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GEOTECHNICAL AND PETROGRAPHIC ASSESSMENT OF THE HISARTANG FORMATION: A CASE STUDY FROM THE NIZAMPUR BASIN, PAKISTAN

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Abstract

The geotechnical properties of sedimentary rocks are fundamentally controlled by their petrographic characteristics, yet this relationship remains critically understudied for the Hisartang Formation in the tectonically complex Nizampur Basin, Pakistan. This study presents an integrated petrographic and geotechnical evaluation to bridge this knowledge gap. A comprehensive methodology involving field sampling, petrographic analysis, and a suite of standardized geotechnical tests (Unconfined Compressive Strength (UCS), Unconfined Tensile Strength (UTS), Point Load Test (PLT), Ultrasonic Pulse Velocity (UPV), Schmidt Hammer Test (SHT), specific gravity, porosity, and water absorption) was employed. Petrographic results reveal the sandstone as a mineralogically and texturally mature subarkose, dominated by quartz (84%) with minor feldspar (15%) and chert (1%). The fabric exhibits tightly packed, sub-rounded to rounded grains with sutured, concave-convex contacts and quartz overgrowths, indicating significant compaction and cementation during diagenesis. Geotechnically, the formation exhibits exceptional properties: low porosity (0.24%) and water absorption (0.12%), high Unconfined compressive strength (123 MPa), tensile strength (16 MPa), and high ultrasonic pulse velocity (5154 m/s). The analysis demonstrates a direct causal link between the quartz-dominated mineralogy, the compact, well-cemented fabric, and the superior mechanical strength. This study conclusively establishes that the Hisartang Formation is a highly competent engineering material, suitable for demanding applications like foundation rock and high-quality aggregate. The findings provide a crucial predictive model for infrastructure development in the region and underscore the necessity of petrographic analysis in geotechnical forecasting.

INTRODUCTION

The geotechnical assessment of rocks is fundamentally linked to their petrographic features, as the physical and mechanical properties of rocks are significantly influenced by variations in their texture and mineralogical composition. Factors such as grain size, grain contacts, porosity, diagenesis, matrix type, and mineralogical composition directly affect the strength, deformability, and overall behavior of rocks under different engineering conditions (Sajid and Arif, 2015; Sajid et al., 2016; Ahmad et al., 2021; Heydarian et al., 2024; Ullah et al., 2025). These intrinsic characteristics serve as primary controls on how a rock mass will respond to stresses imposed by construction, excavation, or natural slope processes, making petrographic analysis a critical predictive tool in geotechnical engineering (Asif et al., 2022; 2024).

The mechanical properties of sandstones are greatly influenced by key mineralogical and textural characteristics. These include mineral composition, density, and hardness, as well as grain size, shape, packing proximity, degree of interlocking, type of grain contacts, and the amount and type of cement and matrix. These attributes are commonly analyzed through routine thin-section studies in the laboratory, where they can be measured with relative ease (Khanlari et al., 2016). For instance, the mineralogy and texture play a vital role in controlling mechanical properties, where quartz, owing to its strong covalent bonds and high elastic stiffness, serves as the principal contributor to sandstone strength (Fereidooni, 2022). Conversely, the presence of weaker minerals like clay or mica, or poorly cemented grains, can significantly reduce overall rock competence and promote failure (He et al., 2019).

The Nizampur Basin, situated within the Himalayan foreland system in Pakistan, presents a geologically complex and dynamic setting. This basin hosts sedimentary sequences, including the Hisartang Formation, that have been subjected to intense tectonic activity and varying diagenetic processes throughout the Cenozoic era (Kamal et al, 2024). The complex tectonic history, involving significant folding and faulting, has imparted a unique structural fabric to the rock units, which inevitably influences their present-day geotechnical behavior (Yaseen et al., 2021). Understanding the properties of these rocks is therefore not only a matter of material science but also of regional geological context.

