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EVALUATING MANSEHRA DOLERITE, NORTHERN PAKISTAN FOR HIGH PERFORMANCE CONCRETE APPLICATIONS: INSIGHTS FROM ENGINEERING AND PETROGRAPHIC CHARACTERISTICS

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ABSTRACT

The growing demand for durable high-performance concrete has highlighted the need for high quality coarse aggregates with strong mechanical and suitable mineralogical properties. In this study, the engineering and petrographic properties of Mansehra Dolerite (MD), a mafic intrusive rock from northern Pakistan, are investigated to evaluate its suitability as a high-strength aggregate for durable infrastructures. A total of 40 representative rock samples were collected from three key regions: Tanawal Area (Group A), Plura Area (Group B) and Oghi Area (Group C). The petrographic analysis of 25 samples from these three groups confirmed the doleritic nature of the rock, characterized by a dominant plagioclase (30–60 %) and clinopyroxene (20–40 %), with accessory orthopyroxene, hornblende, opaque minerals, and minor biotite, quartz, and chlorite. The rocks exhibit typical ophitic to sub ophitic textures with occasional porphyritic features, indicating slow crystallization in an intrusive environment. Petrographic screening indicates low Alkali Silica Reaction (ASR) potential; however, definitive confirmation requires performance based expansion testing standardized by American Society for Testing and Materials (ASTM C1260 and/or ASTM C1293/C1293M), which was not conducted in this study. The engineering tests revealed that the MD aggregates have excellent physical and mechanical properties, including low porosity (0.51–2.80 %), minimal water absorption (0.16–0.96 %), high specific gravity (up to 3.25), and high resistance to impact, crushing, abrasion, and weathering. Group A (Tanawal) samples consistently showed the highest quality, with the lowest impact strength value (4.1–10.5 %) and the lowest abrasion loss (8.5–13.4 %), making them particularly suitable for construction and heavy concrete applications. These results indicate that Mansehra dolerite is a mechanically competent aggregate source, and petrographic observations suggest low ASR potential; Group A material shows the most favorable overall indices for high-strength concrete applications.

1. INTRODUCTION

Globally, the quality of construction materials used in major infrastructure projects such as dams, highways, and bridges are a critical determinant of structural durability, long-term performance, and lifecycle cost efficiency. Selecting materials with superior mechanical and durability properties is essential for ensuring the safety and sustainability of such large-scale developments under varying environmental and loading conditions (Simões, 2024). These coarse aggregates play a vital role in high strength concrete (HSC), influencing not only its mechanical properties but also its long-term stability and resilience (Vishalakshi et al., 2018). Conventionally, coarse aggregates in concrete have been used in the form of various local lithologies, such as limestone, sandstone, and river gravels (Eziefula et al., 2020). Nevertheless, increasing field performance and laboratory testing data have shown that these materials have significant shortcomings, particularly in terms of durability under harsh environmental conditions (Chan et al., 2023; Liu and Tia, 2012). Among the most urgent issues is the alkali-silica reaction (ASR), a harmful chemical reaction between reactive silica in aggregates and the alkalis in cement paste, which causes expansion, cracking, and ultimate failure of concrete structures (Luo and Nagai, 2024; Souza et al., 2016). In addition, Alkali Aggregate Reactions (AAR) potential remain a critical concern for long-term structural performance of infrastructures which generally occur due to the presence of unstable or deleterious minerals in the aggregates which lead to internal expansion, map cracking, spalling, and strength reduction over time (Karthik et al., 2020; Luo et al., 2022). Therefore, the rock aggregates with stable and low reactive mineralogical compositions like dolerite, dunite and limestone etc. offer high resistance to AAR (Ismaeel et al., 2019; Lukschová et al., 2009). This resistance enhances its suitability for high performance concrete applications, especially in critical infrastructure where long-term durability is paramount.

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The northern Pakistan holds significant potential for the dam projects due to availability of ample water resources, suitable topography and favorable geology. Among the several major dam projects in Northern Pakistan, many were constructed by using ASR susceptible aggregates which now facing serious challenges such as seepage, microcracking, and structural degradation (Chaudhry et al., 2021; Majid, 2013). The northern areas of Pakistan generally crop out thick column of igneous of and metamorphic rocks diverse geological settings with some shallow marine sedimentary succession which is found along the lower reaches of Himalayan ranges (Khan et al., 2021; Zafar et al., 2023). The majority of rocks found in the upper reaches of Northern Pakistan, particularly those utilized in construction and infrastructure projects, are geologically young and frequently contain reactive forms of silica which makes them susceptible to ASR whereas lower reaches are dominantly comprised of various excellent sedimentary aggregates without deleterious mineral constituents (Hussain et al., 2025; Ullah et al., 2024). In parallel, recent advances in advanced cementitious composites (e.g., engineered cementitious composites and self-healing SMA-reinforced systems developed for aggressive freeze–thaw and chloride environments) reinforce that long-term performance depends on tight crack control and robust constituent materials, including durable, low-absorption aggregates. Accordingly, reliable petrographic and physico-mechanical qualification of local mafic aggregates (such as Mansehra Dolerite) remains directly relevant to high-performance concretes and abrasion-/impact-prone hydraulic infrastructure (Umar et al., 2024; Qian et al., 2024; Umar et al., 2025a; Umar et al., 2025b; Umar et al., 2025c).

The present study offers a comprehensive evaluation of the petrographic and engineering properties of Mansehra Dolerite, focusing on its suitability for high-strength concrete to meet the increasing demand of high strength aggregate due to construction of various Hydropower Projects in the Mansehra and adjoining regions.

2. GEOLOGY OF STUDY AREA

The Mansehra Region (Fig. 1) of Khyber Pakhtunkhwa Province, Northern Pakistan is geologically located in the Northern Metamorphic Zone of Lesser Himalayas and falls in the domain of Upper Indus River Basin. The Siran River, Ichrian Nala and Kunhar River are the major streams of the region with enormous Hydropower potential, which ultimately drained into Indus River along the western boundary of the region. The region is geologically characterized by a thick sequence of Precambrian pelite-psamite sequence of Tanawal Formation further intruded by Paleozoic granites (Baig, 1990). Tanawal Formation mainly consists of schists and quartzite with rare conglomerates (Calkins et al., 1975). The granitic rocks are further classified into three distinct groups including Mansehra Granite (MG), Susalgali Granite Gneiss (SGG) and Hackle Granite (HG). The MG is porphyritic, characterized by the large phenocrysts of K-feldspar and mainly consists of feldspar and quartz with minor biotite and muscovite. SGG is similar in mineralogy and show gneissic texture whereas HG is nonporphyritic (Naeem et al., 2021). The pelite-psamite sequence and granitic rocks are further intruded by dolerite dykes. Dolerite is brown to yellowish brown at surface and dark grey to blackish grey appears on fresh surface (Figs. 2A and 2B). It is frequently hard and massive. It is frequently medium to coarse grained with grain size ranging from 0.5 mm to 5 mm. Quartz veins cut the dolerite at places (Fig. 2C). Dykes are generally devoid of discontinuities but are often fractured at places (Fig. 2D). The thickness of dolerite dykes varies from 5 m to 8 m with variable distribution ranging from few tens' meters to hundreds of meters (Fig. 1).

3. MATERIALS AND METHOD

3.1. SAMPLE COLLECTION AND ANALYSIS

Forty dolerite samples were taken in three different geological locations of the Mansehra Region of Northern Pakistan (Fig. 1) including Tanawal (Group A), and Phulra (Group B), Oghi (Group C). To conduct petrographic analysis, 25 representative samples were selected, and thin sectioned at the Rock Cutting Laboratory, Institute of Geology, University of the Punjab, Lahore. Thin sections were studied at Mineralogy Laboratory, Institute of Geology under polarizing microscope to determine the mineralogical composition, textural characteristics, and microstructural properties of the dolerite as per instructions of ASTM C295 (Noushini and Castel, 2018). Petrographic examination was carried out following ASTM C295/C295M. Performance-based ASR expansion testing (Accelerated Mortar Bar Test, ASTM C1260; and Concrete Prism Test, ASTM C1293/C1293M) was not performed in the present study; therefore, ASR non-reactivity is inferred from petrographic criteria and published mineralogical/geochemical context, and should be confirmed by C1260/C1293 where required by project specifications.

