Mineralogical and Textural Controls on the Strength and Durability of Construction Rocks: A Quantitative Petrographic Approach

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Abstract

Understanding the mechanical strength and long-term durability of construction rocks is essential for ensuring the safety and sustainability of engineering structures. These properties are primarily governed by a rock's mineralogical composition and textural characteristics. However, existing studies often rely on qualitative assessments or limited empirical correlations. This study adopts a fully quantitative petrographic approach to evaluate the influence of mineralogical and textural parameters on the performance of construction-grade rocks. A diverse set of igneous, metamorphic, and sedimentary rock samples was analyzed using thin-section microscopy, scanning electron microscopy (SEM), and digital image analysis. Measured petrographic parameters included modal mineralogy, grain size, grain boundary complexity, interlocking index, packing density, and porosity. These were statistically correlated with results from uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), bulk density, ultrasonic P-wave velocity (UPV), and slake durability index (SDI) tests. Findings reveal that rocks with high quartz content, fine-grained textures, and strong grain interlocking exhibit higher strength, lower porosity, and superior durability. Conversely, elevated mica, chlorite, and clay content, along with irregular grain shapes and high pore connectivity, significantly reduce rock integrity. Threshold values for key petrographic indicators were identified to support predictive evaluation of construction suitability. This study presents a practical, non-destructive classification framework for assessing construction rocks based on quantitative petrography. The approach enhances early-stage material selection, reduces reliance on destructive testing, and lays the foundation for future integration with digital petrography and machine learning tools in geotechnical applications.

Keywords

Petrography, Construction Rocks, Rock Durability, Mineralogy, Textural Analysis, Mechanical Strength

1. Introduction

In the field of civil and geotechnical engineering, the selection of suitable construction materials is a critical factor that directly affects the stability, longevity, and performance of infrastructure. Among these materials, natural rock remains a primary choice for foundations, retaining walls, dams, pavements, [1] tunnels, and building stone. However, the mechanical strength and durability of rocks vary widely due to their complex internal structures and mineralogical compositions. While conventional laboratory tests such as uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), and slake durability index (SDI) are commonly used to assess rock quality, these tests are often time-consuming, expensive, destructive, and impractical in certain situations particularly during preliminary site investigations or when dealing with weathered or inaccessible rock masses. A more efficient and predictive approach involves understanding and quantifying the fundamental characteristics that control rock performance. Among the most influential of these characteristics are mineralogical composition and textural attributes, including grain size, grain shape, fabric orientation, packing density, interlocking, and porosity. These microstructural features dictate the strength, deformability, and weathering resistance of rocks under both static and dynamic loading conditions. Rocks composed predominantly of quartz and feldspar, with fine grains and well-interlocked textures, typically exhibit high mechanical strength and good resistance to environmental degradation. [2] Conversely, rocks containing soft minerals such as micas or clays, or those with poorly bonded grains and high porosity, tend to be weaker and less durable. Despite the critical role of these factors, there remains a lack of comprehensive, quantitative frameworks that systematically correlate petrographic features with engineering performance parameters.

Historically, empirical correlations have been proposed between certain textural parameters and mechanical properties. However, many of these studies have relied on qualitative assessments or limited sample sizes, lacking consistency and reproducibility. Additionally, previous research often isolates either mineralogical or textural variables, without considering their combined and possibly synergistic effects. There is also a notable gap in the development of threshold-based classification systems that translate petrographic observations into actionable criteria for construction suitability. In the context of sustainable construction and smarter infrastructure planning, there is a growing need for data-driven, non-destructive methodologies that leverage petrographic insights for reliable rock performance evaluation.

This study aims to address these gaps by employing a quantitative petrographic approach to analyze how mineralogical and textural features influence the strength and durability of construction rocks. Thin-section petrography, scanning electron microscopy (SEM), and digital image analysis techniques are used to extract measurable parameters such as modal mineralogy, grain size distribution, grain boundary complexity, interlocking index, and packing density. These are statistically correlated with results from mechanical and durability tests, including UCS, BTS, density, porosity, and SDI. The goal is not only to identify the most critical microstructural controls on rock performance but also to define threshold values that can guide the classification of rocks for engineering use. By establishing quantitative relationships between petrographic properties and mechanical strength, this research contributes to The development of predictive, non-destructive tools for rock evaluation. Furthermore, it proposes a scientifically grounded guideline system for selecting construction-grade rocks, thereby aiding engineers, geologists, and decision-makers in material selection, site characterization, and quality control processes. Ultimately, this study bridges the gap between geological microscopy and geotechnical performance, offering new insights into how the intrinsic fabric of rocks governs their behavior in applied engineering contexts.

Table 1. Common Petrographic Parameters and Their Influence

Parameter	Definition	Influence on Strength & Durability
Quartz (%)	Quartz content	↑ Strength, hardness, chemical resistance
Feldspar (%)	Feldspar content	Moderate; reduces durability when altered
Mica/Clay (%)	Phyllosilicate content	↓ Strength; promotes weakness/weathering
Grain Size (mm)	Avg. mineral size	Fine ↑ strength; coarse ↓ it
Grain Shape	Angularity	Angular ↑ interlock, strength
Packing (%)	Grain packing	High density ↑ cohesion, ↓ porosity
Interlocking	Grain contact	Complex ↑ strength
Porosity (%)	Void fraction	High ↓ strength, durability
Microcracks	Crack density	High ↓ strength, ↑ deterioration

The key petrographic parameters considered in this study, along with their definitions and typical influence on rock strength and durability, are summarized in table 1

2. Literature Review

The performance of construction rocks in engineering applications is a function of their inherent geological properties, particularly mineralogical composition and textural characteristics. Over the past few decades, considerable research has been conducted to explore how these microstructural features govern rock strength, durability, and overall mechanical behavior. This section critically reviews the key findings in this domain, identifying gaps that justify the present study.