Despite its geological prominence within the Nizampur Basin, the Hisartang Formation has received limited attention from a geotechnical standpoint. Previous investigations have primarily emphasized regional stratigraphy, structural evolution, and hydrocarbon potential, leaving comprehensive petrographic and geomechanical assessments notably absent (Khattak et al., 2021; Rahim et al., 2024). This scarcity of dedicated research has resulted in a substantial knowledge gap, impeding the accurate prediction of the formation's behavior in engineering contexts. Consequently, critical applications essential to the region's expanding infrastructure, including foundation design, slope stability analysis, and tunneling projects, face significantly elevated risks due to a poor understanding of the subsurface conditions.

Furthermore, although the Hisartang Formation constitutes a major stratigraphic unit within the tectonically active Nizampur Basin, integrated studies correlating its intrinsic petrographic attributes with engineering properties are markedly lacking. The absence of such correlations compromises the reliable estimation of the formation's mechanical performance, introducing potential uncertainties in project planning and execution. This study aims to address these deficiencies by systematically evaluating the influence of mineral composition, texture, and diagenetic history on the geomechanical behavior of the formation. Through an integrated analytical approach, this study aims to advance the mechanistic understanding of the factors controlling the strength and deformation behavior of the Hisartang Formation sandstones. The resulting insights will provide valuable guidance for engineering design, risk mitigation, and sustainable resource development within the Nizampur Basin and other analogous geological settings.

Regional and Local Geology of the Nizampur Basin and Hisartang Formation

Regional Geological Setting

The Nizampur Basin is a small but significant intermontane basin located in the northwestern region of Pakistan, within the broader context of the Himalayan foreland system. It lies at the southern margin of the Himalayan Fold-and-Thrust Belt, a complex tectonic province formed by the ongoing continental collision between the Indian and Eurasian plates (Anjum et al., 2022). This collision, initiating in the Cenozoic era, has resulted in intense compressional forces, producing a series of thrust faults, folds, and uplifted sedimentary basins along the entire orogenic belt (Yin, 2010). The Nizampur Basin itself is considered a piggyback basin, developed atop active thrust sheets and is bounded by major tectonic features, including the Main Boundary Thrust (MBT) to the north and older Precambrian metamorphic rocks of the Indian Shield to the south (Hashmi et al., 2018). This dynamic tectonic setting has profoundly influenced the basin's depositional history, structural architecture, and the subsequent diagenetic evolution of its sedimentary fill.

The stratigraphic sequence of the basin comprises a thick pile of Cenozoic sedimentary rocks, ranging from Paleocene to recent deposits. These sediments were primarily sourced from the rising Himalayas and deposited in various fluvial, deltaic, and shallow marine environments as the foreland basin evolved. The sequence typically includes, from oldest to youngest, the Lockhart Limestone, Patala Formation, Margalla Hill Limestone, Chorgali Formation, and the Rawalpindi Group (comprising the Murree and Kamlial formations), which are overlain by the Siwalik Group molasse deposits and recent alluvium (Awais et al., 2012).

Local Geology and the Hisartang Formation

Within this regional framework, the Hisartang Formation represents a distinct lithostratigraphic unit exposed within the Nizampur Basin. The formation is named after the Hisartang village, where it exhibits typical and well-exposed sections. It is primarily composed of coarse-grained to pebbly sandstone, interbedded with variegated mudstone and siltstone, and occasional conglomerate layers. The sandstone units are typically thick-bedded to massive, exhibiting colors ranging from grey and brown to reddish-brown, indicative of varying oxidizing conditions during and after deposition (Hussain et al., 1989; Shah 2009).

Structurally, the Hisartang Formation has been subjected to the compressional stresses that dominate the region. The unit exhibits moderate to steep dips and is often folded into broad synclines and anticlines. It is also cross-cut by several joint sets and minor faults, which influence its geomechanical behavior and weathering patterns. The formation uncomfortably overlies the Eocene carbonate sequences (e.g., Margalla Hill Limestone) and is in turn overlain by recent alluvial deposits. Understanding this complex geological history, from deposition in a high-energy fluvial system to subsequent tectonic deformation, is crucial for interpreting its present-day petrographic and geotechnical characteristics (Hashmi et al., 2018; Yaseen et al., 2021).