3.2. ENGINEERING TEST ANALYSIS

The engineering properties of MD were characterized through a comprehensive series of laboratory tests, including the Los Angeles abrasion test, soundness test, water absorption, specific gravity, porosity, flakiness index, elongation index, aggregate impact value (AIV), and aggregate crushing value (ACV). All tests were conducted in accordance with ASTM standards to ensure accuracy, reliability, and comparability of the results. For the relationships presented in Figure 6, simple linear regression was applied, and the coefficient of determination (R^2) was calculated and reported on each plot.

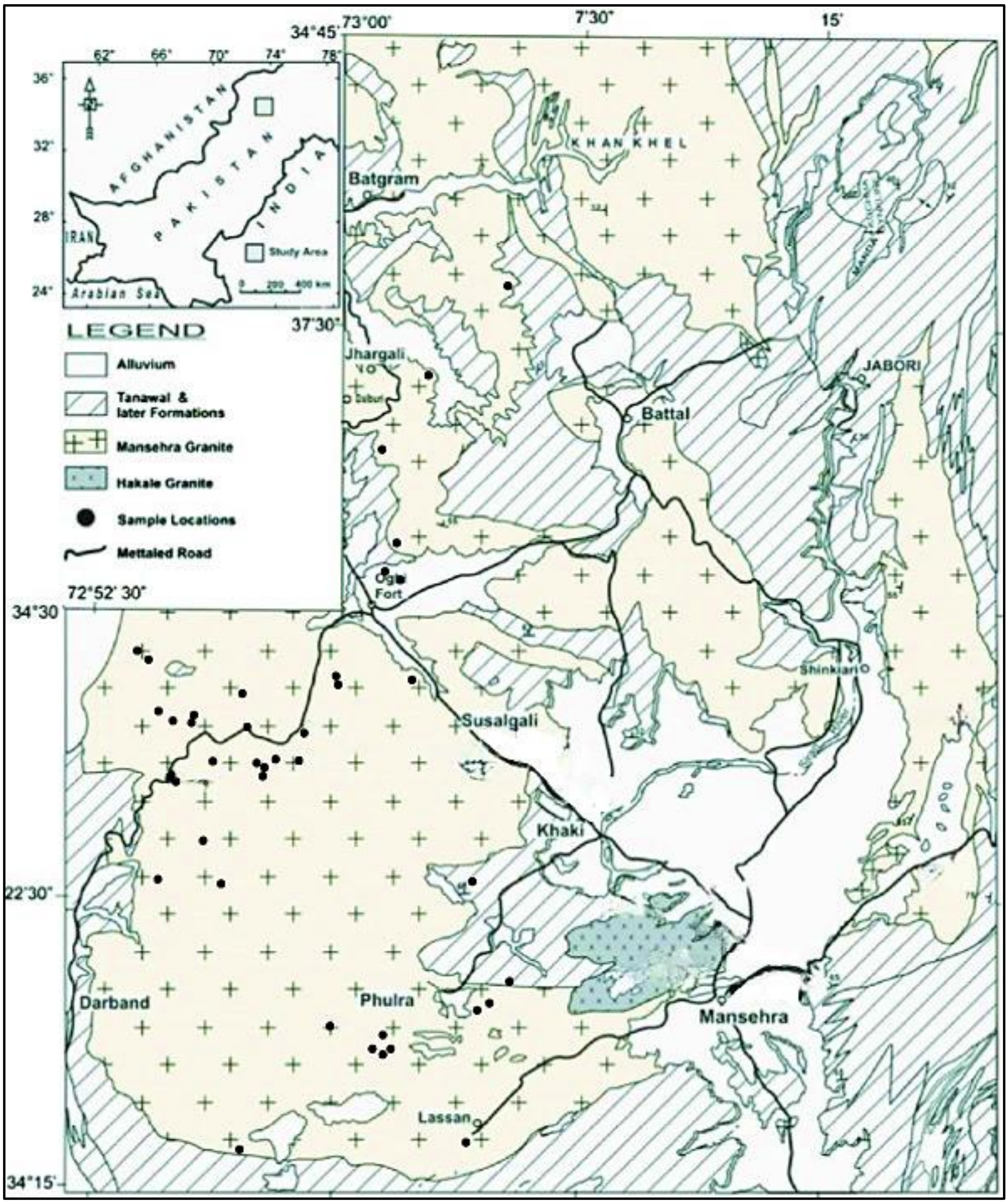

Fig. 1 Geological map of the Mansehra Region (modified after Shams, 1967) with sample collection sites.

3.2.1. LOS ANGELES ABRASION (LA) VALUE

The Los Angeles abrasion machine was used to test abrasion resistance as per ASTM C131 (ASTM, 2006). A measured amount of aggregate was put in a rotating drum with steel balls and rotated a certain number of times. The LA value was recorded as the percentage of material that passed through a sieve after the test. The lower the values, the greater the abrasion resistance, which is necessary in concrete dams and roads that are subjected to mechanical abrasion.

3.2.2. SOUNDNESS

Soundness testing was conducted by sodium sulfate cycles, according to ASTM C88 (ASTM, 2013). To mimic the effects of weathering, including freeze-thaw cycles, aggregates were soaked and dried in a sodium sulfate solution multiple time. The mass loss was determined after a certain number of cycles. The low values of soundness loss are a sign of high resistance to physical and chemical weathering, which increases the durability of the aggregate in exposed or submerged conditions.

3.2.3. WATER ABSORPTION

The water absorption was determined according to ASTM C127 (ASTM, 2015). The aggregates were oven-dried and cooled and then placed in water for 24 hours. The weight gain caused by water absorption was measured and reported as a percentage of the dry weight. The low absorption values (usually <1 % in

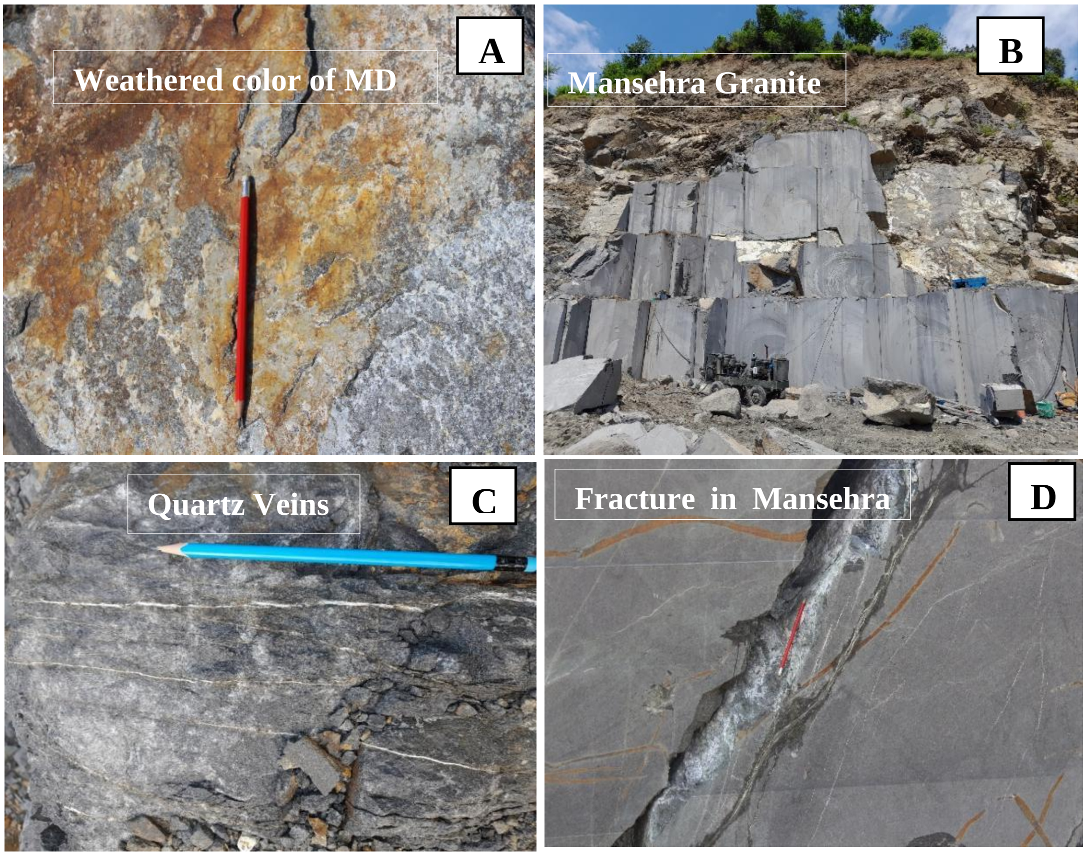

Fig. 2 Field photographs: (A) The Mansehra dolerite displays reddish-brown coloration in the form of reaction rings of secondary iron-bearing minerals (B) Showing upper contact between Mansehra Granite and Mansehra Dolerite in the study area (C) White quartz veins having 1 to 3 mm thickness at Nambal Katha area (D) Showing fracture in Mansehra Dolerite at Quarry site.

