an accessory). Plagioclase is the most widespread crystal family and often occur in the form of subhedral to euhedral grains that exhibit polysynthetic twinning and deformation traits like undulose extinction that discloses dynamic metamorphism through preference of directed fault planes. Quartz occurs as interstitial grains showing undulatory extinction, suggesting post-crystallization deformation. Hornblende and other amphiboles frequently display two prominent cleavage directions intersecting at approximately  $56^\circ$  and  $124^\circ$ , and are commonly aligned to define a schistose to gneissic foliation. Biotite occurs as subhedral to anhedral flakes, often intergrown with amphiboles, while muscovite appears as elongated flakes parallel to foliation, highlighting the development of metamorphic fabric. Epidote forms granular to elongated grains, locally intergrown with amphiboles, whereas tourmaline occurs as euhedral prismatic crystals disseminated in the matrix. Allanite is present as a minor accessory phase, mostly associated with biotite and amphibole. The rocks are coarse-grained, with abundant white and brown minerals contributing to the overall texture. The fabric is granoblastic to lepidoblastic, characterized by a planar alignment of ferromagnesian minerals and interlocking plagioclase and quartz grains. Collectively, these petrographic features indicate medium- to highgrade regional metamorphism under amphibolite facies conditions, followed by tectonothermal overprinting that produced deformation features such as crystal bending, mineral alignment, and undulose extinction.

#### 3.1. Macro- and Microstructural Characteristics of Amphibolite

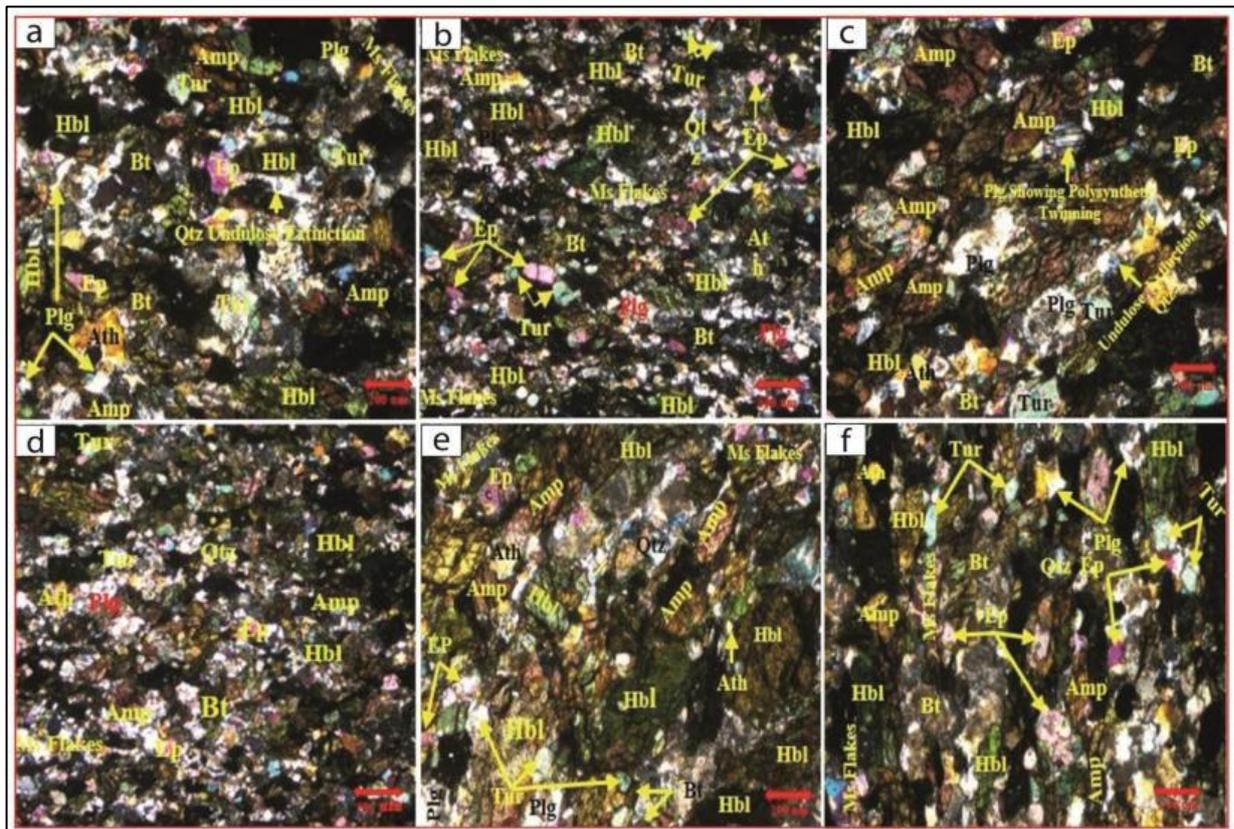
The amphibolite exhibits a foliated and banded fabric, with mafic bands of hornblende and biotite alternating with felsic layers of plagioclase and quartz, indicating deformation under compressive stress. Lineation, streaking, and minor folding further suggest tectonic activity during metamorphism. Microscopically, the rock shows a granoblastic to lepidoblastic texture dominated by plagioclase, quartz, hornblende, amphibole, and biotite, with accessory epidote, muscovite, and tourmaline. Plagioclase and quartz display undulose extinction and recrystallization, reflecting strain, while hornblende and amphibole occur as elongated, aligned crystals forming a strong preferred orientation. Biotite and muscovite define micaceous laminae, enhancing schistosity, whereas accessory phases mark zones of metasomatic alteration. These features collectively indicate recrystallization, tectonic overprinting, and ductile deformation under amphibolite-facies conditions.