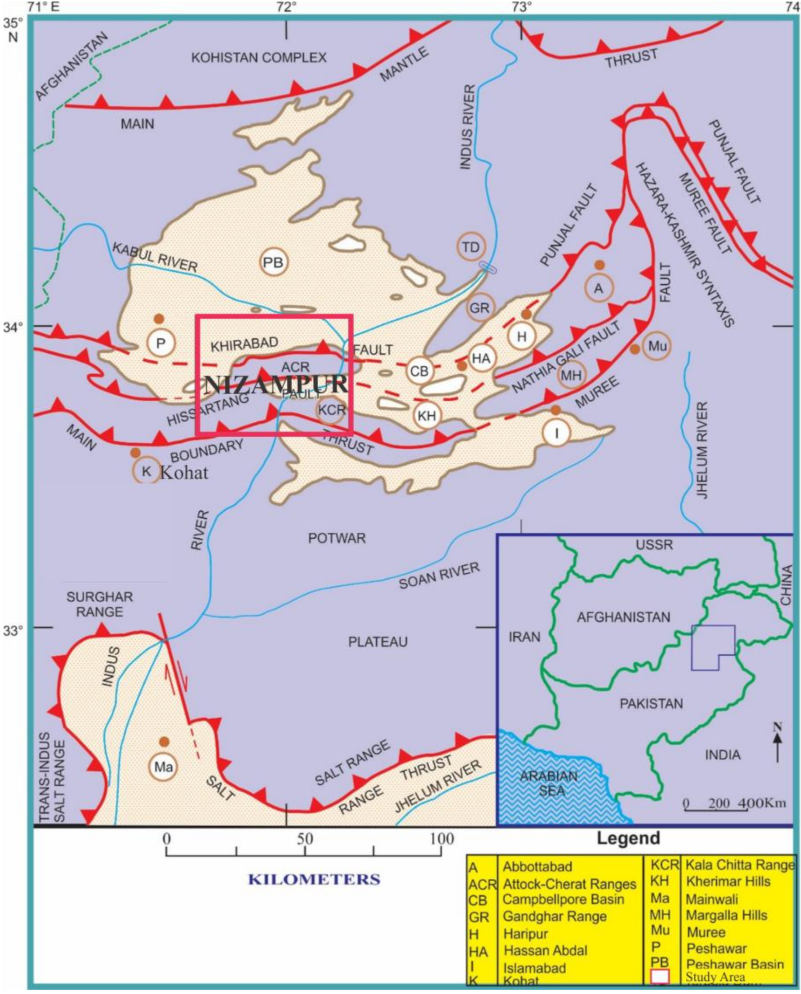

Figure 1: Tectonic map of northern Pakistan showing major structural boundaries (after Hylland and Riaz, 1988). The study area (Nizampur basin) is shown as a box on the map.

Materials and Methods

Field Investigation and Sample Collection

A comprehensive field campaign was undertaken within the Nizampur basin of northwestern Pakistan to acquire representative rock samples from the target sandstone formation (Figure 2). During this campaign, bulk samples were systematically collected from fresh, unweathered outcrops. Detailed macroscopic descriptions of the outcrops were meticulously documented, including notes on mineralogical composition, textural attributes (such as grain size and sorting), bedding thickness, and rock color.

The sampling strategy was designed to ensure the integrity and representativeness of the specimens. Samples were deliberately selected from locations exhibiting minimal signs of surficial weathering and an absence of macroscopic fractures to guarantee homogeneity and isotropy, which are fundamental prerequisites for obtaining reliable and consistent laboratory results. To secure fresh material, multiple techniques were employed. These included the extraction of large blocks using rock hammers and chisels, the creation of small trenches to expose unweathered rock beneath superficial layers, and, where necessary, core drilling to obtain samples from depth. Following collection, all samples were immediately sealed in durable bags to prevent contamination and minimize moisture absorption during transport, thereby preserving their in-situ characteristics for subsequent analysis.

Figure 2: Field Photographs of the studied Hisartang Formation in Nizampur basin.

Laboratory Analysis

The laboratory investigation was designed to comprehensively characterize the samples through a multi-faceted approach encompassing petrographic, mineralogical, and geotechnical analyses.