MD samples) reflect lower porosity and better resistance to moisture ingress, which is critical to long-term performance in submerged or saturated environments like dam structures.

3.2.4. SPECIFIC GRAVITY

The pycnometer method was used to measure specific gravity of coarse aggregates according to ASTM C127 (ASTM, 2015). This parameter indicates the density and quality of the aggregate material. The greater the specific gravity, the stronger and more durable the aggregates. The results were given as apparent, bulk (oven-dry), and bulk (saturated surface dry) specific gravity.

3.2.5. POROSITY

Saturation and buoyancy method were used to determine porosity. Aggregates were dried in an oven at 105 °C 24 hours and then immersed in water 24 hours (Neville, 1995). The pore volume was calculated as the difference between the dry and saturated weights and porosity was given as a percentage of the total volume. This test assists in determining the estimation of the void spaces in the aggregate, which is a very important indicator of durability and permeability.

3.2.6. FLAKINESS INDEX

British Standards (BS) 812 Part 105.1 was used to determine the flakiness index (No, 1992). The aggregates were sieved using a slotted gauge to determine the flaky particles, which were weighed and given as a percentage of the total sample. Concrete made with aggregates of low flakiness indices has improved compaction, strength, and workability.

3.2.7. ELONGATION INDEX

The BS 812 Part 105.2 (No, 1992) standard was used to measure the elongation index. The aggregate particles that were retained on certain sieves were put through a length gauge and the elongated particles weighed. The reduced elongation index will provide a better interlocking of the aggregate particles and minimize the chances of weak areas in concrete structures.

3.2.8. AGGREGATE IMPACT VALUE (AIV)

The Aggregate Impact Value test was used to determine the impact resistance of the MD aggregates in accordance with BS 812 Part 112 (BSI, 1990). One sample was hit 15 times with a normal hammer that was dropped at a constant height. The weight of the material that passed through a 2.36 mm sieve was

Table 1 The model mineralogical composition of Mansehra Dolerite (vol. %).

Sample	PG	CX	OR	Opaque	HB	Quartz	Biotite	Chlorite	Serpentine
A-1	55	30	5	3	5	0	2	0	0
A-2	55	25	6	4	6	0	2	0	2
A-3	55	25	15	3	0	2	0	5	0
A-4	35	35	10	5	7	0	3	3	0
A-6	50	30	10	3	7	0	2	0	0
A-7	60	25	5	5	4	0	1	0	0
A-8	55	5	30	4	5	0	1	3	0
A-9	41	27	13	7	10	0	2	0	0
A-10	42	30	15	5	5	0	2	0	0
A-11	42	22	25	2	5	1	1	0	0
A-12	50	35	5	2	7	0	1	0	0
A-13	35	27	10	5	4	0	2	0	0
A-14	50	20	18	2	7	0	2	0	0
A-15	55	23	15	2	7	0	1	2	0
A-19	53	30	5	4	5	0	2	0	0
A-21	50	30	10	3	5	0	2	0	0
B-1	35	30	10	5	15	0	2	0	0
B-2	40	25	12	5	5	0	2	2	0
C-1	45	25	15	5	10	0	0	0	0
C-2	30	40	20	2	5	0	2	0	0
C-3	52	25	10	3	8	0	2	0	0
C-4	45	25	15	5	4	0	2	2	0
C-5	55	22	15	4	4	3	2	0	0
C-6	46	26	15	3	6	0	2	0	0
C-7	55	20	12	4	7	0	1	0	3
A mean ± SD (n=16)	48.9 ± 7.6	26.2 ± 7.1	12.3 ± 7.3	3.7 ± 1.4	5.6 ± 2.1	0.2 ± 0.5	1.6 ± 0.7	0.8 ± 1.6	0.1 ± 0.5
B mean ± SD (n=2)	37.5 ± 3.5	27.5 ± 3.5	11.0 ± 1.4	5.0 ± 0.0	10.0 ± 7.1	0.0 ± 0.0	2.0 ± 0.0	1.0 ± 1.4	0.0 ± 0.0
C mean ± SD (n=7)	46.9 ± 8.7	26.1 ± 6.5	14.6 ± 3.1	3.7 ± 1.1	6.3 ± 2.2	0.4 ± 1.1	1.6 ± 0.8	0.3 ± 0.8	0.4 ± 1.1

PG* Plagioclase, OR* Orthopyroxene, Hornblende HB*, CX* Clinopyroxene

Group (Locality)	Plagioclase (PG)	Pyroxenes (CX + OR) *	Opaques
A (Tanawal)	35–60	30–47	2–7
B (Plura)	35–40	37–40	5–5
C (Oghi)	30–55	32–60	2–5

determined and AIV was determined. The lower percentages of AIV are associated with improved resistance to sudden shock or impact, which is preferable in high-load structures.

3.2.9. AGGREGATE CRUSHING VALUE (ACV)

The ACV test was carried out to determine the compressive strength of the aggregates under a load that is applied gradually as specified in BS 812 Part 110 (BSI, 1990). The test was conducted by subjecting a cylindrical sample of aggregate to a standard load and recording the volume of material crushed to a size less than 2.36 mm. The lower the ACV, the greater the crushing resistance, and the greater the structural integrity of concrete in high-strength applications.

4. RESULTS

4.1. PETROGRAPHIC ANALYSES OF MANSEHRA DOLERITE

In this study, 25 representative thin sections of MD samples were prepared and examined under a polarizing microscope at various magnifications to document their mineralogical and micro-structural characteristics. The petrographic analyses show that Mansehra Dolerite is essentially composed of plagioclase and clinopyroxene with minor quantities of orthopyroxene, hornblende, quartz, biotite, olivine, magnetite, and secondary alteration products such as chlorite and serpentine (Table-1).

Plagioclase content ranges from 30 % to 60 % by volume, while clinopyroxene makes up approximately 20 % to 40 % (Figs. 3A and 3B). Orthopyroxene constitutes 5 % to 30 % (Figs. 3A and 3B) with opaque minerals (magnetite and ilmenite) ranging from 2 % to 7 % (Fig. 3C). Hornblende is present in amounts between 4 % and 15 %, whereas quartz, biotite, chlorite, and serpentine are all generally minor phases (0 %–5 %) (Table 1). Texturally, the dolerite exhibits a well-developed ophitic texture, which is characteristic of shallow intrusive igneous bodies (Fig. 3B). In this texture, large subhedral to euhedral crystals of plagioclase are enclosed by pyroxene

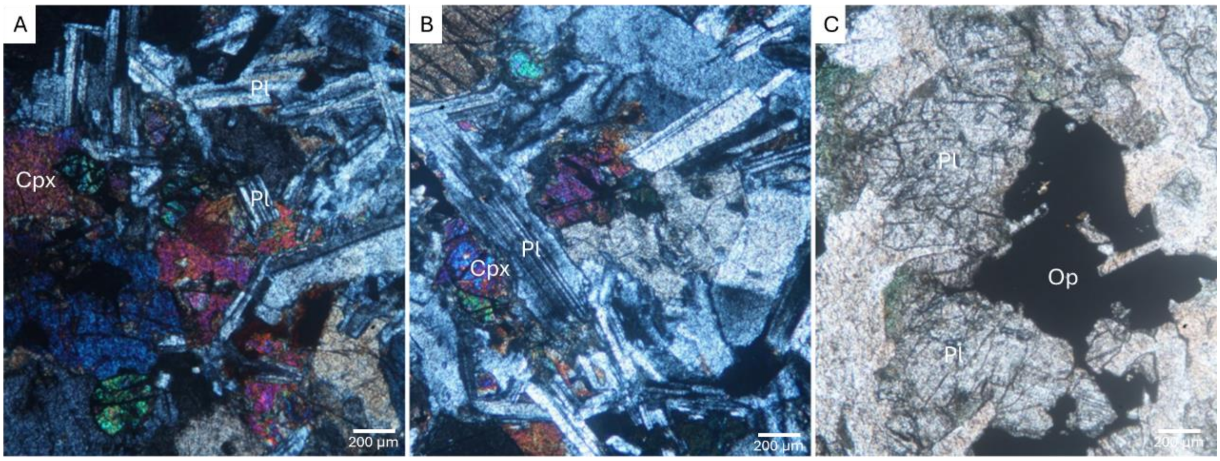

Fig. 3 Microphotographs showing mineralogical and textural features in Mansehra Dolerite; (A) Plagioclase laths (grey crystals) and Pyroxene crystals (coloured minerals) in Mansehra Dolerite (B) Pyroxene in between the plagioclase laths showing ophitic texture in Mansehra Dolerite (C) Opaque minerals (black crystals) in Mansehra Dolerite.

