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**| RESEARCH ARTICLE**

# Characterization and Engineering Evaluation of Tholeiitic to Calc-Alkaline Rock Assemblages in Achin District, Nangarhar Province, Eastern Afghanistan

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**| ABSTRACT**

Magmatic lithofacies assemblages serve as crucial archives of lithospheric evolution, while simultaneously acting as high-durability geomaterials for heavy industrial infrastructure. This study presents an integrated petrological, whole-rock geochemical, and petrophysical characterization of the sub-alkaline intrusive suites within the Gaodara area (Achin District, Nangarhar Province, Eastern Afghanistan) to resolve their petrogenesis and engineering utility. Systematically sampled outcropping suites and adjacent country formations were evaluated utilizing polarized-light thin-section microscopy, X-ray fluorescence (XRF) spectrometry, and hydrostatic displacement densitometry. Petrographic analysis identifies a distinct plutonic-hypabyssal bimodal system. The intrusive core comprises phaneritic, unevolved olivine gabbros exhibiting relict hypidiomorphic-granular to ophitic fabrics dominated by calcic plagioclase, clinopyroxene, and fractured olivine. Conversely, the enclosing country rock framework consists of intermediate, fine-to-medium-grained calc-alkaline tonalites containing quartz, plagioclase, biotite, and hornblende. Whole-rock major-oxide geochemistry confirms a distinct sub-alkaline bimodal distribution. The primitive, mantle-derived gabbroic core displays a highly refined tholeiitic differentiation path characterized by low silica ($SiO_2$ down to 36.69 wt.%), prominent iron enrichment ($Fe_2O_3$ up to 18.31 wt.%), and elevated magnesium numbers (MgO up to 20.70 wt.%). Conversely, the surrounding tonalitic country rocks follow a more evolved calc-alkaline trend, reaching high silica parameters ($SiO_2$ up to 82.36 wt.%) and elevated potassium fractions ($K_2O$ up to 4.09 wt.%). Geotechnical testing reveals that these crystalline microstructural arrays directly dictate the rock mass durability. The dense, interlocking tholeiitic fabric yields a highly compact rock matrix with a low mean effective water absorption of 0.13%, an elevated mean bulk density of 3.06 g/cm$^3$, and a mean specific gravity of 3.07. Ultimately, these exceptional petrophysical and geochemical attributes confirm that the Gaodara tholeiitic-to-calc-alkaline bimodal suite provides high-resistance, low-porosity geological formations ideally suited for heavy civil engineering, industrial dimension stone production, and high-durability construction applications.

**| KEYWORDS**

Achin, Tholeiitic, Calc-alkaline, gabbro, Tonalite, Engineering evaluation, Petrography, Geochemistry.

**| ARTICLE INFORMATION**

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## 1. Introduction

Tholeiitic and mafic magmatic rocks serve as critical keys for unlocking deep mantle dynamics, lithospheric evolution, and continental rift or post-collisional tectonic regimes across the globe (Frost & Frost, 2014; Winter, 2014). Unlike typical alkaline magmatic suites distinctly enriched in incompatible elements and volatile components, sub-alkaline tholeiitic to calc-alkaline rock series provide excellent insights into fractional crystallization pathways and crustal assimilation processes within magmatic arcs and collisional margins (Rollinson, 2014; Marks & Markl, 2017). These characteristic chemical signatures point to specific petrogenetic processes, which typically involve varying degrees of partial melting of a modified subcontinental lithospheric mantle (SCLM) or an asthenosphere mantle source (White, 2020). During magma ascent through the upper lithosphere, these deep-seated melts undergo complex evolution, frequently resulting in coeval mafic-felsic bimodal systems where primitive intrusive components sit alongside highly evolved host rocks (Rollinson, 2014). Consequently, studying these intrusive frameworks offers vital constraints on the thermal and chemical architecture of the Earth's upper mantle and ancient crustal basements. Within orogenic belts, the temporal and spatial distribution of these basic-to-acidic complexes helps geologists map out the transition from active convergence to post-collisional extension (Dilek & Furnes, 2011). [1]

The regional geology and structural framework of eastern Afghanistan are shaped by the prolonged tectonic collision between the Indo-Pakistan and Eurasian plates (Yin & Harrison, 2000). This major collisional boundary created a complex network of accreted micro-terranes, deep-seated suture zones, and localized magmatic arcs (Treloar & Searle, 1993). The Gaodara area, located within the Achin District of Nangarhar Province, sits inside this complex zone, structurally wedged near the intersection of the Kabul and Jalalabad blocks (Abdullah & Chmyriov, 2008). This regional architecture features highly deformed metamorphic basements, Neoproterozoic to Paleozoic country rocks, and younger Mesozoic to Cenozoic plutonic intrusions (Siehl, 2015). Despite its strategic geological position along the western margin of the Tethyan orogenic belt, this crystalline basement lacks high-resolution analytical mapping (Shroder, 2014). As a result, the petrogenetic history, crystallization depths, and tectonic affinity of the Gaodara intrusive suites remain poorly understood, leaving a significant gap in the regional geological record of the country (Ruleman et al., 2007).