Petrographic thin sections were prepared from the collected samples at the National Centre of Excellence in Geology (NCEG), University of Peshawar. These thin sections were examined under a Nikon ECLIPSE LV100ND polarizing microscope to determine their mineralogical composition and quantify key textural features, including grain size, shape, sorting, and cementation patterns. High-resolution photomicrographs of diagnostic textures and mineral assemblages were captured using an attached Nikon DS-Fi2 camera system for detailed documentation and analysis.

The physical and mechanical properties of the sandstones were determined through a suite of standardized geotechnical tests (Figure 3). Cylindrical core specimens with a nominal diameter of 55 mm and a length-to-diameter ratio between 2.0 and 2.5 were precision-drilled from the bulk samples in accordance with ASTM D4543-19. The testing program included the determination of specific gravity and water absorption (ASTM C127), ultrasonic pulse velocity (Aydin, 2014), Schmidt hammer rebound hardness (ASTM D5873), Unconfined compressive strength (ASTM D2938), Unconfined tensile strength (ASTM D3967), and the point load index (ASTM D5731). All tests were conducted in the geotechnical laboratory of the National Centre of Excellence in Geology (NCEG) University of Peshawar (UoP), adhering strictly to the prescribed standard procedures to ensure the accuracy, reproducibility, and comparability of the results.

Figure 3: Photographs showing various geotechnical tests. **a)** showing Point Load Test of the core samples; **b)** showing Unconfined Compressive Strength test of the core samples; **(c)** showing Unconfined Tensile Strength test of the core samples; **e)** showing Ultrasonic Pulse Velocity test of the core samples.

Results

Petrographic Results

Mineralogical Composition and Classification

Petrographic analysis of the Hisartang Formation (HF) sandstone reveals a mineralogically mature composition dominated by stable silicate minerals. Quantitative point counting indicates a pronounced dominance of quartz, which constitutes an average of 84% of the detrital fraction. This quartz percentage includes both monocrystalline grains, exhibiting uniform extinction, and less common polycrystalline varieties (Figure 4). Feldspar minerals, primarily potassium feldspar (microcline and orthoclase) with minor plagioclase, form the second most abundant component at 15%. Accessory lithic fragments, consisting overwhelmingly of chert, account for the remaining 1% of the framework composition. The virtual absence of unstable rock fragments, such as volcanic or shale clasts, and the low feldspar content are notable.

Based on this mineralogical assemblage, the HF sandstone is classified as a subarkose according to the ternary diagram of Pettijohn et al., 1987, which plots the relative percentages of quartz, feldspar, and lithic fragments. This classification places it in a transitional category between quartz arenite and arkose, indicating a source terrain that contained significant feldspathic rocks, such as granite or gneiss, but which underwent substantial chemical weathering and mechanical reworking prior to final deposition.

Grain Size and Textural Attributes

Grain size analysis performed on thin sections classifies the HF sandstone as medium to coarse-grained sand, adhering to the Wentworth (1922) scale. The grains are moderately to well-sorted, indicating a consistent energy level in the depositional environment that effectively segregated the sediment by size.

The texture of the sandstone is characterized by tight packing of the framework grains, resulting in low original intergranular porosity (Figure 4). The grains are predominantly sub-rounded to rounded, a morphology that signifies an extensive history of mechanical abrasion during prolonged transport or reworking in a high-energy setting, such as a beach or a fluvial channel.

Diagenetic Features and Grain Contacts

The nature of grain-to-grain contacts provides critical insight into the post-depositional diagenetic history of the rock (Molenaar et al., 2025). The contacts are predominantly long and sutured, with common concave-convex and occasional tangential types. This suite of contact types is a direct result of significant mechanical compaction during deep burial. Sutured contacts, in particular, form by pressure dissolution at grain boundaries under high overburden pressure, where material is dissolved at points of high stress and often reprecipitated in adjacent pore spaces as cement.

Evidence of this chemical diagenesis is present in the form of quartz overgrowths (Figure 4). These are observed as optically continuous, euhedral outgrowths of silica cement precipitated onto the surfaces of detrital quartz grains. The development of these overgrowths, a process termed syntaxial growth, further contributes to the rock's strength by welding grains together and significantly reducing porosity.