crystals, indicating crystallization at moderate depths under relatively slow cooling conditions. This ophitic texture demonstrates the intrusive nature of the dolerite and is consistent with crystallization from a mafic magma at shallow levels. In some samples, porphyritic textures are observed, where phenocrysts of plagioclase and pyroxene are embedded in a finer-grained groundmass. This bimodal texture is interpreted as evidence of a complex cooling history, possibly involving multiple pulses of magma or varying depths of crystallization during emplacement. The modal mineralogy of the studied samples varies within a relatively narrow range, indicating mineralogical consistency across the sampled dykes (Table 1 and Fig. 4). However, some variability exists across the different sample locations and to assess the mineralogical variability of the Mansehra Dolerite (MD) across different geographic localities, three distinct groups were assembled on basis of similar modal compositions including Group A (Tanawal area), Group B (Plura area), and Group C (Oghi area).

Additionally, signs of low-grade metamorphism and alteration are locally present. Some thin sections display secondary minerals such as chlorite and serpentine, resulting from alteration of primary mafic phases. These alteration products indicate the influence of post-emplacement hydrothermal processes and/or weathering.

These microtextural features also have engineering implications. In dolerites, increasing proportions of secondary alteration minerals are commonly associated with higher absorption/porosity and reduced strength and abrasion resistance, whereas relatively fresh textures tend to retain better physico-mechanical performance (Rigopoulos et al., 2010). Microcracks (cooling, tectonic, or weathering induced) act as stress concentrators and preferential transport pathways and can measurably reduce rock stiffness and strength (Griffiths et al., 2017). More generally, cracks often initiate and/or propagate along mineral interfaces; therefore, the condition and chemistry of grain boundaries can modulate fracture processes in polycrystalline materials (Dehm and Cairney, 2022).

Overall, the petrographic features of the Mansehra Dolerite indicate a robust mineralogical framework with coarse-grained crystalline textures favourable for engineering applications. This petrographic interpretation is consistent with published regional whole-rock geochemical data for Mansehra–Oghi dolerites, which report a mafic composition (SiO_2 ≈ 47–49 wt.%) and engineering-relevant density values (SG ≈ 3.2), supporting the plagioclase–pyroxene dominance observed here (Ismaeel et al., 2019; Jadoon et al., 2019). The absence in thin section of recognized reactive silica constituents (e.g., opal/chalcedony/volcanic glass) suggests a relatively low ASR potential for MD, noting that confirmation by standardized ASR testing is recommended where required by project specifications.

4.1.1. LITHOLOGICAL VARIATIONS IN MD

Group A Tanawal comprises samples (T1-T16) representing the Tanawal region. The dominant mineral in these samples is plagioclase, ranging between 35 % and 60 %, with most samples consistently above 50 %. Clinopyroxene is the second most abundant mineral, generally ranging from 22 % to 35 %, indicating a classic mafic composition (Fig. 4). Orthopyroxene is present in variable amounts, from as low as 5 % to as high as 30 %, suggesting heterogeneity in crystallization conditions or magma differentiation stages. Minor but significant quantities of hornblende (4 %–10 %) are present in most samples, contributing to the rock's durability and resistance to weathering. Opaque minerals, mostly magnetite and ilmenite, are consistently observed in

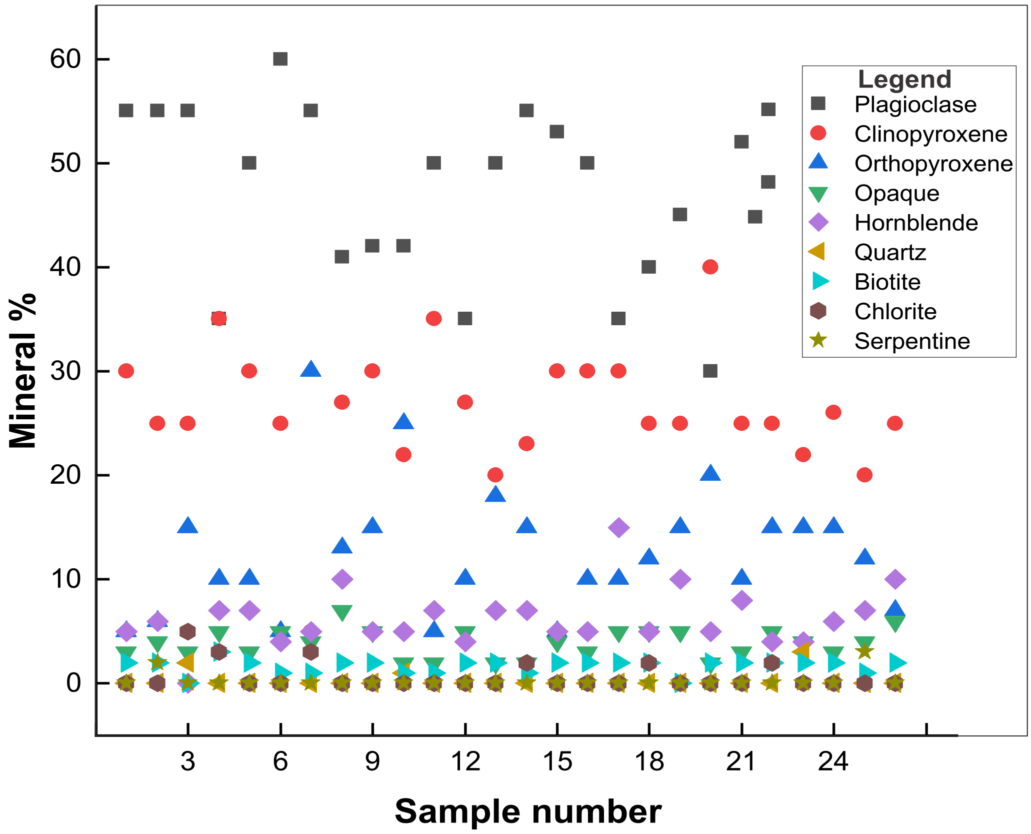

Fig. 4 Scatter plots showing minerals % of the studied samples of Mansehra Dolerite.

small amounts (2 %–7 %). Biotite (1 %–3 %) appears sporadically, and some samples, notably A-3 and A-4, show traces of chlorite and quartz, suggesting minor alteration. A few samples also record serpentine, indicating post-magmatic hydrothermal influence, but only in negligible amounts (up to 2 %). Overall, the Tanawal dolerite is mineralogically mature, with well-balanced plagioclase and pyroxene phases. The low presence of quartz and reactive silica phases reinforces its classification as non-ASR-prone, supporting its suitability for use in high-performance and dam-related concrete. Group B (Plura B1 to B2) includes two samples of Plura region. These samples show a moderately altered mineral assemblage, with plagioclase contents around 35 %–40 % and clinopyroxene between 25 % and 30 %. Orthopyroxene remains significant at 10 %–12 %, and hornblende is notable in B-1 at 15 %, indicating a hydrous crystallization environment or sub-solidus alteration. Biotite and opaque minerals maintain their typical range of 2 %–5 %, while minor chlorite is also present.