**Figure 3** Proportional distribution of mineral constituents of Kamila Amphibolite

**Table 1** Visual Estimation of Minerals in different thin section Views.

S. No	Name	View 1	View 2	View 3	View 4	View 5	Total %age
1	Amphibole	23.5	28.6	31	30	24	27.42%
2	Tourmaline	15	8.8	13.5	12	8.6	11.58%
3	Hornblende	20	16	21	17	19	18.6%
4	Plagioclase	25	23	19	29	27	24.6%
5	Quartz	5	14	9	4	14	9.20%
6	Epidote	10	7	6	5	4.5	6.50%
7	Accessories	1.5	2.6	0.5	3	2.9	2.10%
Total		100%					



**Figure 4** Thin section photomicrographs (a-f) showing hornblende, plagioclase, amphibole, biotite, epidote, quartz, muscovite, and tourmaline with minor allanite. Quartz exhibits undulose extinction, while plagioclase shows polysynthetic twinning. The alignment of mafic and micaceous minerals defines foliation and schistosity, reflecting medium- to high-grade regional metamorphism with deformation features. (Keys: Amp: Amphibole, Ath: Anthophyllite, Bt: Biotite, Ep: Epidote, Hbl: Hornblende, Plg: Plagioclase, Qtz: Quartz, Tur: Tourmaline)

## 4. Results and Discussions

### 4.1. Physical properties

#### 4.1.1. Specific Gravity

Specific gravity is a key parameter for assessing rock density, durability, and strength (Ahmad et al., 2017). In this study, values ranged from 3.005 to 3.024 g/cm<sup>3</sup> across coarse, medium, and fine aggregates, all exceeding the construction standard of 2.55 g/cm<sup>3</sup> (Awad & Nastavkin, 2021). These results confirm excellent geotechnical quality and long-term engineering suitability.

#### 4.1.2. Absorption

Water absorption is a critical parameter for evaluating the durability and stability of construction rocks (Abdelhamid et al., 2020). In this study, values of 0.223% (coarse), 0.370% (fine), and 0.238% (medium) fall well below accepted limits (Bell, 2005; Mokhtari & Nejad, 2013). These low values confirm excellent resistance to weathering, frost action, and long-term engineering suitability.

#### 4.1.3. Porosity

Porosity is a fundamental property influencing the geotechnical performance of rocks (Wyerling et al., 2014). In this study, amphibolites show very low porosity (0.706–0.747%), reflecting dense, durable material. Such values reduce permeability, enhance strength, and improve resistance to frost and weathering, confirming the excellent engineering quality and long-term suitability of the studied amphibolites for construction applications.