In modern engineering geology and industrial mineral rock evaluation, linking petrographic properties directly to physical and mechanical characteristics is essential (Bell, 2007). The engineering durability of an igneous rock depends on its mineral composition, crystal interlocking fabric, grain size distribution, and micro-fracture network (Tugrul & Zarif, 1999). For example, the presence of stable plagioclase frameworks and intergrown pyroxenes within gabbroic bodies typically gives the rock high compressive strength, low effective porosity, and high bulk density (Sousa, 2013). Conversely, secondary alteration processes like sericitization of feldspars, saussuritization of plagioclase, or structural micro-cracking drastically decrease mechanical performance and accelerate environmental weathering (Vernon, 2018). To verify if these rock suites are suitable for heavy infrastructure or industrial dimension stone, field observations must be backed by quantitative laboratory testing based on Archimedes' principle and precise density metrics (Waltham, 2009). Understanding how rock microstructures influence mechanical behavior is necessary to predict how these geological materials will perform under long-term engineering loads (ISRM, 2007; MacKenzie et al., 2017).

Beyond their engineering utility, sub-alkaline mafic complexes and associated country rock structures are primary targets for economic geology and mineral exploration (Robb, 2020). These differentiated plutonic rocks frequently host major magmatic ore systems, including chromium, nickel, copper, and iron deposits (Naldrett, 2004). The prominent surface iron oxidation and prominent gossan-like outcroppings observed in the Gaodara region suggest significant hydrothermal or late-stage magmatic mineralization related to fluid interactions between the main intrusion and the host formations (Peters et al., 2011). Fully unlocking this economic potential requires systematic geochemical fingerprinting (Pearce, 2008). Tracking major oxide concentrations, silica (SiO2) saturation thresholds, and elemental anomalies is necessary to clarify the magmatic history of the area and locate high-value mineralization pathways (Jenner, 1996; Barnes & Maier, 2016).

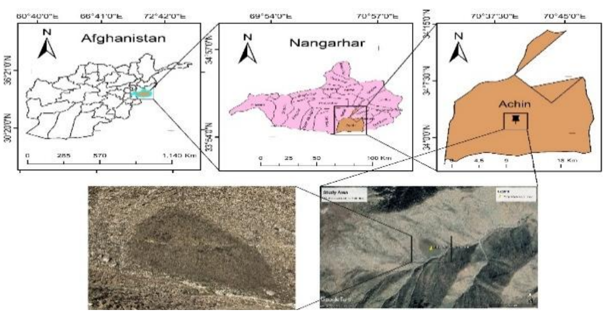
This study provides the first comprehensive, multi-analytical investigation into the petrographic, geochemical, and physical-mechanical properties of the tholeiitic to calc-alkaline rock suites in the Gaodara area of Achin District, Nangarhar Province. The research bridges the gap between fundamental petrology and applied engineering geology through three integrated objectives. First, it defines modal mineralogy, crystal interactions, and alteration states of both the olivine gabbro intrusions and tonalitic country rocks via transmission polarized-light microscopy using 0.03 mm thin sections. Second, it quantifies major and trace elements via X-ray Fluorescence (XRF) spectrometry to identify the chemical classification, sub-alkaline differentiation trends, and magmatic origin. Third, it measures key physical indicators, such as water absorption, bulk density, and specific gravity, to determine the rock's engineering durability and industrial value. Ultimately, this study aims to build a reliable scientific foundation that enhances the regional geological framework of eastern Afghanistan, while identifying critical resources for both infrastructural growth and strategic mining initiatives. [2]

## 2. Geograpy and geological location of Study Area

Achin District is situated roughly 55 kilometers southeast of Jalalabad City in Nangarhar Province. The district shares an international border with Pakistan to the south. Geographically, it covers 517 square kilometers, bound by coordinates 34°02′53″

N and 70°36’36” E. The specific zone of Gawdara sits 5.5 kilometers south of the central district office at an altitude of 1,870 meters above sea level. The Gaodara study area is situated within the Achin District, located in the southeastern quadrant of Nangarhar Province in eastern Afghanistan [ figure1] . Geographically, the area is characterized by rugged, mountainous terrain with field mapping observations recorded at an average elevation of approximately 1,870 meters above sea level. The climate of this region is typically semi-arid to arid, featuring hot summers and relatively cold winters, which influences the mechanical and physical weathering rates of exposed rock faces. The specific zone of interest is marked by high-density outcroppings showing extensive surface iron oxidation, with a primary magmatic exposure width of approximately 75 meters.