The relatively low quartz content and absence of reactive silica minerals again support its use in concrete applications. The higher hornblende content in B-1 suggests this sample may have crystallized at shallower depths or under more hydrous conditions compared to those in Group A. Although the number of samples in Group B is limited, their mineralogical consistency aligns with the broader MD characteristics observed in the Tanawal group, with only minor variations in pyroxene and amphibole content. Group C (Oghi) covers samples C-1 through C-7. The plagioclase content in these samples generally falls within 30 %–55 %, slightly lower than in Group A, and reflects more evolved compositions in some cases. Clinopyroxene ranges from 20 % to 40 %, with orthopyroxene present in moderate amounts (10 %–20 %). Hornblende is typically present at 4 %–10 %, while biotite, opaque minerals, and chlorite follow the same minor patterns as seen in other groups. Interestingly, Sample C-5 contains minor quartz (3 %), the highest observed in the dataset. Petrographic examination did not reveal obvious reactive silica constituents in thin section. The Oghi samples exhibit slightly more textural and mineralogical variability than Groups A and B, possibly due to localized alteration or slight changes in crystallization conditions. Nonetheless, the bulk mineralogy classifies these rocks as doleritic and suggests low petrographic ASR potential; confirmation of ASR performance requires ASTM C1260 and/or ASTM C1293/C1293M testing where specified.

4.2. ENGINEERING FEATURES OF MD

The engineering characterization of Mansehra Dolerite (MD) was conducted on 40 representative aggregate samples collected from three distinct geological regions: Tanawal (Group A), Plura (Group

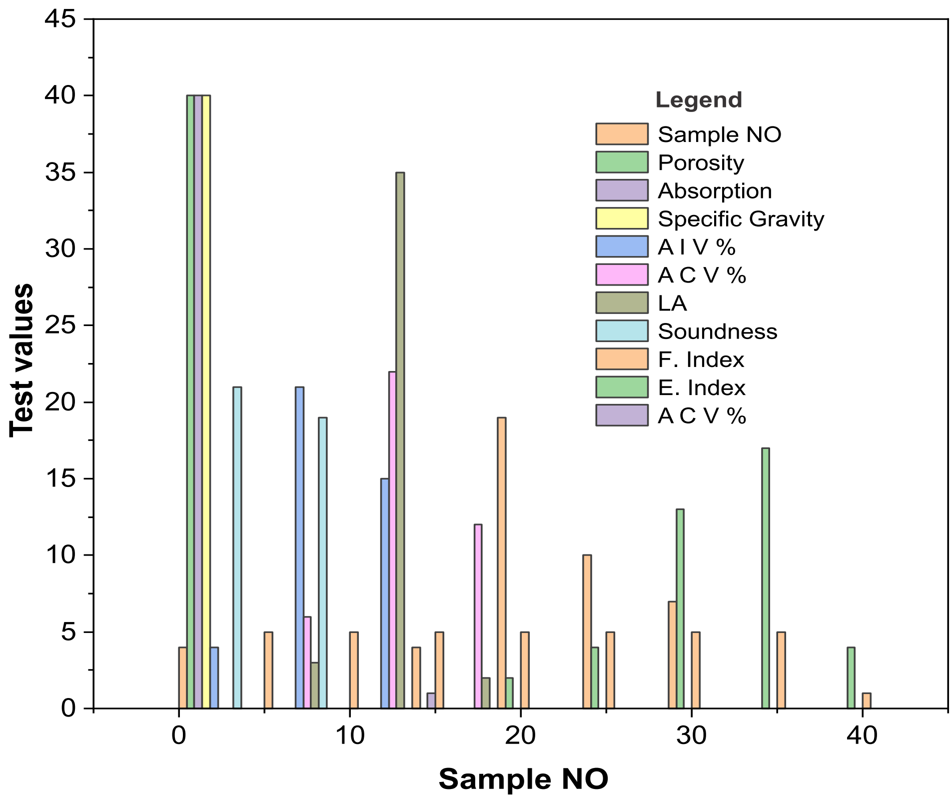

Fig. 5 Graphical representation of **e**ngineering properties of the Mansehra Dolerite.

B), and Oghi (Group C). These regions exhibit varying geological conditions, which are reflected in the physical and mechanical properties of the dolerite. The parameters assessed include porosity, water absorption, specific gravity, aggregate impact value (AIV), aggregate crushing value (ACV), Los Angeles abrasion value (LA), soundness (Na_2SO_4), flakiness index, and elongation index (Fig. 5). The results reveal notable differences across the three groups, which are presented in Tables 2 and 3, respectively.

4.2.1. MECHANICAL STRENGTH CHARACTERISTICS

The mechanical resistance of the aggregates to impact and crushing loads, critical for high-performance concrete, also displays meaningful group-wise variation. The Los Angeles Abrasion (LA) test provides insights into resistance to surface wear, which is vital for road bases and exposed concrete. The Tanawal samples again outperform the rest, with LA values ranging from 8.5 % to 14.3 %, several of which are below 10 %, indicating superior abrasion resistance. The Plura group exhibits a slightly higher range (11.8–15.0 %), with samples such as B-3 and B-6 approaching the upper bound. The Oghi group generally aligns with Plura, with LA values ranging from 12.8 % to 15.1 %, indicating marginally higher wear susceptibility. Soundness testing is critical for evaluating durability against weathering cycles, such as freeze-thaw or sulfate exposure, and follows a parallel trend. The Tanawal group demonstrates excellent resistance, with soundness values ranging from 2.61 to 6.27 %, while the Plura samples range between 5.01 % and 7.68 %, again clustering slightly higher. The Oghi group records the highest soundness values (5.91–7.79 %). These elevated values may reflect the higher porosity and absorption within this group, which could promote internal expansion under weathering stresses.

Moreover, Figures 6 A–M illustrate the linear correlations among key geotechnical and physical properties of Mansehra dolerite aggregate samples. Figures 6 A–D show the relationship between specific gravity and four critical mechanical parameters, Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), Soundness, and Los Angeles Abrasion—where a clear inverse trend is observed, indicating that an increase in specific gravity leads to a decrease in ACV, AIV, Soundness, and abrasion values, thereby reflecting improved aggregate quality. Figure 6E highlights the negative correlation between specific gravity and absorption, suggesting that aggregates with higher absorption generally exhibit lower specific gravity. In continuation, Figures 6F–I demonstrate that absorption strongly influences mechanical performance, as higher absorption values are directly associated with increased ACV, AIV, Soundness, and abrasion, signifying a reduction in aggregate durability. Finally, Figures 6 J–M present the relationship between porosity and the same mechanical indices (ACV, AIV, Soundness, and abrasion), revealing a strong positive correlation: aggregates with higher porosity consistently exhibit elevated mechanical loss values, underscoring the detrimental impact of porosity on strength and resistance.

Table 2 Engineering properties of Mansehra Dolerite with groups.