#### 4.1.4. Flakiness and Elongation

Flakiness and elongation describe aggregate particle shapes that influence engineering performance. Excessively flaky or elongated particles reduce workability, increase voids, and weaken structures. According to NHA standards, values exceeding 30% are unsuitable for construction. In this study, the flakiness index is 12.10%, well within permissible limits, confirming the suitability of the tested aggregates for engineering applications without compromising strength.

### 4.2. Chemical properties

#### 4.2.1. Soundness

Soundness refers to the ability of aggregates to withstand environmental stresses such as weathering, temperature fluctuations, and freeze–thaw cycles (Okogbue & Ugwoke, 2015; Alves & Gomes, 2023). According to ASTM C88-13, the maximum permissible loss is 12%. The tested samples showed minimal loss (0.89–1.27%, average 1.022%), demonstrating excellent resistance to degradation and confirming their long-term durability for construction applications.

### 4.3. Mechanical properties

#### 4.3.1. Los Angeles Abrasion Value (LAA)

The Los Angeles abrasion test evaluates aggregate strength and resistance under both normal and stressed conditions, measuring abrasion, grinding, crushing, and degradation (Umar et al., 2020). ASTM standards specify a maximum limit of 40%. The tested amphibolites recorded values between 9.19 and 10.27, with a mean of 9.80, indicating excellent durability and superior mechanical resistance (Chan et al., 2023).

#### 4.3.2. Aggregate Impact Value (AIV)

The aggregate impact value evaluates the ability of aggregates to resist sudden shocks rather than compressive loads (Das et al., 2021). In this study, values ranged from 13.89% to 14.70%, well below the 25% limit prescribed for road construction (Harrison & Bloodworth, 1994). These results confirm the toughness and suitability of the tested aggregates for engineering applications.

#### 4.3.3. Aggregate Crushing Value (ACV)

The aggregate crushing value test measures the resistance of aggregates to compressive loads, an essential parameter for assessing their suitability in road construction (Lu et al., 2019; Zhang et al., 2013). The amphibolite samples in this

study recorded an average value of 19.68%, well below the 25% limit (Harrison & Bloodworth, 1994), confirming their durability and long-term pavement performance.

#### 4.3.4. Unconfined Compressive Test (UCS)

Unconfined Compressive Strength (UCS) represents the maximum compressive stress a rock can withstand without lateral confinement (Feng et al., 2022). In this study, amphibolite samples recorded UCS values between 61.2 and 66.2 MPa, significantly exceeding the 35 MPa standard for construction materials (Bell, 2005). These results confirm the rock's excellent mechanical strength and durability, supporting its suitability for demanding engineering applications.