2.1 Influence of Mineralogical Composition on Rock Strength and Durability

Mineralogy plays a central role in determining rock mechanical behavior. Quartz, being a hard and chemically resistant mineral, generally enhances compressive and tensile strength, while feldspar contributes to moderate mechanical integrity but may reduce durability when subject to weathering. Several studies, including those by [3] and [4], established that rocks with high quartz content exhibit higher uniaxial compressive strength (UCS) and lower water absorption. In contrast, the presence of phyllosilicates such as micas and clays especially in schists, phyllites, and altered granites has been associated with reduced strength and accelerated deterioration under environmental exposure. [5]

More recent research has focused on the mineral-specific influence on durability, particularly under cyclic wetting and drying, freeze-thaw, or acidic conditions. [6] demonstrated that rocks with significant mica or chlorite content lose structural integrity more rapidly during slake durability tests. Furthermore, mineral alteration processes (e.g., feldspar to kaolinite) can significantly weaken a rock by increasing porosity and reducing grain cohesion, as shown in studies by [7].

2.2 Textural Parameters and Their Mechanical Significance

Beyond composition, textural features such as grain size, shape, packing density, porosity, and grain boundary interlocking are equally crucial in defining rock strength and behavior under stress. Rocks with fine-grained, tightly packed, and angular mineral grains tend to perform better mechanically due to enhanced grain interlocking and reduced pore space. [8] According to [9], smaller grain size leads to higher crack propagation resistance, contributing to greater UCS and tensile strength. Similarly, [10] observed that rocks with irregular, interlocking grain boundaries require more energy for crack initiation and propagation.

The interlocking index, developed in more recent studies using image analysis techniques (e.g., [11], quantifies the complexity and effectiveness of grain contact. Such indices have shown strong statistical correlations with UCS and point load strength index (PLSI), [12] supporting the notion that textural parameters are predictive of macro-scale rock behavior. Meanwhile, porosity remains a universally accepted weakening factor; rocks with higher porosity generally exhibit lower strength, higher water absorption, and poor weathering resistance.

2.3 Quantitative Petrography and Image Analysis

Traditional petrographic analysis was largely qualitative, relying on visual estimates and subjective interpretations. However, advances in digital image processing, scanning electron microscopy (SEM), and automated mineralogy have revolutionized the field by enabling precise, repeatable, and quantitative evaluation of rock textures. [13] Parameters such as modal mineral content, grain size distribution, grain shape descriptors, and pore networks can now be extracted from thin-section images using specialized software [14] (e.g., ImageJ, GeoPetro, or MATLAB-based routines).

Studies like [15] and [16] demonstrate how these tools can establish robust statistical relationships between petrographic indices and mechanical test results. Multivariate regression, principal component analysis (PCA), and machine learning techniques have increasingly been applied to identify the most influential microstructural predictors of rock strength. These advances support the move toward data-driven, non-destructive classification of construction rocks. Figure 1 illustrates the historical evolution of petrographic analysis techniques, reflecting the transition from qualitative to advanced digital and quantitative methods.

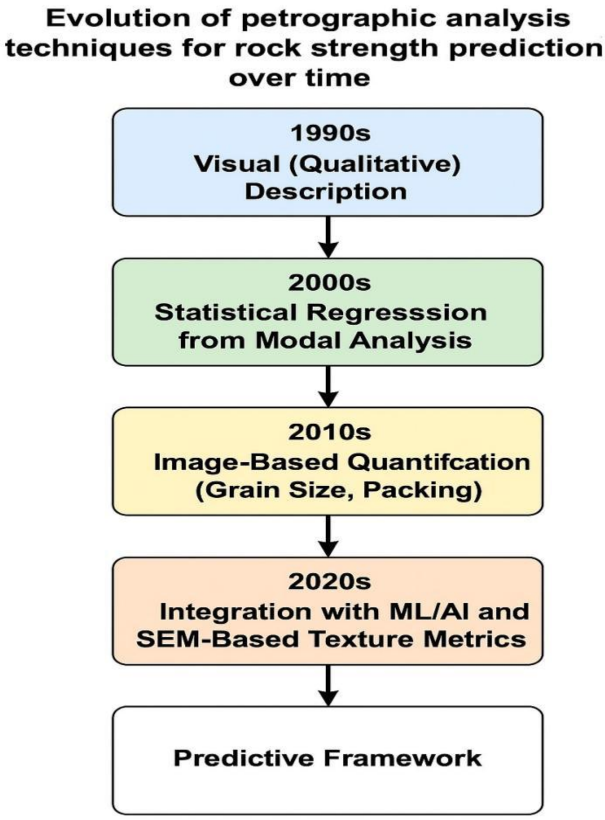

Figure 1. Evolution of petrographic analysis techniques for rock strength prediction over time

2.4 Integration with Durability Assessments

While strength properties are critical for structural design, the durability of rocks under environmental conditions is equally essential especially for projects exposed to moisture, temperature fluctuations, or chemical attack. Slake durability index (SDI), water absorption, and freeze-thaw resistance are common tests used to assess this property. Research by [17] established SDI as a reliable proxy for long-term field performance. However, fewer studies have effectively linked durability metrics with petrographic data.

Recent efforts (e.g., [18] show that certain petrographic traits such as the presence of micropores, secondary mineralization, and weak cleavage planes serve as early indicators of durability failure. The integration of strength and durability modeling based on microstructural data remains an area with significant potential, especially for real-world material selection. Book tabs graphics

Table 2. Summary of selected studies linking petrographic parameters to mechanical and durability properties of rocks

Study	Focus	Parameters Used	Methods	Key Findings
Tugrul & Zarif (1999)	Strength vs. mineral content	Quartz %, Feldspar %, Mica %, Porosity	Petrography, UCS, BTS	Higher quartz → higher UCS; mica reduces strength
Yasar & Erdogan (2004)	Alteration and mechanical degradation	Feldspar alteration, Porosity	Thin section, SEM, UCS	Kaolinite zones weaken rock
Eberhardt et al. (2004)	Grain size vs. crack propagation	Grain size, Fracture density	Fracture modeling	Fine grains increase resistance
Saroglou & Tsiambaos (2008)	Durability linked to microstructure	Microporosity, Clay content, Foliation	SDI, Petrography	Porous and cleaved rocks deteriorate faster
Sousa et al. (2005)	Quantitative image analysis	Grain size, Interlocking, Packing density	ImageJ, Regression analysis	Strong texture-strength correlations

A comparative summary of relevant past studies that link petrographic variables to engineering behavior is provided in table 2, highlighting key parameters, methods, and findings

2.5 Identified Research Gap

Despite the existing body of work, several key gaps remain. Most studies focus on either mineralogical or textural controls, but rarely both in combination. Many investigations rely on small, lithological narrow datasets that limit the generalizability of their findings. Furthermore, while the tools for quantitative petrography have advanced, they are underutilized in establishing standardized guidelines for evaluating rock suitability in construction. There is also limited work in defining threshold values for petrographic variables that can serve as predictive indicators of mechanical and durability performance.