*Figure 1: Geographic and structural location maps of the study area showing (A) the regional position within Afghanistan, (B) the localization of Achin District in Nangarhar Province, (c) the specific bounds of the field site (D) high-resolution satellite imagery detailing the outcropping mafic intrusion footprint (E)*




highly strategic position along the western margin of the Tethyan orogenic belt. It sits directly within a complex geological intersection zone wedged between two major tectonic domains: the Kabul block and the Jalalabad block (Abdullah & Chmyriov, 2008). This regional architecture is heavily influenced by the ongoing northward convergence and collision between the Indo-Pakistan and Eurasian plates, which has produced a highly deformed metamorphic basement (Yin & Harrison, 2000). The localized fault systems and crustal sutures cutting through Nangarhar Province have facilitated the ascent of deep-seated alkaline and mafic intrusive complexes into the older Neoproterozoic and Paleozoic country rocks (Siehl, 2015; Ruleman et al., 2007). Consequently, the geographical and structural layout of the Gaodara area provides an ideal setting for investigating how active tectonic stress zones control magmatic emplacement and subsequent mineralization pathways (Shroder, 2014).

### *2.1 Geographic Coordinats and study area*

The precise spatial boundary of the Gaodara study area is constrained within the high-rugged zones of the Achin District, positioned between latitudes 34°02'N to 34°12'N and longitudes 70°38'E to 70°50'E. This zone represents a critical sector of the Spin Ghar mountain range, which flanks the southern boundary of Nangarhar Province along the international border with Pakistan (Shroder, 2014). The localized study grid specifically targets the outcroppings exposed at an absolute altitude of 1,870 meters above sea level. This high-elevation frontier is characterized by high topographic relief, steep structural slopes, and sharp V-shaped valleys resulting from active tectonic uplift and rapid fluvial incision.

To ensure high-precision structural tracking and reproducible data mapping across regional remote-sensing basemaps, eight specific sample locations were recorded during the field campaign using GPS tracking stations [figure2] (Ruleman et al., 2007). The primary exposure zone (Outcrop 1) is narrowly clustered along latitude 34°02'04'' N to 34°02'30'' N and longitude 70°38'04'' E to 70°39'60'' E, housing sample points A1, A2, A3, and A4. The secondary intrusive phase (Outcrop 2) is demarcated further northeast at 34°11'54'' N and 70°49'31'' E (Sample AB1). The host country rock framework directly surrounding these basic suites is structurally mapped via samples C1, C2, and C3, which lie between latitudes 34°02'05'' N to 34°02'11'' N and longitudes 70°38'52'' E to 70°39'07'' E.

Figure 2 geographical coordinates shown in google earth

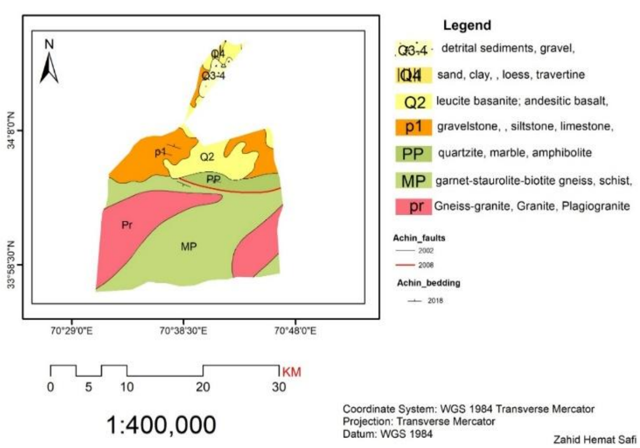
### *2.2 Stratigraphic and Lithological Framework*

Stratigraphically, the Gaodara area comprises a highly complex mixture of ancient metamorphic basement units and younger, intrusive igneous rocks. The basement rock framework is dominated by the Proterozoic to early Paleozoic metamorphic complexes of the Kabul-Jalalabad crystalline core, which includes high-grade gneisses, quartzites, amphibolites, and thick sequences of crystalline marbles (Siehl, 2015). These older metasedimentary and metaigneous country rocks show signs of regional upper-amphibolite to granulite facies metamorphism. The alkaline and mafic plutonic suites under investigation—later classified as olivine gabbros—represent discordant post-metamorphic or syn-tectonic bodies that cut directly through these highly folded basement layers. The contact zones between the intrusive mafic magma and the carbonate-rich country rocks often feature narrow zones of contact metamorphism and hydrothermal alteration. This alteration is visibly marked by the dense surface iron oxidation and gossanous horizons observed during field mapping (Peters et al., 2011).