Maturity and Interpretation

The combined mineralogical and textural characteristics demonstrate that the Hisartang Formation sandstone has achieved a high degree of both physical and chemical maturity.

Physical maturity is evidenced by the well-sorted and well-rounded nature of the grains, indicating that the sediment underwent extensive mechanical reworking and abrasion, which eliminated finer, clay-sized particles and rounded the larger grains (Figure 4).

Chemical maturity is reflected in the overwhelming abundance of the chemically stable mineral quartz and the corresponding scarcity of unstable minerals like ferromagnesian silicates or certain types of feldspar. This indicates that the source material was subjected to intense chemical weathering processes, which effectively broke down and removed less stable components before and during sedimentation.

The petrography of the HF sandstone points to a derivation from a cratonic interior or recycled orogenic source, prolonged transport or reworking in a high-energy depositional system, and a significant diagenetic history involving deep burial compaction and quartz cementation. These factors have collectively produced a strong, coherent, and competent rock mass.

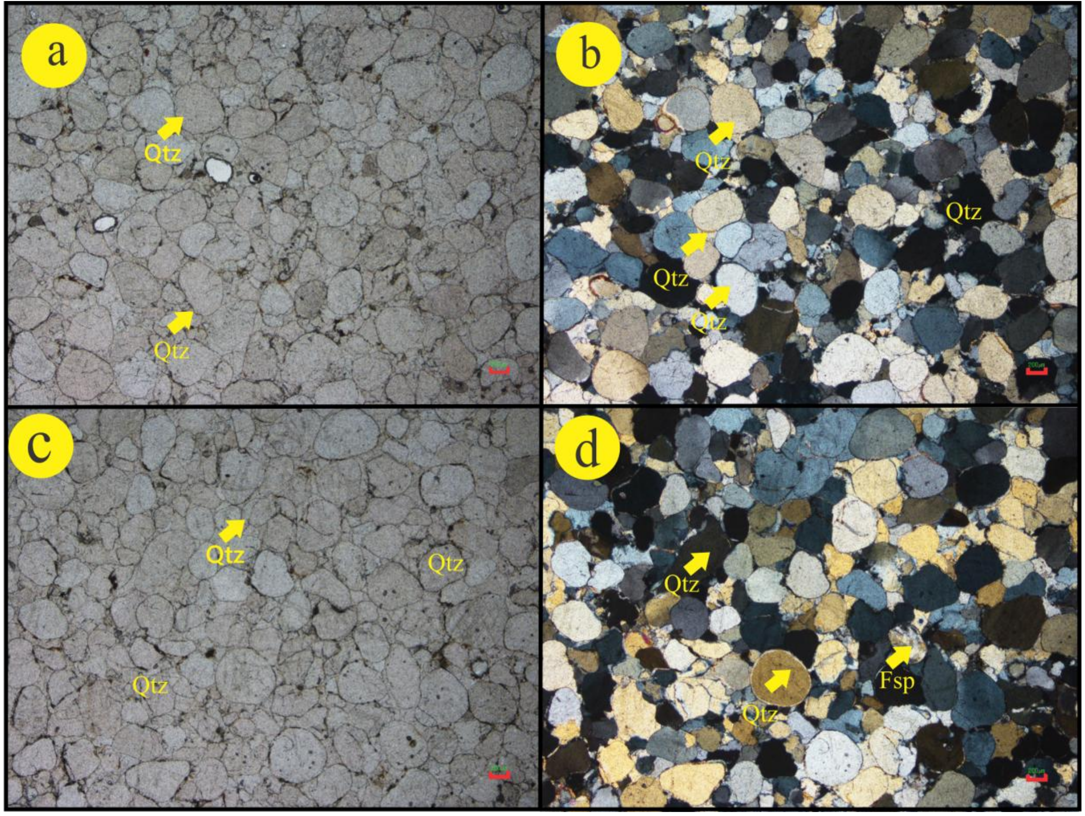

Figure 4: Thin section view of the Hisartang Formation sandstone. Note the well-rounded quartz grains (Qtz) with concave-convex and sutured contacts (examples indicated by arrows), evidence for significant compaction. The texture and mineralogy (dominance of quartz) indicate a physically and chemically mature sandstone.