This study seeks to address these limitations by combining detailed mineralogical and textural analysis with comprehensive mechanical and durability testing across a broader lithological spectrum. By identifying the most influential microstructural parameters and defining quantitative thresholds, the research aims to contribute to the development of non-destructive evaluation tools and classification schemes for construction-grade rocks.

3. Materials and Methods

This study employed a multi-step methodology to investigate the influence of mineralogical and textural parameters on the strength and durability of construction rocks. Representative rock samples were collected from various lithologies, including igneous, metamorphic, and sedimentary types. Standard laboratory procedures were followed to prepare specimens for mechanical testing, including uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), slake durability index (SDI), and ultrasonic pulse velocity (UPV). Petrographic analysis was conducted using thin sections, polarized light microscopy, and scanning electron microscopy (SEM), allowing for the quantification of grain size, mineral composition, porosity, interlocking index, and packing density. Digital image analysis tools were used to extract and analyze these features, and X-ray diffraction (XRD) was performed to validate mineral identification. Statistical tools, including correlation analysis and multivariate regression, were used to model the relationships between petrographic variables and mechanical performance, forming the basis for predictive classification of construction-grade rocks.

Figure 2 outlines the workflow followed in this study, including sampling, laboratory testing, image analysis, and statistical evaluation.

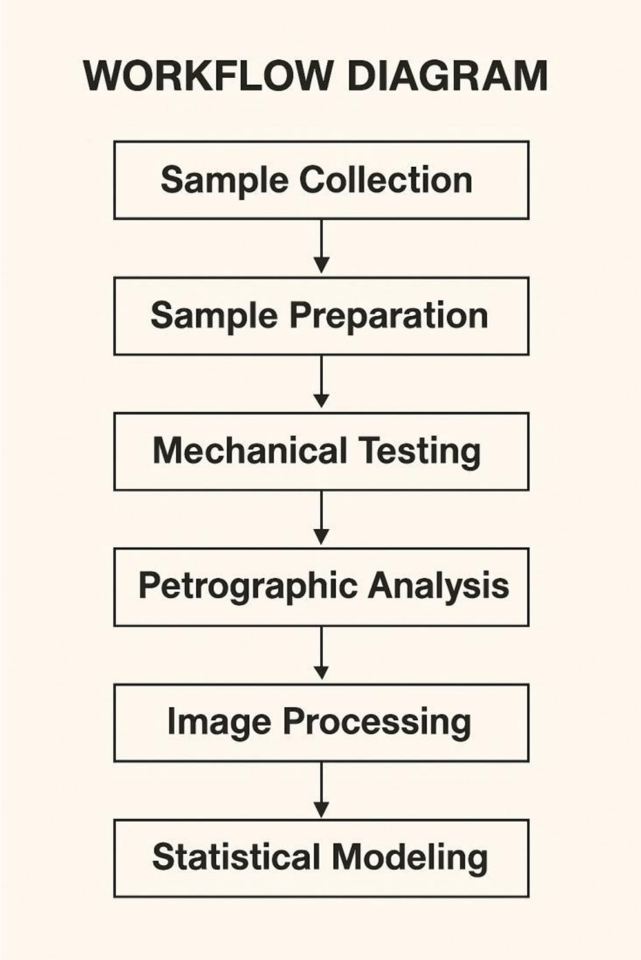

Figure 2. Workflow diagram summarizing the experimental procedures and analytical steps followed in this study

3.1 Sampling Strategy and Lithological Selection

To enable a robust and comprehensive investigation of the mineralogical and textural factors influencing rock strength and durability, a carefully designed sampling strategy was employed. A diverse suite of lithologies was systematically selected to reflect the primary rock types used in civil engineering and infrastructure development. The sampling included igneous rocks (granite, granodiorite), metamorphic rocks (gneiss, schist), and sedimentary rocks (sandstone, limestone), ensuring broad representation across geological environments and material classes. These rock types are widely utilized in applications such as foundations, pavement aggregates, retaining structures, and cladding systems due to their variable but critical mechanical characteristics.

A total of [insert number, e.g., 30] representative rock samples were collected from a combination of active commercial quarries and naturally exposed outcrop sites with a known history of supplying construction-grade materials. All sampling locations were georeferenced using a high-accuracy GPS device (±3 m error margin), and detailed field notes were recorded to capture geological context, degree of weathering, stratigraphic position, and structural features. Priority was given to fresh, intact, and un weathered specimens, free from surface alteration, fracturing, or visible signs of mineral decomposition, to ensure that the tested properties reflected intrinsic material characteristics rather than exogenic degradation.

Each sample was extracted as a block measuring approximately 30 × 30 × 30 cm, using either rock saws or chiseling tools depending on site accessibility and material hardness. The blocks were immediately labeled with unique identifiers and securely packed to prevent mechanical damage during transport. Upon arrival at the laboratory, samples were catalogued and photographed, then stored in controlled indoor conditions prior to further processing. These specimens formed the foundational dataset for subsequent mechanical testing, petrographic analysis, and image-based texture quantification.

3.2 Sample Preparation

All collected rock samples were processed following standardized procedures outlined by the International Society for Rock Mechanics (ISRM) and relevant ASTM testing protocols, ensuring consistency and reproducibility in mechanical and petrographic analyses. Each sample block was first trimmed and shaped using a high-precision diamond-blade rock saw, producing test specimens that conformed to the recommended geometric ratios for laboratory testing. Core cylinders with a diameter-tolength ratio of 1:2 typically 54 mm in diameter and 108 mm in length were prepared for uniaxial compressive strength (UCS) and ultrasonic pulse velocity (UPV) testing. For petrographic examination, thin sections approximately 30 micrometers (μm) thick were prepared using standard polishing techniques, ensuring optimal transparency and resolution under polarized light microscopy. Additionally, small rock chips were pulverized using a jaw crusher and ball mill for X-ray diffraction (XRD) analysis, which was used to validate mineralogical composition identified under the microscope.