### *2.3 Structural Geology and Tectonic Elements*

The localized structural geology of the Gaodara terrain is directly linked to the collision dynamics of the Indo-Pakistan plate squeezing against the Eurasian plate margin (Yin & Harrison, 2000). The study area is situated within a highly compressed tectonic corridor marked by dense faulting, shear zones, and tight crustal folding. A key structural driver in this area is the proximity to the active Spin Ghar Fault zone and the Chaman fault system (Treloar & Searle, 1993). These deep-seated regional strike-slip and reverse fault networks have created a highly fractured crustal environment. This extensive fracturing acted as high-permeability pathways that allowed deep mantle-derived alkaline melts to ascend and pool within the upper crust. The primary olivine gabbro exposure shows a high density of secondary joints and minor faults, which trend predominantly in a Northeast-Southwest direction. These structures match the dominant regional structural grain of eastern Afghanistan and provide the main pathways for late-stage, iron-rich mineralizing fluids (Ruleman et al., 2007).

Figure 3 Geological map of the study area




### **3. Materials and Methods**

A field sampling campaign was executed across two distinct outcroppings to log macroscopic parameters and collect representative rock specimens from the primary mafic intrusion and adjacent host formations. Eight samples were recovered based on lithological variability, documented with precise geographic coordinates (Table 1), and prepared for integrated laboratory characterization. Petrographic thin sections were fabricated by precision-slicing specimens into blocks using a diamond-blade saw at 8,000 rpm, followed by surface polishing with chromium abrasives, thermal drying at 105 °C, and mounting onto glass substrates with Canada balsam before grinding to a standard optical thickness of 0.03 mm. Whole-rock major oxide concentrations were quantified via X-ray fluorescence (XRF) spectroscopy utilizing a 90-second primary exposure window to capture secondary elemental emissions. Physical and geo-mechanical index properties were systematically evaluated using standard ASTM protocols. Water absorption capacity was determined by comparing oven-dried dry weight against 24-hour liquid-saturated weight, while bulk density and specific gravity were evaluated via hydrostatic displacement methods based on the Archimedean buoyancy principle.

*Table 1 Field Sampling Spatial Coordinate Matrix*

| *#S* | *S* **Group** | ***Latitude*** | ***Longitude*** |
|---|---|---|---|
| *A1* | Outcrop 1 | 34º 02´ 04´´ N | 70º 38´ 59´´ E |
| *A2* | Outcrop 1 | 34º 02´ 04´´ N | 70º 39´ 60´´ E |
| *A3* | Outcrop 1 | 34º 02´ 04´´ N | 70º 38´ 58´´ E |
| *A4* | Outcrop 1 | 34º 02´ 30´´ N | 70º 38´ 04´´ E |
| *AB1* | Outcrop 2 | 34º 11´ 54´´ N | 70º 49´ 31´´ E |
| *C1* | Host Country Rock | 34º 02´ 05´´ N | 70º 38´ 54´´ E |
| *C2* | Host Country Rock | 34º 02´ 05´´ N | 70º 38´ 52´´ E |
| *C3* | Host Country Rock | 34º 02´ 11´´ N | 70º 39´ 07´´ E |

## 4. Results and Discussion

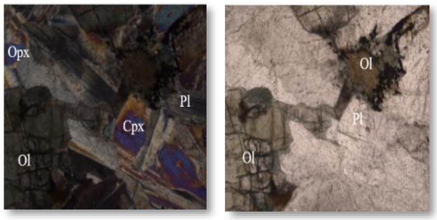
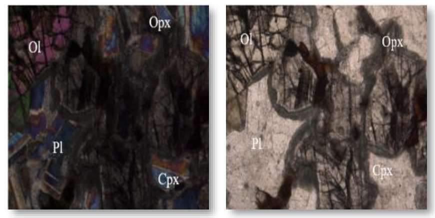
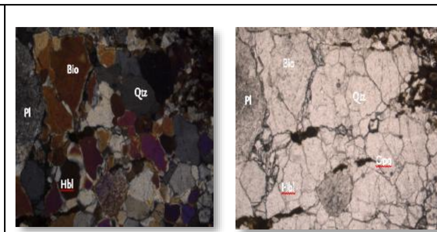
### *4.1. Petrographic Characterization and Mineralogy*