Geotechnical properties

A comprehensive suite of geotechnical tests was conducted on core samples (Figure 5) from the Hisartang Formation (HF) to evaluate its physical and mechanical characteristics. The results, as summarized in Table 1, demonstrate a consistent and favorable engineering profile with low variability between samples, indicating a homogeneous rock unit.

Table 1 Geotechnical analysis of the studied sandstone samples

Formation	**Abbr.**	**Specific gravity**	**Water absorption**	**Porosity**	**UCS**	**UTS**	**PLT**	**UPV**	**SHT**
Hisartang Formation	HF1	2.84	0.12	0.24	125	17	22	5222	45
	HF2	2.82	0.13	0.25	113	15	20	4880	42
	HF3	2.86	0.11	0.24	132	17	22	5393	46
	HF4	2.83	0.13	0.25	119	16	21	5051	44
	HF5	2.85	0.12	0.24	126	17	22	5222	45
	Ave.	**2.84**	**0.12**	**0.24**	**123**	**16**	**21**	**5154**	**44**

The physical properties of the HF sandstone reveal a dense and compact material. The specific gravity values exhibited a narrow range from 2.82 to 2.86, with an average of 2.84, which is typical for quartz-rich sandstones. Complementary to this, the formation displayed very low porosity and water absorption characteristics. Porosity values averaged 0.24% (ranging from 0.24% to 0.25%), while water absorption averaged 0.12% (ranging from 0.11% to 0.13%). These exceptionally low values indicate a well-cemented rock fabric with minimal void space, limiting the potential for water ingress and subsequent weakening.

The mechanical strength properties further confirm the competence of the Hisartang Formation. The Unconfined Compressive Strength (UCS), a critical parameter for assessing load-bearing capacity, ranged from 113 MPa to 132 MPa, yielding an average of 123 MPa. This places the HF sandstone in the strong to very strong rock category. The indirect measure of tensile strength, the Brazilian Tensile Strength (UTS), averaged 16 MPa (range: 15-17 MPa). The Point Load Test Index (PLT), which provides a field-based estimate of strength, showed consistent results with an average of 21 MPa (range: 20-22 MPa), corroborating the high strength values obtained from the UCS tests.

Non-destructive testing methods reinforced the findings from the destructive tests. The Ultrasonic Pulse Velocity (UPV), which is sensitive to internal fractures and material homogeneity, recorded high velocities averaging 5154 m/s (range: 4880-5393 m/s). These high velocities are indicative of excellent elastic integrity and a continuous, well-compacted rock mass. Similarly, the Schmidt Hammer Rebound Hardness (SHT) values averaged 44 (range: 42-46), reflecting a very high surface hardness and resistance to weathering.

The geotechnical results portray the Hisartang Formation as a highly competent engineering material. Its high strength, low porosity, and high integrity, as evidenced by both destructive and non-destructive tests, suggest it is suitable for a variety of demanding geotechnical applications.