To eliminate the influence of moisture on mechanical behavior and ensure uniform testing conditions, all specimens were oven-dried at 105°C for 24 hours prior to testing. This drying protocol ensured the removal of pore water and helped standardize the moisture state across all specimens, particularly critical for strength and durability testing where even minor variations in water content can influence results.

3.3 Mechanical and Durability Testing

A comprehensive suite of standardized mechanical and durability tests was conducted to evaluate the performance of the selected rock samples under engineering-relevant conditions. All tests were performed in accordance with ASTM and ISRM protocols to ensure accuracy, repeatability, and comparability with established benchmarks in geotechnical engineering.

The uniaxial compressive strength (UCS) test was carried out using a servo-controlled compression testing machine following ASTM D7012. Cylindrical specimens were loaded axially at a constant rate of 0.5 MPa/sec until failure, and the peak stress at failure was recorded as the UCS. This test provided a direct measure of the rock's capacity to withstand axial loads.

To evaluate tensile strength, the Brazilian Tensile Strength (BTS) test was performed in accordance with the ISRM suggested method, using disc-shaped specimens with a diameter equal to their thickness. The indirect tensile strength was calculated from the peak load at failure using standard analytical equations.

Bulk density and porosity were determined using the saturation and buoyancy method, as per ASTM C97. Specimens were first oven-dried and then saturated in water to assess water absorption and calculate effective porosity parameters crucial for understanding fluid transport behavior and weathering susceptibility.

The Slake Durability Index (SDI) was assessed using the standard two-cycle test (ASTM D4644). Rock fragments were subjected to wetting and drying cycles inside a rotating drum, simulating natural environmental exposure. The percentage of retained mass after two cycles was recorded as the SDI value, serving as a proxy for long-term durability under moisture-driven degradation.

In addition, Ultrasonic Pulse Velocity (UPV) was measured using a PUNDIT apparatus, which involved transmitting a longitudinal wave through cylindrical samples and recording the travel time. The pulse velocity, expressed in km/s, provided a non-destructive estimate of the rock's internal continuity, elastic modulus, and potential presence of microcracks or voids.

Each mechanical and durability test was performed on a minimum of three specimens per rock type, and average values were reported to minimize the impact of local heterogeneity. These results formed the foundation for correlating physical performance with the underlying mineralogical and textural characteristics identified in subsequent petrographic analysis.

3.4 Petrographic and Mineralogical Analysis

The standard laboratory tests conducted in this study and their corresponding objectives are listed in table 3

Table 3. Laboratory Tests Summary

Test	**Standard**	**Params.**	**Purpose**
UCS Test	ASTM D7012	UCS (MPa)	Axial strength
BTS Test	ISRM	BTS (MPa)	Tensile strength
Density	ASTM C97	ρ, n (%)	Mass-volume
Slake Test	ASTM D4644	SDI (%)	Weathering
UPV Test	ASTM D2845	UPV (km/s)	Elasticity
Petrography	Point Count	Min. (%)	Composition
ImageJ	Digital	Texture	Grain analysis
XRD	Powder	Phases	Minerals ID

To investigate the microstructural characteristics influencing the mechanical strength and durability of the tested rocks, a thorough petrographic and mineralogical analysis was performed. This included both optical petrography using thin-section microscopy and mineralogical confirmation using X-ray diffraction (XRD). The analysis focused on quantifying textural features such as grain size, shape, packing density, interlocking index, porosity, and mineral assemblages parameters that are known to critically influence rock behavior under mechanical loading and environmental stress.

Standard 30 μm-thick thin sections were prepared from representative portions of each rock specimen and examined under polarized light microscopy (PLM) using both plane-polarized light (PPL) and cross-polarized light (XPL) modes. A point-counting technique was employed using a grid-based overlay with at least 1,000 counted points per thin section to quantify modal mineralogy, including the relative proportions of quartz, feldspar (plagioclase and K-feldspar), micas (biotite, muscovite), and accessory or alteration minerals such as chlorite, epidote, and clay phases. Particular attention was given to the presence of weak or weatherable minerals, which are known to compromise durability and strength.

Textural features were further analyzed using digital image analysis software (ImageJ). [19] High-resolution micrographs were processed to extract grain size distribution (mean, median, maximum), grain shape descriptors (e.g., aspect ratio, roundness), and grain boundary complexity. The interlocking index was computed based on the ratio of grain boundary perimeter to grain area, providing a quantitative measure of the mechanical interaction between adjacent grains. Packing density, defined as the percentage of the image occupied by solid mineral grains, was calculated from binarized images using segmentation algorithms.

Figure 3 presents a representative thin-section micrograph showing key features such as mineral phases, grain boundaries, porosity zones, and interlocking texture.