Sample	LA	S	WA	SG	P	F.Index	E.Index	AIV	ACV
A-1	13	5.37	0.37	3.125	1.16	26	35	9.6	13.8
A-2	10.1	2.98	0.24	3.215	0.77	26	35	5.1	9.5
A-3	8.8	2.85	0.2	3.222	0.62	12	23	4.5	8.9
A-4	11.2	3.74	0.31	3.199	0.97	19	31	6.8	11.3
A-5	11.7	4.15	0.35	3.174	1.06	14	16	7.6	11.9
A-6	11.3	3.81	0.33	3.186	1.01	18	30	7	11.6
A-7	13.3	5.64	0.39	3.117	1.23	23	28	10.2	14.2
A-8	12.2	4.44	0.36	3.161	1.09	24	27	8.4	12.5
A-9	11.1	3.67	0.3	3.199	0.94	22	27	6.5	11.1
A-10	8.7	2.73	0.18	3.224	0.58	13	27	4.3	8.6
A-11	12	4.36	0.35	3.165	1.09	19	29	8.1	12.2
A-12	10.2	3.17	0.25	3.214	0.81	17	32	5.3	9.9
A-13	12.5	4.78	0.36	3.138	1.1	19	34	8.8	12.8
A-14	10.4	3.23	0.27	3.213	0.85	19	33	5.5	10.2
A-15	8.5	2.61	0.16	3.246	0.51	15	30	4.1	8.2
A-16	10.8	3.44	0.27	3.208	0.86	14	22	6	10.5
A-17	12.6	4.93	0.36	3.131	1.11	18	27	8.9	13
A-18	13.4	5.76	0.4	3.114	1.26	24	29	10.5	14.6
A-19	11.8	4.28	0.34	3.171	1.08	15	33	7.8	12.1
A-20	11.5	3.92	0.32	3.181	1.01	16	24	7.3	11.8
A-21	10.6	3.31	0.27	3.210	0.85	16	32	5.8	10.4
A-22	10	2.94	0.21	3.217	0.66	23	26	4.9	9.2
A-23	12.3	4.62	0.35	3.147	1.09	15	29	8.5	12.7
A-24	12.8	5.19	0.35	3.126	1.11	27	36	9.4	13.7
A-25	10.9	3.52	0.29	3.204	0.9	17	19	6.2	10.8
B-1	13.9	6.39	0.56	3.103	1.67	19	32	11	15.7
B-2	14.2	6.77	0.59	3.034	1.81	29	35	11.7	16.2
B-3	14.5	7.08	0.63	3.021	1.85	18	31	12.5	17.3
B-4	13.1	5.49	0.41	3.121	1.21	21	25	9.9	14
B-5	12.8	5.01	0.35	3.128	1.11	15	21	9.1	13.3
B-6	15	7.68	0.69	3.002	2.05	20	31	13.4	18.4
B-7	14.7	7.21	0.63	3.011	1.85	25	33	12.8	17.7
B-8	14	6.58	0.58	3.068	1.8	22	28	11.2	15.9
C-1	15.1	7.79	0.96	2.997	2.8	27	34	13.7	18.5
C-2	14.4	6.93	0.59	3.034	1.81	23	29	12.1	16.7
C-3	13.7	6.13	0.44	3.107	1.36	21	26	10.8	15.1
C-4	13.8	6.27	0.52	3.103	1.58	18	31	10.8	15.5
C-5	14.9	7.51	0.67	3.004	2	25	32	13.3	18.2
C-6	13.5	5.92	0.43	3.110	1.32	15	30	10.7	14.8
C-7	14.8	7.38	0.63	3.004	1.87	18	30	13.1	18.1
A mean ± SD (n=25)	11.27 ± 1.39	3.98 ± 0.93	0.30 ± 0.07	3.180 ± 0.039	0.95 ± 0.20	18.8 ± 4.4	28.6 ± 5.0	7.08 ± 1.90	11.42 ± 1.79
B mean ± SD (n=8)	14.03 ± 0.76	6.53 ± 0.89	0.55 ± 0.12	3.061 ± 0.051	1.67 ± 0.33	21.1 ± 4.3	29.5 ± 4.6	11.45 ± 1.46	16.06 ± 1.76
C mean ± SD (n=7)	14.31 ± 0.65	6.85 ± 0.74	0.61 ± 0.18	3.051 ± 0.053	1.82 ± 0.50	21.0 ± 4.3	30.3 ± 2.5	12.07 ± 1.31	16.70 ± 1.58

*LA = Los Angeles abrasion (%); S = soundness Na_2SO_4 (%); WA = water absorption (%); SG = specific gravity (SSD); P = porosity (%); F. Index = flakiness index (%); E. Index = elongation index (%); AIV = aggregate impact value (%); ACV = aggregate crushing value (%).

Table 3 Comparative summary of engineering properties of Mansehra Dolerite.

Parameter	Group A	Group B	Group C
LA Abrasion (%)	8.5 – 14.4	12.8 – 15.0	13.5 – 15.1
Soundness (%)	2.61 – 6.27	5.01 – 7.68	5.92 – 7.79
Water Absorption (%)	0.16 – 0.40	0.35 – 0.69	0.43 – 0.96
Specific Gravity	3.114 – 3.246	3.002 – 3.128	2.997 – 3.11
Porosity (%)	0.51 – 1.26	1.21 – 2.05	1.32 – 2.80
Flakiness Index	12 – 27	15 – 29	21 – 27
Elongation Index	16 – 36	21 – 35	26 – 34
AIV (%)	4.1 – 10.5	9.1 – 13.4	10.7 – 13.7
ACV (%)	8.2 – 14.4	13.3 – 18.4	14.8 – 18.5

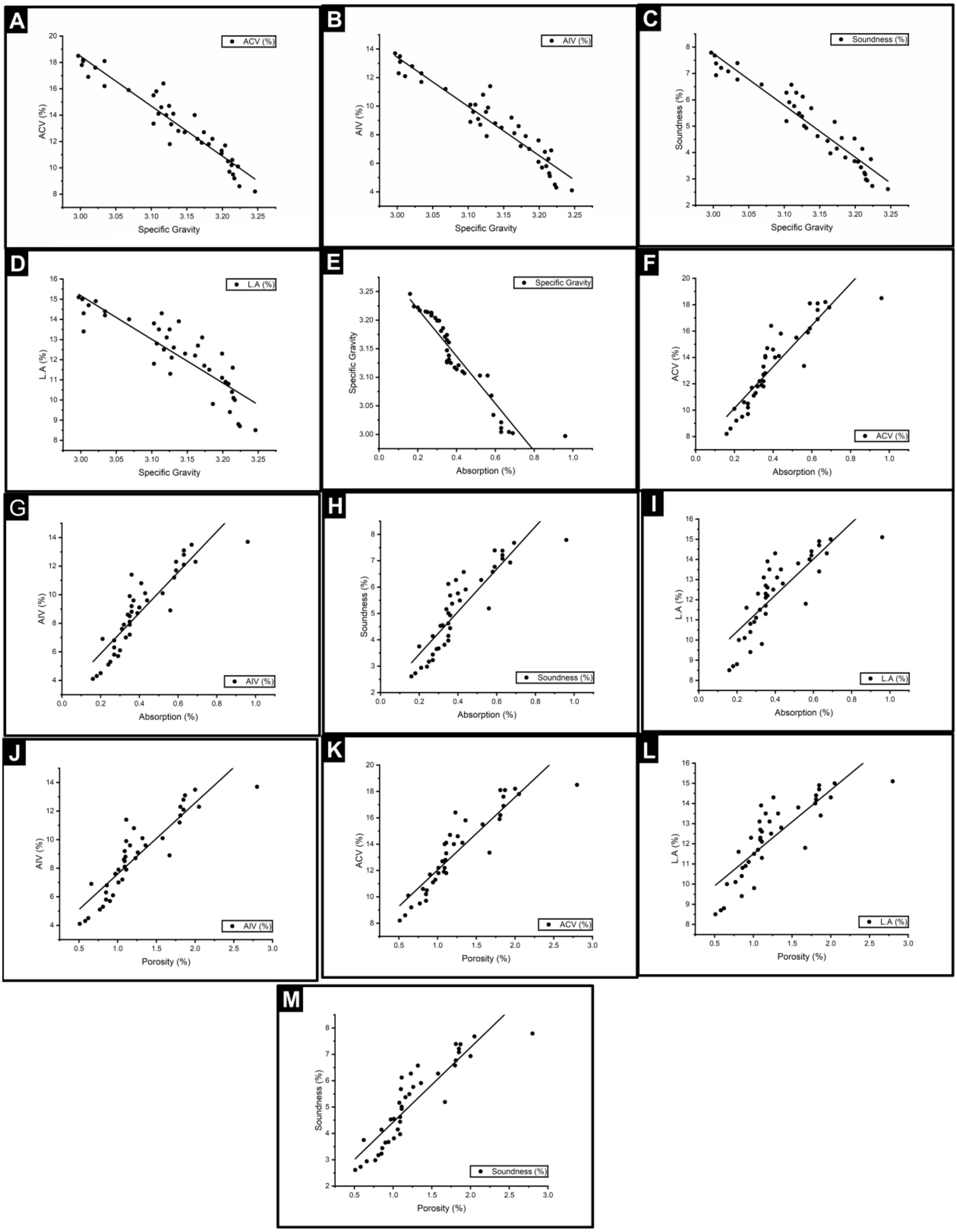

Fig. 6 A–M present the correlations between geotechnical properties of Mansehra dolerite aggregate. Figures A–D show the relationship between specific gravity and Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), Soundness, and Los Angeles Abrasion, indicating that higher specific gravity corresponds to lower ACV, AIV, Soundness, and abrasion values. Figure E depicts the negative correlation between specific gravity and absorption, while Figures F–I illustrate that absorption increases are generally accompanied by higher ACV, AIV, Soundness, and abrasion values. Finally, Figures J–M highlight the direct correlation between porosity and ACV, AIV, Soundness, and abrasion, showing that greater porosity tends to increase the values of these mechanical parameters.