Thin-section petrographic analysis was conducted on eight rock samples collected from the Achin district (Gawdara area, Nangarhar province). The microscopic investigations under plane-polarized (PPL) and cross-polarized light (XPL) revealed that the primary framework-forming mineral assemblages consist of plagioclase, pyroxene (clinopyroxene/orthopyroxene), and olivine shown in [ table 2]

The structural configuration primarily exhibits an allotriomorphic to hypidiomorphic granular texture, typical of deep-seated intrusive mafic rocks. Distinct ophitic and poikilitic microstructures were documented, where idiomorphic plagioclase laths are partially or completely enclosed by larger pyroxene domains. Based on the mineral volume percentages and structural features, the rocks are definitively classified as Olivine Gabbro belonging to the plutonic mafic suite shown in [ figure 2]. Secondary alteration features, including minor uralitization of pyroxenes and saussuritization of plagioclase, indicate post-magmatic hydrothermal or low-grade metamorphic overprinting within the Spinghar tectonic complex.


*Figure 4 Field macroscopic analysis of the outcropping mafic bodies reveals intense chemical weathering along with distinct acoustic properties. Hand specimens display a prominent concentric reddish-brown oxidation rind enclosing a dense, unweathered core composed of fresh olivine gabbro. This weathering margin forms through the oxidation of primary ferromagnesian minerals and accessory magnetite, converting divalent iron into trivalent iron oxides like hematite or goethite upon sub-aerial exposure. When struck with a geological hammer, the highly compact crystalline core emits a sharp, high-pitched metallic ring, confirming the exceptional density, structural integrity, and low porosity of the fresh intrusive rock mass.*

*Table 2 Summary of petrographic features, primary mineral assemblages, and microstructural characteristics of the studied rock samples from the Gaodara area*

| | | |
|---|---|---|
|  |  |  |
| Sample A1 is an diorite gabbro collected from Outcrop 1, featuring a coarse-grained granular texture and a massive structure. Its primary mineral composition consists of plagioclase (labradorite and anorthite), pyroxenes (orthopyroxene and clinopyroxene), and olivine, with accessory chromite, magnetite, and ilmenite. Formed deep within a plutonic magmatic environment, this high-resistance rock possesses excellent mechanical strength highly suitable for structural construction purposes. | Sample AB1 is a plutonic olivine gabbro collected from Outcrop 2, characterized by a coarse-grained granular texture and massive structure. The primary mineral assemblage consists of plagioclase (labradorite and anorthite), pyroxenes (orthopyroxene and clinopyroxene), and olivine, accompanied by accessory chromite, magnetite, and ilmenite. Its deep magmatic origin imparts high structural strength, making this rock mass highly valuable for heavy construction applications. | Sample C1 is a tonalite recovered from the surrounding country rocks, exhibiting a fine- to medium-grained granular texture and a massive structure. The primary mineralogy comprises quartz, plagioclase, biotite, and hornblende, supplemented by accessory microcline, orthoclase, and epidote phases. Originating from a hypabyssal, intermediate magmatic environment, this rock type possesses high mechanical durability suitable for robust engineering and construction applications. |

### ***4.2. Geochemical Composition and Classification***

X-ray fluorescence (XRF) spectrometry was utilized to determine the major oxide and elemental variations within the sampled profiles. The geochemical analysis confirms the mafic/sub-alkaline character of the intrusive body. The mean silica (SiO_2) concentration was measured at 48.66%, which falls securely within the classic 45% - 52% threshold designated for basic/mafic magmatic complexes.

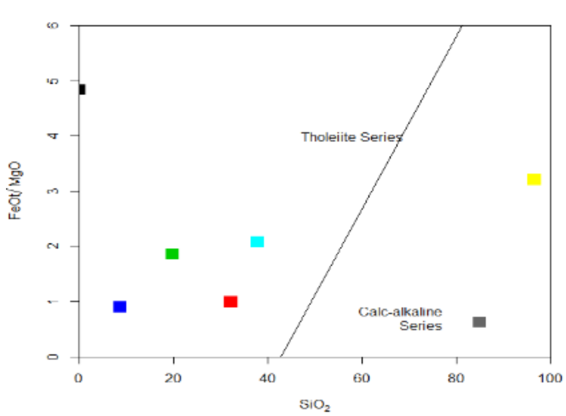
The elevated concentrations of iron oxides (Fe_2O_3 / FeO) and magnesium oxide (MgO) align with the visual macro-observations of strong surface oxidation and iron-staining across the outcropping blocks as shown in [table 4]. The chemical configuration suggests that the magmatic lineage originated from a mantle-derived tholeiitic to transitional alkaline magma stream, typical of a rifted or back-arc tectonic setting within the regional structural framework of eastern Afghanistan.