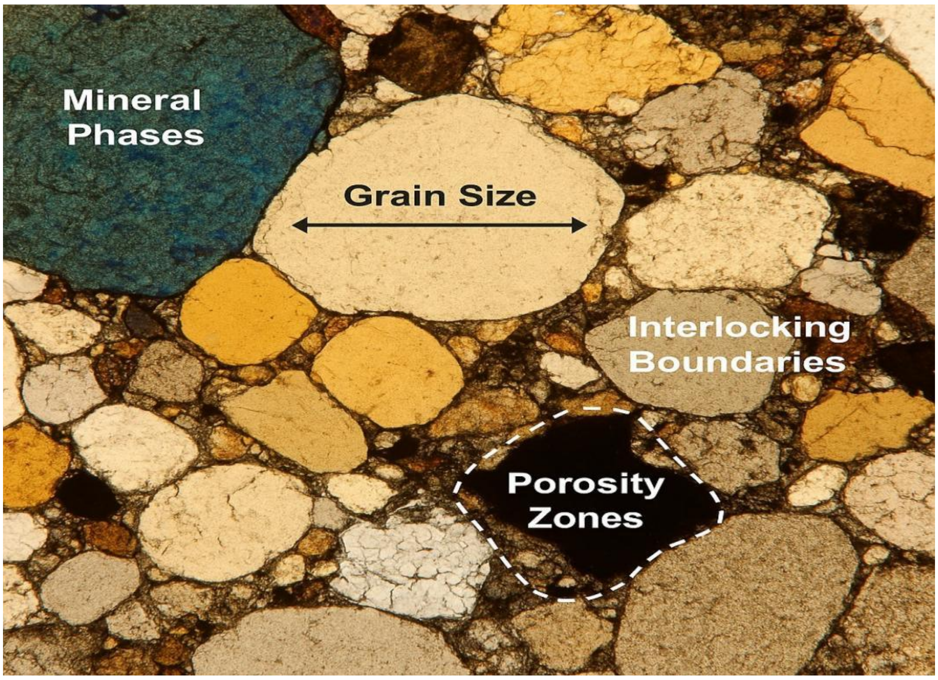

Figure 3. Representative thin-section image showing mineral phases, grain size, interlocking boundaries, and measured porosity zones

Microporosity was assessed using both optical thin-section observations and backscattered electron (BSE) imaging under scanning electron microscopy (SEM). Porous regions, microcracks, and secondary voids were quantified by thresholding grayscale images and calculating area ratios. These porosity metrics were cross-referenced with bulk porosity values obtained from physical testing for validation.

To complement the petrographic observations, X-ray diffraction (XRD) analysis was performed on powdered rock samples using a Bruker D8 Advance diffractometer. The scans covered a 2 range of 5° to 70° with a step size of 0.02°, allowing identification of major and minor crystalline phases. XRD results were particularly valuable for confirming the presence of fine-grained or cryptocrystalline minerals, clay alteration products, and complex polymorphs that may not be distinguishable under optical microscopy alone.

All petrographic and mineralogical data were entered into a centralized database and later correlated statistically with mechanical and durability test results. This comprehensive approach allowed for a high-resolution evaluation of how microstructural variability both compositional and textural governs the performance of construction rocks under applied stress and environmental exposure.

3.5 Statistical and Correlation Analysis

To evaluate the influence of mineralogical and textural parameters on the mechanical strength and durability of construction rocks, a comprehensive statistical analysis was conducted. The objective was to identify significant relationships, isolate the most influential variables, and build a quantitative framework capable of explaining performance variations based on petrographic attributes.

All petrographic, mechanical, and durability data collected from laboratory tests and image analysis were compiled into a structured database. Before analysis, the dataset was screened for outliers and missing values. Descriptive statistics mean, median, standard deviation, and coefficient of variation were calculated for each variable to understand their distribution and variability across rock types.

The first stage of analysis involved computing Pearson correlation coefficients (r) to assess linear relationships between individual petrographic variables (e.g., quartz %, grain size, interlocking index, porosity) and mechanical properties such as UCS, BTS, and SDI. Correlations were interpreted based on strength and direction (positive or negative), with p-values < 0.05 considered statistically significant. Strong correlations were observed between certain parameters such as quartz content, grain interlocking, and packing density and UCS, indicating their predictive potential.

To better understand the combined effects of multiple parameters, multiple linear regression (MLR) models were developed using mechanical strength and durability indices as dependent variables. Predictor variables were selected using stepwise regression based on statistical significance and collinearity diagnostics (variance inflation factor, VIF ,< 5). The models were validated using R^2, adjusted R^2, mean absolute error (MAE), and root mean square error (RMSE) as evaluation metrics. Regression residuals were examined to confirm assumptions of normality, homoscedasticity, and independence.

In addition, Principal Component Analysis (PCA) was employed to reduce data dimensionality and visualize interrelationships among variables. [20] PCA helped identify key clusters and dominant principal components that explained the majority of variance in the dataset. This technique was particularly useful in grouping rock types based on textural-mineralogical profiles and performance characteristics.

All statistical analyses were performed using SPSS, Python (pandas, seaborn, scikitlearn), and Microsoft Excel, ensuring cross-validation and reproducibility. The results from this section formed the basis for developing threshold guidelines and predictive models presented in the following section.

4. Results

The experimental investigation produced a comprehensive dataset linking mineralogical composition and textural features of various construction rocks with their mechanical strength and durability properties. The results are presented in the following subsections according to property type and analytical dimension.

4.1 Mechanical Strength Test Results

The mechanical strength of the tested rock specimens exhibited a wide range of values, reflecting significant lithological diversity and microstructural variability among the sampled units. The Uniaxial Compressive Strength (UCS) values ranged from 48 MPa to 172 MPa, indicating differences in mineral composition, grain structure, and textural integrity. Granites and granodiorites consistently recorded the highest UCS values, with an average of approximately 155 MPa, [21] attributable to their high quartz and feldspar content, low porosity, and tightly interlocked granular texture. In contrast, metamorphic rocks such as schists and sedimentary rocks like limestones exhibited notably lower UCS values, averaging around 55 MPa. This reduction in strength is likely due to the presence of weak, platy minerals such as mica and chlorite, as well as higher pore space and structurally aligned fabric planes that act as failure zones.

The Brazilian Tensile Strength (BTS) measurements followed a similar pattern. BTS values ranged from 4.8 MPa to 15.3 MPa, with the highest values again observed in quartz-rich igneous rocks. These results are consistent with the expected mechanical behavior of coarse crystalline, silicic rocks, where grain cohesion and interlocking contribute positively to resistance against tensile failure.

Ultrasonic Pulse Velocity (UPV) tests revealed pulse speeds varying between 2.5 and 5.9 km/s. Higher pulse velocities were associated with dense, low-porosity rocks that exhibited excellent textural interlocking and homogeneity. Notably, granites, quartzites, and dense sandstones recorded the highest UPV values, while fractured or clay-rich samples such as schists and partially altered limestones showed reduced wave velocities due to internal heterogeneities, microcracking, and compositional anisotropy.