#### 4.3.5. Unconfined tensile strength (UTS)

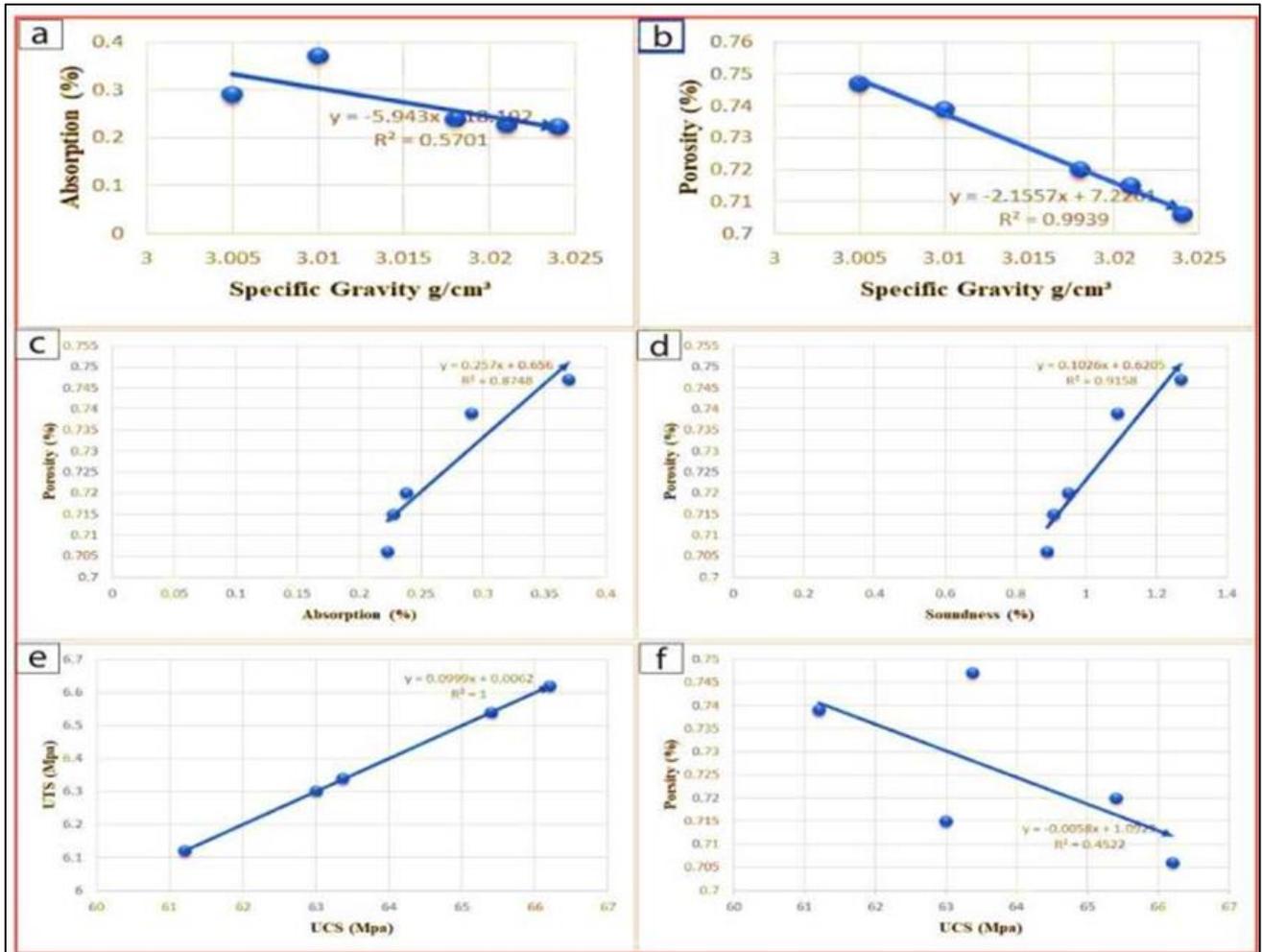
Tensile strength reflects a rock's resistance to failure under tension (Hashiba & Fukui, 2015). In this study, uniaxial tensile strength (UTS) was determined using the Brazilian Disc Test (Bell, 2005), which avoids bending stresses associated with direct testing. The amphibolite samples yielded UTS values of 6.128–6.628 MPa, averaging 6.387 MPa, confirming the test's reliability and practical applicability (ASTM D3976).