Table 3: The elemental weight percentages present a clear correlation with the previously established whole-rock major oxide configurations, highlighting the distinct chemical boundaries between the intrusive complex and the host rocks. Silicon (Si) acts as the primary differentiating factor, rising sharply from a range of 12.71% to 23.89% in the mafic suite (A-1 through AB-1) up to a maximum of 42.27% in the felsic country rocks (C-1 and C-2). Conversely, the ferromagnesian core indicators, Iron (Fe) and Magnesium (Mg), show heavy enrichment within the diorite gabbroic bodies, peaking at 10.63% Fe and 11.11% Mg in the highly primitive sample A-4 before dropping to near-negligible values under 1.1% in the surrounding country profiles. This clear chemical shift represents a classic calc-alkaline to tholeiitic separation, suggesting a multi-stage plutonic injection into an older, highly evolved silicate layer.

| Elements | A-1 | A-2 | A-3 | A-4 | AB-1 | C-1 | C-2 | C-3 |
|---|---|---|---|---|---|---|---|---|
| Si | 12.71 | 22.20 | 18.54 | 15.28 | 23.89 | 42.27 | 41.24 | 37.81 |
| Fe | 6.18 | 8.29 | 9.15 | 10.63 | 9.27 | 0.52 | 0.98 | 0.67 |
| Mg | 1.90 | 7.98 | 5.08 | 11.11 | 4.68 | 0.83 | 0.96 | 1.05 |
| Al | 0.94 | 4.31 | 4.33 | 4.50 | 6.71 | 6.19 | 6.26 | 7.20 |
| Ca | 4.95 | 7.30 | 5.17 | 9.03 | 3.42 | 0.53 | 0.76 | 1.66 |
| K | 0.07 | 0.64 | 0.50 | 0.70 | 0.41 | 3.71 | 2.57 | 25.12 |

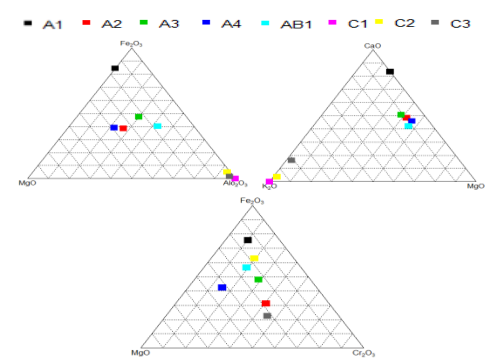
*Table 4: The major oxide distribution highlights a distinct bimodal compositional split between the intrusive suite and the surrounding country rocks. Samples A1 through AB1 represent normal-silica, mafic compositions characterized by high iron oxide and magnesium oxide concentrations, which peak at 18.31% and 20.70% respectively, confirming a classic diorite gabbroic profile. Conversely, country rock samples C1 through C3 exhibit highly evolved, felsic characteristics dominated by exceptionally high silica content up to 82.36% and elevated potassium oxide concentrations up to 4.09%. This extreme chemical divergence suggests that the sub-alkaline mafic pluton intruded into a pre-existing intermediate-to-felsic tonalitic host environment.*

| Oxides | A1 | A2 | A3 | A4 | AB1 | C1 | C2 | C3 |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 56.38 | 51.05 | 50.53 | 36.69 | 56.13 | 82.36 | 82.03 | 78.50 |
| $Fe_2O_3$ | 18.31 | 12.74 | 16.67 | 17.06 | 14.55 | 0.68 | 1.30 | 0.94 |
| MgO | 6.55 | 14.23 | 10.75 | 20.70 | 8.53 | 1.26 | 1.49 | 1.70 |
| $Al_2O_3$ | 3.66 | 8.75 | 10.43 | 9.55 | 13.92 | 10.65 | 11.00 | 13.21 |
| CaO | 14.37 | 10.98 | 9.22 | 14.19 | 5.26 | 0.68 | 0.99 | 2.26 |
| $K_2O$ | 0.17 | 0.83 | 0.77 | 0.95 | 0.54 | 4.09 | 2.90 | 2.95 |




**A) comparative diagram of SIO2**

*The classification of magmatic suites into tholeiitic and calc-alkaline series dates back to empirical studies in the 1920s, which are effectively differentiated using the AFM triangular diagram. Plotting these component total weight percentages reveals either the iron-enrichment Fenner trend for tholeiitic systems or the iron-depleted Bowen trend characteristic of calc-alkaline series. This critical magmatic evolution paths diverge based on initial oxygen*