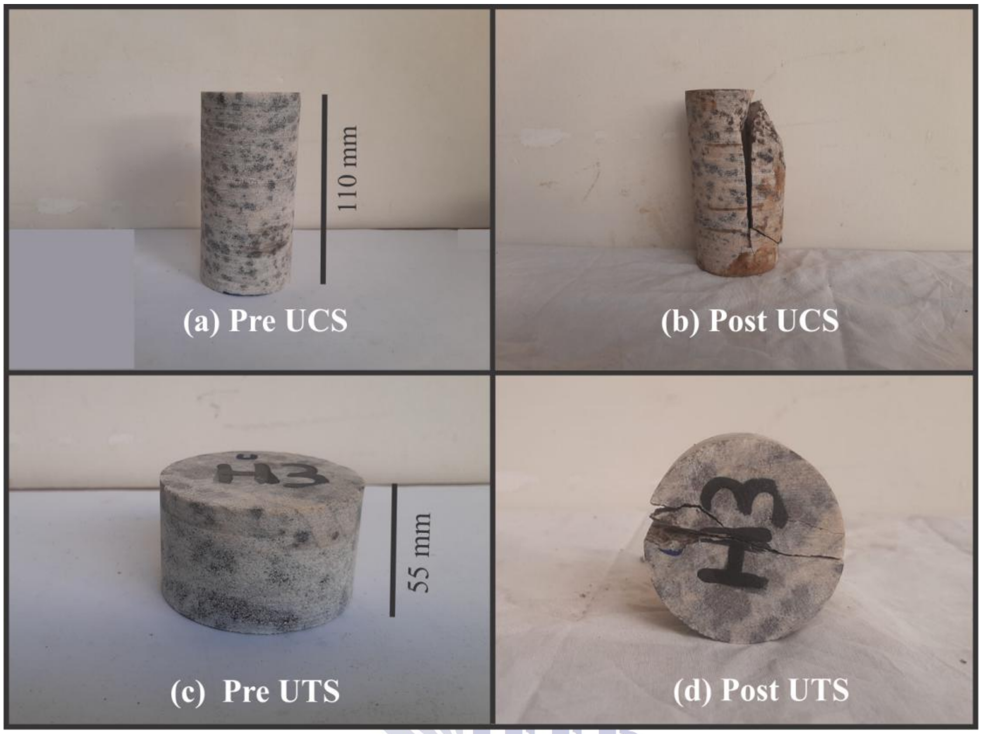

Figure 5: Laboratory test specimens from the Hisartang Formation before and after strength testing. (a) Cylindrical rock core sample (55 mm diameter) prepared for Unconfined Compressive Strength (UCS) testing. (b) The same sample after UCS testing, showing characteristic failure mode. (c) Brazilian disc sample prepared for Indirect Tensile Strength (UTS) testing. (d) The same sample after UTS testing, demonstrating typical tensile splitting failure. Scale bar applies to all images.

Discussion

Synthesis of Petrographic and Geotechnical Characteristics

The integrated analysis of the Hisartang Formation (HF) sandstone reveals a direct and compelling correlation between its intrinsic petrographic attributes and its measured geotechnical performance. The high degree of both physical and chemical maturity, as determined from thin section analysis, is the fundamental factor responsible for the formation's superior engineering properties. The overwhelming dominance of quartz (84%), a mineral renowned for its high strength, hardness, and chemical stability, provides a strong framework that inherently resists compressive and tensile stresses. This mineralogical control is a primary reason for the high Unconfined Compressive Strength (UCS) and Unconfined Tensile Strength (UTS) values, averaging 123 MPa and 16 MPa, respectively. The scarcity of weak minerals, such as clay or mica, eliminates potential planes of weakness, further enhancing the rock's overall competence.

The textural characteristics observed petrographically provide an equally critical explanation for the geotechnical results. The tight packing of grains and the development of long, concave-convex, and sutured contacts are direct manifestations of extensive mechanical compaction and pressure dissolution during diagenesis. These processes have dramatically reduced the original pore space and increased the area of grain-to-grain contact, thereby facilitating more effective stress transfer across the rock fabric. This is quantitatively confirmed by the exceptionally low porosity (avg. 0.24%) and water absorption (avg. 0.12%) values. Low porosity directly contributes to high strength by minimizing the points where stress concentrations can initiate micro-cracks. Furthermore, the precipitation of quartz overgrowths as a cementing agent has effectively welded the detrital grains together, transforming a granular sediment into a coherent, indurated rock mass. This syntaxial cementation is a key diagenetic process that has significantly enhanced the rock's integrity, as reflected in the high Ultrasonic Pulse Velocity (UPV avg. 5154 m/s), which is a sensitive indicator of a continuous and well-cemented medium.

Comparative Analysis with Established Classifications and Other Formations

The geotechnical properties of the HF sandstone align exceptionally well with its classification as a mature subarkose. Its strength values place it firmly within the "strong" to "very strong" categories according to standard rock mass rating systems. When compared to other sandstones globally (Bjørlykke & Jahren, 2010), the HF formation exhibits properties superior to many less mature or more porous sandstones. For instance, its average UCS of 123 MPa far exceeds that of weaker, clay-rich sandstones but is consistent with values reported for other well-cemented, quartzose sandstones from stable cratonic settings (Cook et al., 2015). The strong correlation between the Point Load Index (avg. 21 MPa) and the UCS further validates the reliability of both measurement techniques for this homogeneous rock type.