4.2.2. INTERPRETATION OF CORRELATIONS BETWEEN PHYSICAL AND MECHANICAL INDICES

For Figure 6, simple least-squares linear regression yielded strong relationships between density/transport proxies and mechanical loss indices. The inverse relationships between specific gravity and mechanical loss were particularly strong (SG–ACV: $R^2 = 0.969$; SG–AIV: $R^2 = 0.958$; SG–soundness: $R^2 = 0.971$; SG–LA: $R^2 = 0.904$). Absorption showed consistently positive associations with mechanical losses (Abs–SG: $R^2 = 0.891$; Abs–ACV: $R^2 = 0.892$; Abs–AIV: $R^2 = 0.860$; Abs–soundness: $R^2 = 0.883$; Abs–LA: $R^2 = 0.811$), and porosity also correlated positively with the same indices (P–AIV: $R^2 = 0.871$; P–ACV: $R^2 = 0.902$; P–LA: $R^2 = 0.827$; P–soundness: $R^2 = 0.893$).

The superior mechanical performance of Group A (Tanawal) aggregates is best explained by their mineralogical maturity and microstructural integrity. Petrographically, Group A dolerites are dominated by primary plagioclase and abundant pyroxenes (clinopyroxene with variable orthopyroxene), while secondary alteration phases (chlorite/serpentine) are generally minor, indicating limited hydrothermal/weathering overprint. This “fresh” mafic mineral assemblage promotes high density and stiffness, which is reflected in Group A’s consistently higher specific gravity (≈3.114–3.246) and lower porosity/water absorption (porosity ≈0.51–1.26 %; absorption ≈0.16–0.40 %). Mechanically, the rock’s well-developed ophitic texture where pyroxene crystals enclose and tightly interlock plagioclase laths enhances grain-to-grain interlocking, reduces weak altered interfaces, and increases resistance to crack initiation and propagation under impact and compressive loading. Consequently, Group A exhibits the lowest aggregate impact and crushing losses and superior abrasion resistance relative to Groups B and C, consistent with the documented inverse relationships between density (specific gravity) and mechanical loss indices in the dataset. Collectively, these results emphasize the interdependence of specific gravity, absorption, porosity, and mechanical behavior, providing a comprehensive understanding of the geotechnical performance of Mansehra dolerite aggregates.

The Tanawal group excels again with Aggregate Impact Values (AIV) as low as 4.1 % and a maximum of only 11.4 %, indicating excellent toughness and shock resistance. Aggregate Crushing Values (ACV) are similarly impressive, ranging from 8.2 % to 16.4 %, with several samples exhibiting values below 12 %, indicating a high load-bearing capacity. The Plura group, although competent, shows relatively higher AIV (8.9–12.8 %) and ACV (13.3–17.8 %). This modest increase suggests a slight reduction in mechanical strength, possibly attributed to micro fracturing or textural irregularities. The Oghi group demonstrates AIV values between 9.6 and 13.7 % and ACV values from 14.1 to 18.5 %, indicating that it has the lowest impact and crushing resistance among the three. Although AIV and ACV are commonly reported in BS/Commonwealth practice, in ACI/ASTM-based specifications aggregate resistance to degradation is most often evaluated using Los Angeles (LA) abrasion loss (ASTM C131/C535), and ASTM C33/C33M specifies a maximum LA abrasion mass loss of 50 % for gravel/crushed gravel/crushed stone (ACI, 2007, 2016; ASTM International, n.d.). For impact resistance limits, BS 882:1992 provides application dependent limiting values for AIV, including a maximum of 25 % for pavement wearing surfaces / heavy-duty concrete floor finishes, which are directly relevant to high wear concrete in hydraulic infrastructure (British Standards Institution, 1992). Accordingly, the measured AIV (4.1–13.7 %) and ACV (8.2–18.5 %) values, together with the low LA abrasion losses, indicate a tough aggregate suitable for high stress concrete applications (e.g., spillways, stilling basins, and other abrasion-prone hydraulic elements), subject to project specific qualification requirements.

4.2.3. PHYSICAL CHARACTERISTICS OF MD

Specific gravity trends further reinforce these distinctions. The Tanawal samples consistently exhibit high specific gravity (3.114–3.246), indicating the presence of denser mafic minerals, such as pyroxene and plagioclase. The Plura group maintains a slightly lower but still robust gravity range of 3.002–3.128, while the Oghi samples span from 2.997 to 3.110, marginally lower than the other groups. This decrease aligns with the higher porosity observed, as denser rock typically implies lower void content.

The flakiness and elongation indices, indicators of aggregate geometry affecting workability and packing, show less drastic intergroup divergence but still reflect trends worth noting. The Tanawal group presents flakiness indices ranging from 12 % to 27 % and elongation from 16 % to 36 %, suggesting a relatively well-balanced shape distribution, suitable for dense packing and high interlock in concrete. The Plura group exhibits similar ranges (FI: 15–29 %, EI: 21–35 %), although some samples, such as B-2, show elevated flakiness. The Oghi samples, while mostly comparable (FI: 15–27 %, EI: 26–34%), exhibit slightly more elongated grains on average, which may impact workability and compaction efficiency in fresh concrete mixes.

Porosity and water absorption, indicators of internal microstructure and durability, vary noticeably across the groups (Fig. 5). The Tanawal group exhibits the lowest porosity, ranging from 0.51 % to 1.26 %, and correspondingly low water absorption (0.16 % to 0.40 %), demonstrating a dense microstructure with minimal void spaces. This is consistent with the observation of strong interlocking mineral grains, as seen petrographically. In contrast, the Plura group exhibits a moderate porosity range (1.11–2.05 %) and slightly elevated absorption values (0.35–0.69 %), suggesting a more open texture, possibly due to subtle weathering or local textural variations. Meanwhile, the Oghi group, particularly sample C-1 (Chijri), presents the highest porosity (up to 2.80 %) and maximum absorption (0.96 %), reflecting a relatively porous matrix. Despite this, most Oghi samples remain within the acceptable range for use in durable concrete.

The comparative analysis of Mansehra Dolerite aggregates from Tanawal (Group A), Plura (Group B), and Oghi (Group C) (Table-3) reveals distinct trends in physical and mechanical properties. Overall, the Tanawal group exhibits the most favorable engineering characteristics, marked by low porosity and water absorption, high specific gravity, and exceptional resistance to impact, crushing, and abrasion. These properties indicate a dense, durable, and mechanically strong material suitable for high-strength concrete and critical infrastructure applications. In contrast, the Plura group exhibits moderate porosity and absorption, with slightly reduced strength and durability indicators, although these remain within acceptable engineering limits. Its performance suggests a competent aggregate source for general structural use. The Oghi group exhibits the highest porosity and absorption values, accompanied by relatively higher abrasion and soundness losses, indicating a more porous and slightly less durable lithology. Nevertheless, its mechanical strength remains sufficient for use in concrete, particularly where exposure conditions are controlled or supplementary durability measures are applied. This group-wise variation underscores the importance of site-specific characterization of dolerite sources to ensure optimal material selection for diverse construction demands.

5. DISCUSSION

The engineering and petrographic properties of MD collectively demonstrate its exceptional potential as a superior construction aggregate, particularly for high-strength concrete and dam infrastructure. The data indicate that MD consistently meets and often exceeds the performance benchmarks required for durable and long-life concrete, especially when compared to other commonly used aggregates in Pakistan. A central finding is MD's immunity to Alkali-Silica Reaction (ASR), a distress mechanism responsible for cracking and long-term strength loss in concrete. The petrographic analysis reveals a minimal quartz content (0–3 %) and absence of strained or amorphous silica phases, classifying MD as ASR-resistant (ASTM C295; (Fournier et al., 2010). This contrasts sharply with the aggregate sources implicated in dam seepage issues across Pakistan, where ASR-active cherts and volcanic glass are often present (Munir, 2016). The use of MD, therefore, addresses a major root cause of structural failures in existing dams like Tarbela and Warsak, where ASR- related degradation has been documented (Majid, 2013).

The low porosity (0.51–2.80 %) and water absorption values (<1 %) across all MD samples are particularly noteworthy. ASTM C127 and ASTM C128 define standardized test methods for determining aggregate absorption and specific gravity; acceptance limits are specification-dependent (e.g., project or agency requirements). In practice, lower absorption and porosity are generally preferred for durable concrete, and the measured values for MD (absorption 0.16–0.96 %; porosity 0.51–2.80 %) indicate a dense aggregate consistent with durability-oriented specifications, which typically set thresholds below 2 % for absorption and under 3 % for porosity (Neville, 1995). In contrast, aggregates from sedimentary sources such as limestones and sandstones commonly used in dam structures in northern Pakistan have shown water absorption exceeding 2.5 %, leading to durability concerns over time (Ali et al., 2024). This difference is critical in dam projects where hydrostatic pressure and wet-dry cycles accelerate deterioration.