Overall, the mechanical strength results underscore the strong influence of lithology and microstructural integrity on rock performance. Rocks with high quartz content, compact fabric, and minimal secondary alteration consistently demonstrated superior load-bearing capacity and internal cohesion characteristics essential for their suitability in construction applications.

4.2 Durability and Physical Properties

The durability and physical behavior of the tested rocks were assessed using slake durability index (SDI), bulk density, and porosity measurements. These parameters provide insight into the rock's resistance to environmental degradation and structural breakdown under cyclic wetting, drying, and other field-related weathering conditions. [22]

The Slake Durability Index (SDI) revealed significant variation between rock types. Quartz-rich igneous rocks (granites and quartzites) showed exceptionally high durability, with SDI values ranging from 94% to 98% after two cycles, indicating excellent resistance to disintegration. Conversely, metamorphic schists and fine-grained sedimentary rocks such as some limestones and clay-rich sandstones exhibited lower durability, with SDI values ranging from 52% to 68%, suggesting substantial degradation when subjected to repeated moisture fluctuations. Rocks containing higher proportions of micas, chlorite, or clay minerals displayed particularly poor durability, as these minerals promote water absorption, swelling, and progressive weakening of grain boundaries. [23]

Bulk density measurements ranged from 2.35 to 2.82 g/cm³, with the highest values corresponding to dense, crystalline igneous rocks. These rocks typically exhibited well-packed granular textures and minimal internal voids. Sedimentary rocks, particularly those with visible pore spaces or secondary cementation, recorded lower densities, reflecting a more porous structure.

Measured porosity values ranged from 0.9% to 8.7% across the sampled lithologies. Rocks with porosity < 2% (e.g., granites, quartzites) demonstrated superior mechanical and durability performance, while those with porosity > 6% (e.g., schists, porous limestones) showed increased water absorption, reduced strength, and lower SDI values. A strong inverse correlation (r = -0.84) was observed between porosity and both UCS and SDI, affirming that porosity plays a critical role in controlling strength and degradation behavior.

These findings indicate that rock durability is closely governed by both mineral composition and textural attributes particularly the presence of hydrophilic minerals and the extent of pore connectivity making these parameters essential indicators of long-term performance in engineering applications.

4.3 Petrographic and Mineralogical Observations

Petrographic examination and X-ray diffraction (XRD) analysis provided a detailed understanding of the internal fabric, mineralogical composition, and textural attributes of the tested rock samples.

Modal mineralogy, determined by point-counting on thin sections, showed that quartz content ranged from 18% to 60%, feldspar (plagioclase and K-feldspar) from 12% to 54%, and mica/chlorite/clay content from 2% to 27%. High-strength and high-durability rocks, particularly granites and quartzites, consistently had quartz contents exceeding 45% and minimal weak minerals. In contrast, samples with elevated mica or chlorite content (>20%), such as phyllites and schists, exhibited poorer mechanical properties and significantly lower durability values.

Grain size analysis, performed via digital image processing, revealed that average grain diameters ranged from 0.2 mm to 2.5 mm. Rocks with finer grains (0.5 mm) typically showed higher UCS and SDI values, supporting the hypothesis that finegrained textures enhance mechanical performance by promoting uniform stress distribution and inhibiting crack propagation.

Grain shape and boundary characteristics also influenced performance. Samples with sub-angular to angular grains and complex grain boundaries displayed higher interlocking indices (0.75), which corresponded to higher UCS and UPV values. Wellinterlocked grains mechanically reinforce each other, reducing stress concentrations and improving load transfer. Packing density values exceeded 85% in dense igneous rocks but dropped to as low as 68% in porous or weakly cemented sedimentary rocks.

Microporosity, observed in thin sections and back-scattered SEM images, further confirmed the role of pore structure in performance. Rocks with irregular, interconnected pore spaces and microcracks particularly those containing secondary clay minerals or weathered feldspar displayed lower strength and greater susceptibility to disintegration under cyclic loading.

Finally, XRD analysis validated the optical mineral identification, confirming the presence of key crystalline phases such as quartz, orthoclase, albite, biotite, chlorite, calcite, and kaolinite. In altered samples, XRD detected secondary minerals not visible in thin section, including illite and smectite, both of which negatively influenced the rock's mechanical and durability performance.

4.4 Correlation and Statistical Analysis Results

Statistical analyses revealed strong, quantifiable relationships between the petrographic parameters and the mechanical and durability performance of the tested rocks. The Pearson correlation matrix showed that quartz content, grain packing density, and interlocking index exhibited strong positive correlations with uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), and slake durability index (SDI). Conversely, porosity and mica/clay content showed strong negative correlations with the same mechanical indicators.