## 5. Regression Analysis

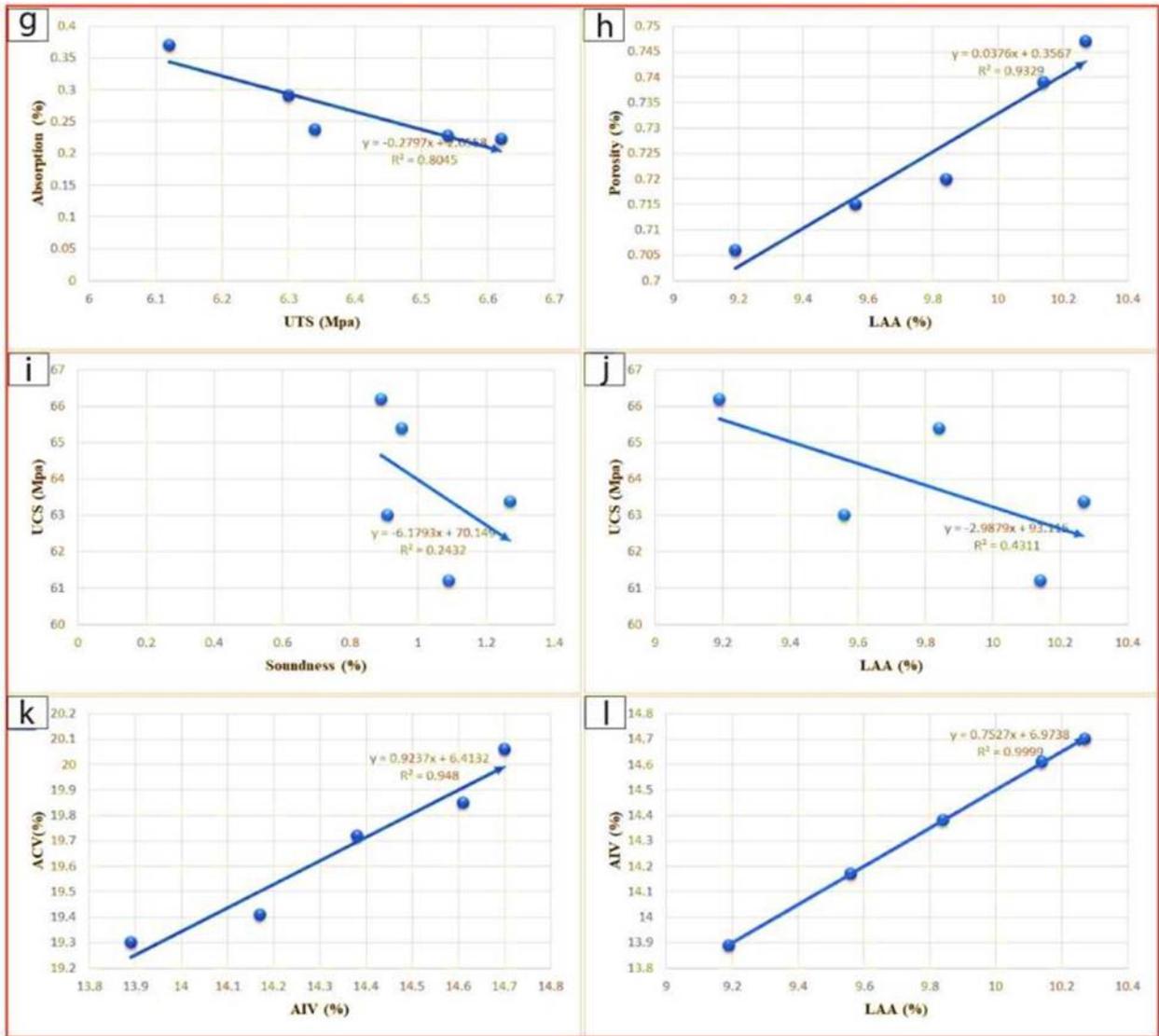
In geology, regression analysis can be described as a statistical approach to the analysis of relationships between geological parameters. It is used to determine the correlation between rock strength and porosity, density, and the composition of the rock. Fitting a regression line or curve allows geologists to estimate one property of rock based on another, and to understand the geological variables controlling the behavior of the rocks.

**Table 2** Representing Results of Chemical, Mechanical, and Physical Analysis.

Sample	SG gm/cm <sup>3</sup>	Absorption %	Porosity %	F.I & E.I %	Soundness %	LAA %	AIV %	ACV %	UCS Mpa	UTS Mpa
Limits	≥ 2.55	≤ 2.0 - 2.5	< 2-3	≤ 30	≤ 12	≤ 40	≤20	≤ 30	≥ 35	≥ 3.5
References	ASTM C127, C 128	ASTM C127,C128	Indirectly obtained	ASTM D4791	ASTM C88	ASTM C131,C535	BS 812	BS 812	ASTM D7012	ASTM C496
KM-1	3.005	0.370	0.747	12.10	0.89	9.19	13.89	19.30	61.20	6.12
KM-2	3.010	0.291	0.739	14.10	0.91	9.56	14.17	19.41	63.00	6.30
KM-3	3.018	0.238	0.720	11.90	0.95	9.84	14.38	19.72	63.37	6.34
KM-4	3.021	0.228	0.715	12.30	1.09	10.14	14.61	19.85	65.40	6.54
KM-5	3.024	0.223	0.706	10.10	1.27	10.27	14.70	20.06	66.20	6.62
Mean	3.015	0.270	0.725	12.10	1.022	9.80	14.35	19.68	63.83	6.38