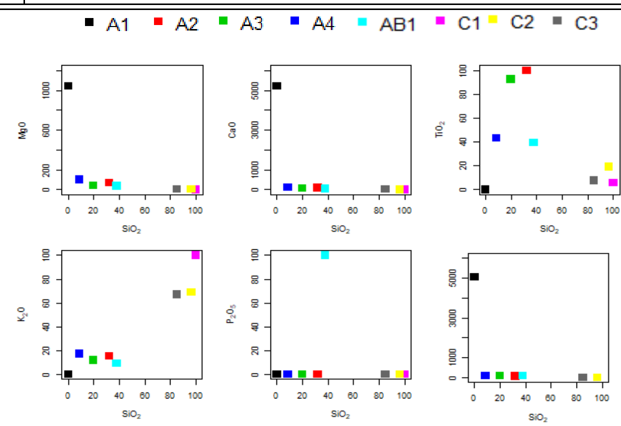

B) **comparative diagram of Trigonal oxides**

*The geochemical comparison reveals that aluminum oxide concentrations in the country rocks are significantly higher than iron oxide and magnesium oxide. While chromium, iron, and magnesium oxide percentages remain uniform across most profiles, they peak distinctively in sample C3, whereas potassium oxide dominates over magnesium and calcium oxides in samples C1, C2, and A1. Petrographic evidence identifies these host structures as felsic tonalites dominantly composed of quartz,*

| | |
|---|---|
| *fugacity and volatile concentration within the parent melt (Vermeesch & Pease, 2021). Consequently, early fractional crystallization of magnesium-rich silicates drives the tholeiitic trend, whereas early crystallization of magnetite under highly oxidizing conditions depletes iron, producing the calc-alkaline series as formalized by Miyashiro in 1975.* | *biotite, plagioclase, and hornblende. These mineral frameworks naturally concentrate light elements like aluminum and potassium over heavier ferromagnesian complexes, a distribution validated by the trends illustrated in Figure 4.5a and b (Käpyaho, 2006).* |

C) **comparative diagram of Geochemistry**

*The bivariate variation diagrams illustrate the geochemical correlation trends between silicon dioxide and various major oxides across the sampled rock suites. These Harker plots compare the relative distribution of magnesium oxide, calcium oxide, titanium dioxide, potassium oxide, phosphorus pentoxide, and chromium oxide against shifting silica concentrations. The geochemical dispersion effectively distinguishes the primitive, low-silica mafic profiles from the highly evolved, silica-rich compositions of the country rocks. These distinct evolutionary pathways reflect the magmatic differentiation and fractional crystallization processes governing the entire intrusive complex.*




### *4.3. Physico-Mechanical Evaluation*

The geotechnical suite of testing targeted the physical integrity, structural compactness, and durability traits of the Olivine Gabbro specimens.

Water Absorption (W%): The samples demonstrated exceptional structural density, yielding an average water absorption capacity of only 0.13%. This low value implies negligible interconnected porosity, minimizing vulnerability to frost wedge action and chemical weathering.

Bulk Density (D_s): The average bulk density reached 3.06 g/cm³ (g/ml) which is shown in [table 5]. This high value correlates directly with the abundance of high-mass ferro-magnesian minerals (pyroxenes, olivine, and accessory magnetite) identified in the petrographic sections.

Specific Gravity (SG): The average specific gravity was calculated via Archimedean principles to be 3.07.

The combined mechanical matrix indicates a highly compact, robust rock mass with substantial compressive strength, making these geological formations highly valuable from both economic deposit extraction and industrial engineering standpoints.

Table 5 summary of the physical & Mechanical analysis (specific gravity, Density & water absorption)

| *#S* | *TOW(C)* | *W1 (gr)* | *W2(gr)* | *W3(gr)* | *SG* $(\frac{w1}{W2-W3})$ |
|---|---|---|---|---|---|
| *A2* | 20 | 513.6 | 514.2 | 348.4 | 3.09 |
| *A3* | 20 | 323 | 323.4 | 214.6 | 2.96 |
| *A4* | 20 | 240 | 240.2 | 164.4 | 3.17 |
| *C2* | 20 | 400.2 | 402.2 | 248.6 | 2.60 |
| *C3* | 20 | 288.2 | 289.8 | 177.8 | 2.57 |

The physical and mechanical testing results summarize here which indicate a distinct contrast in specific gravity between the gabbroic intrusive samples and the surrounding country rocks. Within the intrusive suite, sample A4 exhibits the highest specific gravity at 3.17, while sample A3 displays the lowest at 2.96, yielding an overall mean value of 3.07 for the primary outcrop profiles. Conversely, the tonalitic country rocks show lower structural densities, with sample C2 measuring 2.60 and sample C3 dropping to 2.57, establishing a host-rock average of 2.585. As graphically demonstrated in Figure 4.6 and Figure 4.9, these specific gravity variations are directly proportional to bulk density while maintaining an inverse relationship with the total water absorption capacity.