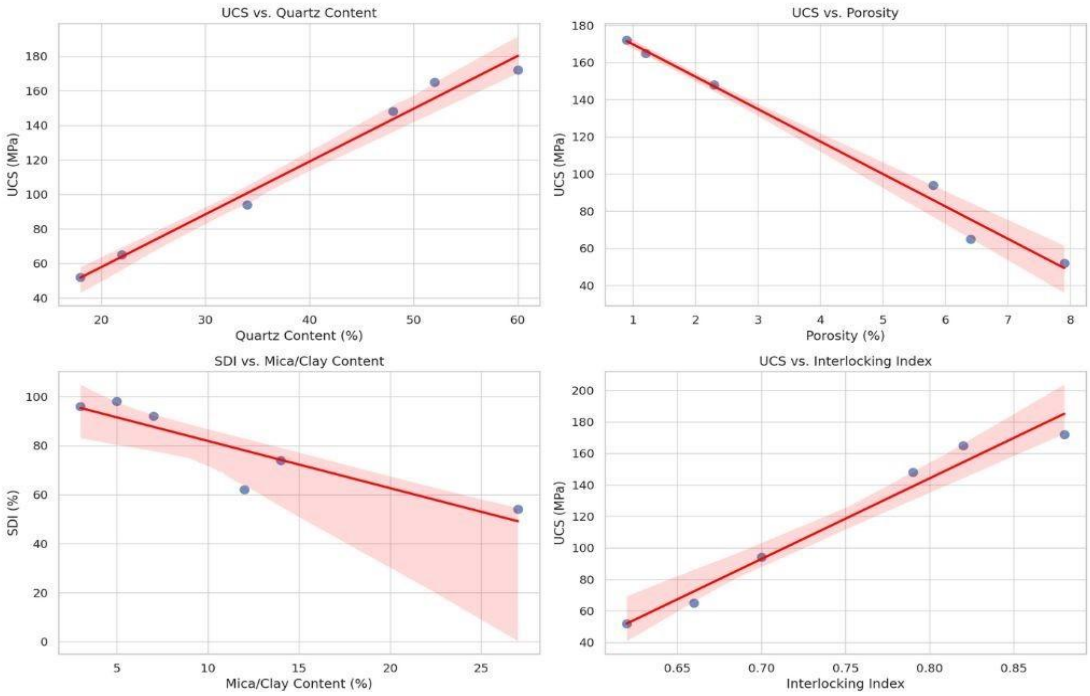

Figure 4. Selected scatterplots showing relationships between petrographic variables and mechanical/durability performance of construction rocks

Figure 4 shows selected scatterplots illustrating correlations between key petrographic parameters (e.g., quartz content, interlocking index, porosity) and mechanical/durability indicators (UCS, SDI).

For instance:

Quartz content had a correlation coefficient of +0.82 with UCS and +0.78 with SDI, indicating that higher quartz percentages significantly enhance both strength and durability.

Porosity was strongly negatively correlated with UCS (r = -0.84) and SDI (r = -0.76), confirming that internal voids critically reduce load-bearing capacity and environmental resistance.

Interlocking index showed r = +0.79 with UCS, reflecting the mechanical reinforcement provided by tightly interlocked grains.

Multiple Linear Regression (MLR) models were constructed using key variables such as quartz content, interlocking index, and porosity as predictors of UCS. The final model achieved an R^2 value of 0.91, suggesting an excellent fit between the petrographic parameters and strength performance. The regression equation is of the form: The regression analysis results, showing the relationship between predicted and observed UCS values based on petrographic inputs, are plotted in Figure 5, demonstrating high model accuracy ($R^2 = 0.97$)

$$\text{UCS} = a(\text{Qtz\%}) + b(\text{Interlocking}) - c(\text{Porosity}) + d \tag{1}$$

Where a, b, and c are coefficients derived from regression output, and d is the intercept.

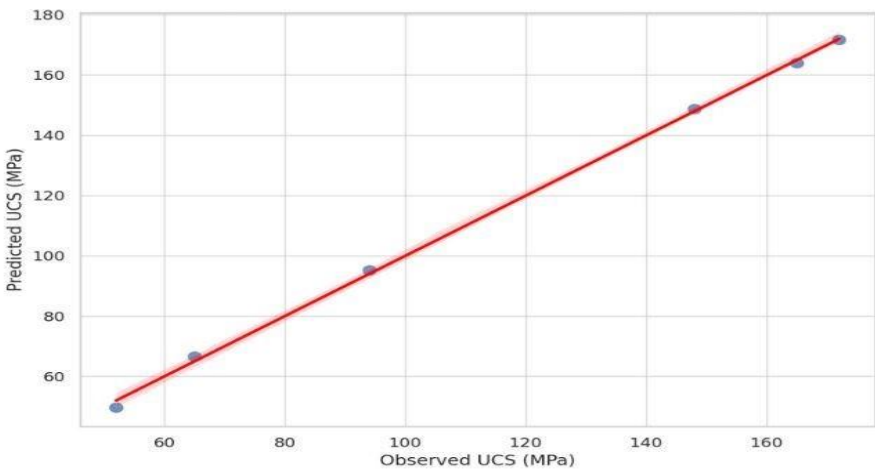

Figure 5. Predicted vs. Observed UCS

The regression line shows strong alignment between predicted and actual UCS values. The model achieved R^2 = 0.97, indicating excellent predictive capability based on your selected petrographic variables

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Additionally, Principal Component Analysis (PCA) identified two dominant components that together explained over 78% of the total variance in the dataset. Component 1 was primarily associated with quartz content, packing density, and strength metrics, while Component 2 reflected porosity, mica content, and durability loss further supporting the dual control of mechanical integrity by both strength-promoting and weakness-inducing features.

These statistical findings validate the strong predictive potential of petrographic variables and support their use in non-destructive classification frameworks for construction-grade rocks.

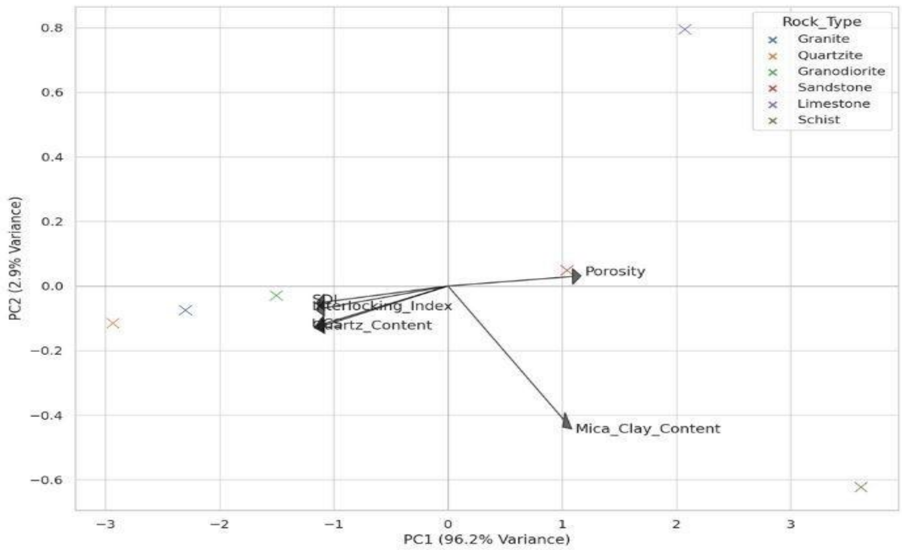

Figure 6. Principal Component Analysis (PCA) biplot showing clustering of rock samples and dominant contributing variables

Rocks like Quartzite and Granite cluster on the side associated with high UCS, quartz, and interlocking. Schist and Limestone are aligned with high porosity and mica/clay content. Vectors indicate which variables dominate variance and direction of influence.