**Figure 5** Regression Analysis Display (a) Inverse trend line between absorption and specific gravity, (b) Negative trend line between porosity and specific gravity, (c) Direct trend line between porosity and absorption, (d) Positive relationship between soundness and porosity, (e) Linear relationship between UCS and UTS, (f) Indirect relationship between UCS and porosity



**Figure 5** Continues... (g) Inverse trend line between Absorption and UTS (h) Positive trend line between Los Angeles abrasion and porosity (i) Positive trend line between UCS and Soundness (j) Inverse Trend line between UCS and LAA (k) Direct trend line between ACV & AIV (l) Positive trend line between AIV & LAA.

**5.1. Integrated Evaluation of Kamila Amphibolite**

Such correlation studies of the amphibolite samples clearly show that there exist important interrelationships among the geotechnical parameters in question. Water absorption evidences a sharp decreasing trend on the basis of rising specific gravity (Fig. a), thus showing that the denser rocks of compact internal structures preserve less moisture. The same trend is also visible in porosity, which decreases as specific gravity increases (Fig. b), and this fact once again proves that denser amphibolite is defined with a lower number of pore spaces. On the other hand, porosity correlates directly and positively with the measures of absorption (Fig. c) and soundness (Fig. d), indicating that both the uptake of water and the ease of weather-related processes are mainly dictated by the size and availability of the pore cell. A strong positive correlation between uniaxial compressive strength (UCS) and uniaxial tensile strength (UTS) (Fig. e) indicates that compressive strength exerts a significant control on tensile behavior, reflecting the mechanical coherence of the rock. On the other hand, porosity displays a slight decreasing trend with UCS (Fig. f), reinforcing the observation that stronger rocks are typically less porous and more compact. Similarly, absorption diminishes with increasing UTS (Fig. g), confirming that mechanically competent and structurally sound rocks tend to exhibit lower permeability. Porosity also shows a positive relationship with Los Angeles Abrasion (LAA) values (Fig. h), which implies that rocks more prone to abrasion are comparatively more porous and therefore mechanically weaker. UCS demonstrates a weak negative correlation with soundness (Fig. i) and a moderate negative trend with LAA (Fig. j), suggesting that both weathering resistance and abrasion resistance play an important role in influencing the overall compressive strength of amphibolite. Additionally, the Aggregate Crushing Value (ACV) correlates positively with the Aggregate Impact Value

(AIV) (Fig. k), showing that samples more vulnerable under impact loading also tend to be weaker under crushing conditions. Finally, a strong positive correlation between AIV and LAA (Fig. l) further highlights that amphibolite samples experiencing higher abrasion losses are also more susceptible to impact failure, ultimately reflecting their reduced durability and long-term engineering performance.