The non-destructive test results provide a consistent narrative of high quality. The high Schmidt Hammer rebound values (avg. 44) confirm the surface hardness and resistance to abrasion, which is a direct consequence of the quartz-dominated mineralogy and strong intergranular bonding. Similarly, the high UPV values not only confirm low porosity but also indicate an absence of significant micro-fracturing, suggesting the rock mass is of high quality and likely to perform well as a foundation or construction material.

Engineering Implications and Applications

The combination of high strength, low porosity, and high durability makes the Hisartang Formation sandstone a highly suitable material for a wide range of geotechnical and construction applications. Its high load-bearing capacity (UCS) recommends it for use as a foundation rock for heavy structures such as dams, bridges, and high-rise buildings. Its resistance to weathering, indicated by its chemical maturity and low water absorption, suggests good long-term performance in slopes and cuttings, reducing the risk of deterioration and failure. Furthermore, its high aggregate crushing value (inferred from its strength) and resistance to abrasion would make it a valuable source of high-quality aggregate for concrete and road base in infrastructure projects.

However, the presence of sutured contacts and quartz cement, while enhancing strength, can also impart a degree of brittleness. This must be considered in applications where the rock may be subjected to dynamic loading or where its fracture behavior is critical.

The discussion unequivocally demonstrates that the exceptional geotechnical properties of the

Hisartang Formation sandstone are not accidental but are fundamentally controlled by its petrographic characteristics. The journey from sediment to rock, which involved extensive weathering to create a quartz rich assemblage, prolonged transport to round and sort the grains, and deep burial diagenesis to compact and cement them, has resulted in an engineering material of high quality. This study successfully establishes a quantitative and qualitative link between mineralogy, texture, diagenesis, and engineering behavior, providing a predictive model that can be applied to similar sedimentary units in the region for safe and efficient engineering design.

Conclusion

This study successfully achieved its primary objective of conducting a comprehensive geotechnical evaluation of the Hisartang Formation by establishing strong correlations with its petrographic characteristics. The integrated analysis leads to the following definitive conclusions:

1. Petrographic Control on Engineering Properties: The exceptional geotechnical behavior of the Hisartang Formation is unequivocally governed by its intrinsic petrographic attributes. The overwhelming abundance of strong and stable quartz minerals (84%) provides a competent framework, while the near-absence of weak minerals eliminates potential failure planes.
2. Impact of Diagenesis: The textural maturity, which is evidenced by tight grain packing, sutured contacts, and extensive quartz cementation, is a product of significant mechanical compaction and chemical diagenesis during deep burial. These processes are directly responsible for the rock's very low porosity and high integrity, which in turn dictate its high strength and durability.
3. Superior Geotechnical Competence: The laboratory results consistently classify the formation as a strong to very strong rock material. The high values for UC (123 MPa), UTS (16 MPa), PLT (21 MPa), and UPV (5154 m/s) collectively confirm its outstanding mechanical performance and homogeneity.
4. Engineering Significance: The combination of high strength, low porosity, and resistance to weathering makes the Hisartang Formation sandstone a highly suitable resource for critical engineering applications. It is recommended for use as a foundation for heavy infrastructure (dams, bridges), as a high-quality aggregate for concrete, and in slope stability projects where long-term performance is essential.

This research addresses a critical data gap for the Nizampur Basin by developing a predictive model in which the petrographic fingerprint of a sandstone, including its mineralogy, texture, and diagenetic history, can be used to reliably forecast its geotechnical behavior. The findings highlight the essential role of integrated petrographic-geotechnical studies in mitigating risks associated with infrastructure planning, facilitating safe design, and promoting the sustainable use of geological resources in the Himalayan foreland and other similar geological settings. Future research should focus on examining scale effects and the influence of in-situ discontinuities on rock mass properties.

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