A consolidated overview of petrographic and mechanical test results for representative rock types is shown in table 4, illustrating variation in quartz content, porosity, strength, and durability indicators.

Table 4. Petrographic & Mechanical Properties

Rock Type	Qtz (%)	M/C (%)	GrSz (mm)	Por (%)	UCS (MPa)	BTS (MPa)	SDI (%)	UPV (km/s)
Granite	52	5	0.4	1.2	165	14.5	98	5.6
Quartzite	60	3	0.3	0.9	172	15.3	96	5.9
Granodiorite	48	7	0.6	2.3	148	12.8	92	5.4
Sandstone	34	14	1.2	5.8	94	9.2	74	3.9
Limestone	22	12	0.9	6.4	65	6.1	62	3.1
Schist	18	27	1.5	7.9	52	4.8	54	2.7

Note: Values are representative averages. Exact values may vary based on mineral zoning, local fabric orientation, and alteration state.

5. Discussion

Figure 6 provides a Principal Component Analysis (PCA) biplot that visualizes the clustering of rock types and the influence of dominant petrographic variables on mechanical and durability characteristics. The results of this study strongly reinforce the hypothesis that the mechanical strength and durability of construction-grade rocks are significantly governed by their underlying mineralogical and textural characteristics. The integration of petrographic data with mechanical and durability test results has revealed robust and statistically meaningful correlations, validating the importance of quantitative petrographic analysis in geotechnical material classification and performance prediction.

One of the most significant findings is the positive influence of quartz content on both uniaxial compressive strength (UCS) and slake durability index (SDI). Quartzrich rocks, such as granite and quartzite, consistently exhibited superior mechanical and environmental performance due to the inherent hardness and chemical resistance of quartz grains. This finding aligns with previous studies (e.g., Tugrul & Zarif, 1999; Yasar & Erdogan, 2004), yet the present research goes further by quantifying quartz influence in a multivariate context, showing a strong correlation coefficient (r = +0.82) and a high degree of explanatory power ($R^2 = 0.91$) in regression modeling. The study's use of multiple predictors combining quartz content with interlocking index and porosity also highlights the synergistic effects of composition and texture, offering a more holistic view than mineral content alone.

Texture-related variables, particularly the interlocking index and packing density, emerged as equally critical in determining rock performance. Rocks with tightly interlocked, angular grains demonstrated higher load-bearing capacity, resistance to crack propagation, and improved cohesion. This is attributed to enhanced grain-to-grain friction and energy dissipation during stress loading. Conversely, rocks with poorly interlocked or rounded grains exhibited reduced mechanical strength, consistent with the mechanics of stress concentration around less cohesive contacts. The interlocking index, in particular, showed strong correlations with both UCS and ultrasonic pulse velocity (UPV), supporting its utility as a reliable indicator of internal fabric integrity. These results support and extend the findings of Eberhardt et al. (2004) and Sousa et al. (2005), providing new evidence that quantified texture can be as predictive as bulk mineralogy.

Equally important is the role of porosity and clay/mica content in undermining rock integrity. The negative correlations between porosity and both UCS (r = -0.84) and SDI (r = -0.76) confirm that internal voids act as mechanical discontinuities, promoting early failure and enhanced permeability that accelerates weathering. Clay and mica minerals, due to their platy morphology and high water affinity, further weaken rocks by reducing cohesion and promoting slaking, as seen in the lower durability values of schists and clay-bearing sandstones. These insights highlight the dual importance of composition and microstructural geometry in assessing rock suitability, especially in environments exposed to wetting-drying cycles or freeze-thaw action.

The Principal Component Analysis (PCA) further clarified the multivariate structure of the dataset, revealing that the first two principal components captured over 78% of the total variance. Quartz content, interlocking index, and porosity dominated PC1, while clay content and grain size contributed most to PC2. This dimensional reduction illustrates that a limited set of carefully selected petrographic variables can explain the majority of performance behavior, enabling the development of simplified, yet accurate predictive tools for practical engineering use.

From an applied perspective, the findings offer a pathway toward the development of non-destructive, petrography-based classification systems for construction-grade rocks. By establishing threshold values for key variables such as quartz content > 45%, interlocking index > 0.75, and porosity < 3% engineers can make informed decisions about material suitability before investing in full-scale mechanical testing. This is particularly valuable in early design phases, remote site assessments, or resource-limited settings.

6. Conclusion

This study has demonstrated that the mechanical strength and durability of construction rocks are fundamentally controlled by a combination of their mineralogical composition and textural characteristics. By integrating detailed petrographic analysis including modal mineralogy, grain size, interlocking index, and porosity with standardized mechanical and durability testing, the research has provided a robust, data-driven framework for evaluating rock performance in engineering applications.

Key findings indicate that rocks with high quartz content, fine-grained textures, strong grain interlocking, and low porosity consistently exhibit superior uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), and slake durability index (SDI). In contrast, rocks containing elevated proportions of mica, chlorite, or clay minerals, coupled with higher porosity and poor grain cohesion, demonstrate reduced mechanical integrity and environmental resistance. The results confirm that both compositional and geometric microstructure must be considered together to accurately assess the suitability of rocks for construction use.

Statistical modeling, including multiple linear regression and principal component analysis, further validated these relationships and revealed that a small number of quantified petrographic variables can predict rock performance with high accuracy (R^2 0.91). These results establish a strong scientific basis for developing non-destructive, petrography-based prediction tools that can significantly enhance early-stage material selection and reduce the reliance on destructive laboratory testing.

In practical terms, this research offers valuable threshold guidelines for example, quartz content > 45%, interlocking index > 0.75, and porosity < 3% which can serve as early indicators of high-performance rock materials. The proposed framework can be directly applied in civil and geotechnical engineering projects, particularly in contexts requiring rapid material classification, quality control, or resource evaluation.

Overall, this study contributes to bridging the gap between geological microstructure and engineering performance. It advances the potential of quantitative petrography as a powerful, predictive tool in rock mechanics and lays the groundwork for future integration with machine learning, automated image analysis, and digital petrographic systems in construction material assessment.

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