## 6. Discussion

The petrographic and geotechnical evaluation of the Kamila amphibolites from Kuza Drushkhela, Swat, highlights their strong potential as construction-grade aggregates. Petrographic analysis revealed that the rocks are primarily composed of amphibole, hornblende, plagioclase, and epidote, with accessory minerals such as quartz, biotite, muscovite, and tourmaline. Their interlocking granular to lepidoblastic textures indicate medium- to high-grade metamorphism under amphibolite facies, which contributes significantly to strength and durability. Physically, the samples exhibited high specific gravity values (3.005–3.024 g/cm<sup>3</sup>), very low porosity (0.70–0.74%), and minimal water absorption (0.22–0.37%), reflecting a dense rock fabric with limited pore connectivity that reduces susceptibility to weathering. Mechanically, the amphibolites yielded excellent results, including unconfined compressive strength values of 61–66 MPa, uniaxial tensile strength averaging 6.3 MPa, Los Angeles abrasion values of ~9.8%, and aggregate crushing values of ~19.6%, all of which fall within ASTM, AASHTO, BS, and NHA standards, confirming their suitability for structural concrete, pavements, and heavy engineering works. Regression analysis further emphasized strong correlations between porosity, absorption, and mechanical strength, underscoring the influence of microstructural density on performance. These findings are significant in addressing the growing demand for durable and cost-effective construction materials in northern Pakistan, where the Swat region of the tectonically active Kohistan Island Arc contains abundant yet underutilized metamorphic and igneous rocks. The use of Kamila amphibolite as a local aggregate source could reduce reliance on distant quarries, lowering both transportation costs and environmental impacts, while its high compressive strength and low abrasion values confirm its suitability for high-load infrastructure such as highways, bridges, and dams. Furthermore, low porosity and absorption (<1%) suggest excellent resistance to freeze-thaw cycles, chemical weathering, and moisture-induced deterioration, particularly relevant in the Himalayan landscape where extreme climatic variations prevail. The results align with previous regional and international studies on amphibolite and similar metamorphic rocks, with Ahmad et al. (2017) reporting specific gravity values of 2.85–3.10 g/cm<sup>3</sup> in northern Pakistan, Abdul Rahim et al. (2022) documenting absorption values below 0.5%, and global research (e.g., Bell, 2005; Wyering et al., 2014) attributing low porosity to recrystallization processes. The UCS values obtained in this study (61–66 MPa) exceed the 35 MPa benchmark recommended by Bell (2005) and fall within the range reported by Umar et al. (2020) for strong metamorphic aggregates, while Los Angeles abrasion values (~9–10%) remain far below the 40% threshold, reaffirming durability. The observed positive correlation between compressive and tensile strength further concurs with Tsiambaos and Sabatakakis (2004). Despite these promising results, limitations exist, including the restricted sampling from a single quarry exposure, reliance on laboratory-based testing, and the lack of chemical reactivity assessment, particularly with respect to alkali-silica reactions. Nonetheless, the study provides a strong scientific basis for recommending that Kamila amphibolite is a sustainable local aggregate, supporting infrastructure, lowering costs, and using durable local materials.

### List of Abbreviations

Acronym	Abbreviation
ASTM	American Society for Testing and Materials
AASHTO	American Association of Highway and Transportation
NHA	National Highway Authority
LAA	Los Angeles Abrasion Value
AIV	Aggregate Impact Value
ACV	Aggregate Crushing Value
UCS	Unconfined Compressive Test
UTS	Unconfined Tensile Strength
MMT	Main Mantle Thrust

## 7. Conclusions

The amphibolites are medium- to coarse-grained, dominated by amphibole, hornblende, plagioclase, and epidote, with accessory quartz, biotite, and muscovite. The interlocking textures and foliation indicate medium- to high-grade metamorphism under amphibolite facies, enhancing rock strength and coherence. High specific gravity ( $>3.0 \text{ g/cm}^3$ ), very low porosity (0.70–0.74%), and minimal water absorption ( $<0.40\%$ ) confirm the dense and durable nature of the rock, making it resistant to chemical and climatic weathering. The rocks exhibit excellent engineering performance with uniaxial compressive strength between 61–66 MPa, tensile strength averaging 6.3 MPa, Los Angeles abrasion values around 9.8%, and aggregate crushing values below 20%. All parameters fall within ASTM, AASHTO, BS, and NHA specifications for construction aggregates.

Regression analysis reveals strong interrelationships: porosity and absorption negatively correlate with strength, while compressive and tensile strengths show a positive association. These relationships highlight the influence of rock fabric and density on durability. Considering their petrographic coherence, physical density, and mechanical resilience, Kamila amphibolites are highly suitable as coarse aggregates for concrete, pavement, and heavy engineering projects in northern Pakistan. Broader sampling, long-term durability assessments, and alkali-silica reactivity studies are recommended to further validate their regional application.

## Compliance with ethical standards

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### *Disclosure of conflict of interest*

No conflicts of interest have been disclosed by any of the authors (Iftikhar Ali<sup>1\*</sup>, Lu Haifang<sup>1</sup>, Rahat Ullah Khan<sup>1</sup>, Muhammad Nadeem Waheed<sup>2</sup>, Imran Ahmad<sup>3</sup>, Danyal Khan<sup>5</sup>,

### *Statement of ethical approval*

None of the authors of this study used human or animal participants in any of their experiments.

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