| ***#S*** | ***MASS (GR)*** | ***W1(ML)*** | ***W2(ML)*** | ***VG=W2 - W1(ML)*** | ***DS=M/VG(GR/ML)*** |
|---|---|---|---|---|---|
| **A2** | 340.8 | 700 | 810 | 110 | 3.09 |
| **A3** | 414.4 | 700 | 830 | 130 | 3.0 |
| **A4** | 321.6 | 700 | 810 | 110 | 2.92 |
| **C2** | 408.2 | 700 | 858 | 158 | 2.58 |
| **C3** | 251.6 | 700 | 797 | 97 | 2.59 |

Density ( Volume gravity(vg) VG=W2-W1(ml)), ( Density of the stone DS=M/VG(gr/ml))

The geo-mechanical density evaluation reveals a significant contrast between the heavy intrusive rock suite and the lighter host formations. Samples A2 through A4 exhibit elevated density values ranging from 2.92 g/ml to a maximum of 3.18 g/ml, which directly reflects the high-mass ferromagnesian mineral concentrations identified during petrographic analysis. In contrast, the country rock samples C2 and C3 demonstrate lower structural densities, clustering tightly around an average of 2.585 g/ml due to their highly evolved quartz-feldspathic framework. These findings, derived via standard fluid displacement measurements, confirm the excellent compactness and superior structural strength of the mafic intrusive formations relative to their host environment.

| *#S* | *TOW(C°)* | *W1(gr)* | *W2(gr)* | *Absorption (%)* $(W2-W1)/W1\ 100$ |
|---|---|---|---|---|
| *A2* | *20* | *234* | *234.2* | *0.08* |
| *A3* | *20* | *457* | *458* | *0.21* |
| *A4* | *20* | *590.6* | *591.2* | *0.1* |
| *C2* | *20* | *572.2* | *574.8* | *0.45* |
| *C3* | *20* | *462.6* | *465.4* | *0.6* |

*The water absorption laboratory testing indicates exceptionally high structural compactness and low porosity across all investigated samples, with a clear distinction between the rock groups. The mafic intrusive units (A2 through A4) display negligible water absorption values ranging from 0.08% to 0.21%, highlighting a tightly interlocking crystalline fabric with minimal interconnected pore spaces. Conversely, the country rocks (C2 and C3) exhibit slightly elevated absorption rates of 0.45% and 0.60%, respectively. This minor increase aligns with the lower structural densities of the host formations and indicates a more open microstructural network. Overall, the sub-1% absorption values across the entire suite confirm excellent resistance to moisture-induced degradation, making the intrusive gabbroic bodies particularly suitable for high-durability industrial and construction applications.*

## 5. Conclusion

The integrated petrographic, geochemical, and geo-mechanical evaluation of the Gaodara crystalline exposures in Achin District, Nangarhar Province, establishes a highly constrained, sub-alkaline bimodal magmatic complex consisting of a tholeiitic olivine gabbro intrusion situated within a calc-alkaline tonalitic basement. Polarized-light microscopy and X-ray fluorescence spectrometry validate this bimodal framework, detailing a sharp chemical divergence where the primitive, coarse-grained gabbroic core exhibits low silica down to 36.69 wt.% alongside high ferromagnesian oxides (up to 20.70 wt.% MgO and 18.31 wt.% $Fe_2O_3$), while the host tonalites reflect a highly evolved silica-rich profile reaching 82.36 wt.% $SiO_2$. Geotechnical laboratory metrics confirm that these crystalline microstructures directly dictate the engineering durability of the rock mass, with the dense interlocking fabric of the gabbro yielding an elevated mean bulk density of 3.06 g/ml, a specific gravity of 3.07, and an exceptionally low water absorption capacity of 0.13%. Ultimately, these physical and chemical parameters demonstrate excellent structural integrity and minimal micro-porosity, establishing this high-resistance, low-porosity magmatic formation as an ideal, long-term geological resource for heavy infrastructure, industrial dimension stone, and heavy construction applications.

## 6. Suggestions

To further advance the understanding of the Gaodara bimodal crystalline complex, future research should prioritize high-precision U-Pb zircon isotopic dating to determine the exact absolute crystallization age of these rock assemblages. Geochemical modeling utilizing trace and rare earth elements is required to define mantle source characteristics and magma melting depths, which should be coupled with mineral geothermobarometry calculations to resolve upper-crustal emplacement pressures and temperatures. Finally, expanding the field mapping boundaries will help clarify contact metamorphic margins and potential structural pathways for economic mineralization, while destructive unconfined compressive strength testing on rock core specimens will provide definitive engineering design data for industrial construction applications.

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