5.1. *DURABILITY IMPLICATIONS OF WATER ABSORPTION AND SPECIFIC GRAVITY*

From a durability standpoint, the combination of low water absorption/porosity and high specific gravity indicates a dense, weakly altered aggregate fabric, which generally reduces internal water storage in aggregate pores and limits moisture driven deterioration mechanisms under repeated wetting drying. At the concrete scale, lower absorption/sorptivity is consistently associated with lower permeability and improved resistance to transport controlled damage, including sulfate attack and chloride ingress, provided that the concrete mixture also achieves low w/cm and adequate curing in line with durable-concrete guidance. Accordingly, the comparatively lower WA and higher SG of Group A suggest a more favorable durability contribution in aggressive exposure conditions than Groups B–C, even though all groups remain within standard acceptance limits. (ACI, 2001; Zhang and Zong, 2014; Ryu and Monteiro, 2002).

5.2. *RELATIONSHIP BETWEEN MINERALOGY AND STRENGTH*

The mechanical strength indicators including Aggregate Impact Value (4.1 13.7 %), Crushing Value (8.2–18.5 %), and Los Angeles Abrasion (8.5–15.1 %) collectively point to MD's high resistance to fragmentation, impact, and wear. These values align with the British Standard BS 812 and AASHTO T96 limits for heavy-duty applications (BSI, 1990). Specifically, Group A (Tanawal) samples demonstrated superior mechanical strength, likely due to their higher specific gravity (up to 3.246) and lower porosity, indicating localized variations in cooling history may reflect and mineral density. This performance is also consistent with Group A's predominantly fresh mafic mineral assemblage (plagioclase + pyroxenes) and well-developed ophitic/sub-ophitic interlocking texture, which together promote higher density and reduce mechanically weak pathways along altered rims and grain interfaces. In doleritic aggregates, increased secondary alteration products are commonly associated with deterioration of key physico-mechanical indices, whereas fresher mafic assemblages typically retain higher strength and abrasion resistance (Rigopoulos et al., 2010); similarly, intrusive rocks with more mafic composition and lower weathering grades generally show higher specific gravity and strength (Yasir et al., 2022).

The observed modal variability in Group A particularly orthopyroxene (5–30 %) and minor quartz (≤3 %) is not expected to negatively affect the engineering indices because the rock remains fundamentally mafic and dominated by a dense plagioclase pyroxene framework. Mafic Mineral Assemblage in the clinopyroxene/orthopyroxene proportion primarily reflects mafic mineral partitioning and does not introduce weaker or highly porous phases; instead, aggregate performance is more sensitive to microcracking and alteration degree than to modest variations within the primary mafic mineral assemblage (Rigopoulos et al., 2010). Quartz, where present, occurs as sparse, crystalline grains and petrographic screening did not identify reactive silica forms such as cryptocrystalline/microcrystalline quartz or highly strained quartz (ASTM C295/C295M; RILEM, 2003; Antolík et al., 2023). Accordingly, within the limits of petrographic observation, this minor quartz content is interpreted as non-deleterious for the measured physico-mechanical behavior, while definitive ASR confirmation remains dependent on performance-based expansion tests where required (ASTM C295/C295M).

These physico-mechanical trends are consistent with international findings for mafic intrusive aggregates (dolerite/gabbro). For example, ophiolitic dolerites from northern Greece show that increasing secondary alteration products systematically weaken engineering performance, with higher absorption/porosity and poorer fragmentation/abrasion related indices compared with fresher dolerites (Rigopoulos et al., 2010). A similar overall picture is reported for dolerites used as construction materials in West Africa, where low water absorption and strong mechanical behavior are characteristic of relatively fresh dolerite aggregates (Oden et al., 2013). At the concrete scale, high-strength concretes produced with gabbro aggregate have been reported to exhibit among the highest compressive/flexural strength and abrasion resistance compared with several other lithologies, underscoring the performance advantage of dense, interlocking mafic aggregates (Kılıç et al., 2008). More broadly, reviews of aggregate geology confirm that porosity, microcracks, and textural features are recurrent controls on Los Angeles abrasion and related mechanical indices, supporting the interpretation of the correlations observed here (Adomako et al., 2021).

5.3. INFLUENCE OF MICROTEXTURE AND ALTERATION ON PERFORMANCE

An interesting contrast arises in Group B (Plura) and Group C (Oghi), which exhibit slightly higher porosity and mechanical degradation indices. However, these values remain within safe engineering limits. The slight increase in values may be attributed to localized tectonic disturbances or more rapid cooling histories, as inferred from the slight increase in fine-grained matrix and hornblende content. Such variations underline the importance of site-specific assessment before large-scale aggregate use, even within the same lithological unit (Bell, 2007). Texturally, MD exhibits an ophitic to sub-ophitic structure, which promotes interlocking of mineral grains and enhances mechanical interlock in concrete matrices.

The presence of secondary minerals such as chlorite and biotite in minor quantities further suggests some low-grade metamorphic overprinting, which may increase the toughness of the rock. These textures are ideal for resisting internal microcracking, a property crucial for concrete longevity in hydraulic structures (Jhatial et al., 2023). In the present study, microcracks were identified petrographically, but microcrack density was not quantified. Comparable experimental and micromechanical studies indicate that increasing microcrack density often concentrated within the aggregate paste interfacial transition zone (ITZ) is associated with reduced stiffness/strength and modified stress strain response in concrete (Shah and Chandra, 1968; Erdem et al., 2012; An et al., 2017). Rock mechanics evidence similarly shows that measured microcrack density provides a defensible microstructural basis for stiffness and strength loss in intact rocks (Griffiths et al., 2017). Accordingly, future work could quantify microcrack density (e.g., thin-section image analysis or μCT) to strengthen microstructure property interpretation for MD aggregates. Environmentally and economically, MD offers added advantages. Its durability minimizes the need for repair or replacement, reducing lifecycle costs. Furthermore, being locally available in the Hazara region, it can reduce transportation-related emissions and costs, aligning with sustainable construction goals (Jhatial et al., 2023). Given Pakistan's growing focus on water security and hydropower development, the strategic use of MD in future projects could significantly enhance performance and reduce long-term maintenance liabilities.

Our results establish that the study not only validates the mechanical robustness and ASR resistance of Mansehra Dolerite but also underscores its value as a strategic resource for national infrastructure. With proper quarrying, testing, and quality control, MD has the potential to replace traditional reactive aggregates currently used in critical dam and structural applications, offering long-term durability, economic efficiency, and environmental benefits.

Notably, this study evaluated Mansehra dolerite primarily at the aggregate level (petrography and standardized aggregate indices) and did not include concrete mixture preparation or compressive strength testing using Groups A–C. Therefore, although the group wise trends suggest that Group A is expected to yield improved concrete performance relative to Groups B and C, mixture-level verification using controlled concrete mixes is recommended as a necessary next step (e.g., compressive strength per ASTM C39/C39M, with consistent w/c ratio and grading).

6. CONCLUSION

The growing demand for durable high-performance concrete has highlighted the need for high-quality coarse aggregates with strong mechanical and mineralogical properties. In this study, the engineering and petrographic properties of Mansehra dolerite (MD), a mafic intrusive rock from northern Pakistan, are investigated to evaluate its suitability as a high-strength aggregate for durable infrastructures.

The following conclusions were drawn from the results

1. Mansehra Dolerite aggregates exhibit very low porosity (0.51–2.80 %) and water absorption (<1%), meeting the standards for high-strength concrete applications.
2. The specific gravity values range between 2.997 and 3.246, reflecting the dense, durable nature of the dolerite rock.
3. Aggregates showed low Aggregate Impact Values (AIV: 4.1–13.7 %), Crushing Values (ACV: 8.2–18.5 %), and Los Angeles Abrasion (LA: 8.5–15.1 %), indicating high resistance to mechanical degradation.
4. Soundness values ranged between 2.61–7.79 %, remaining well within acceptable limits, and flakiness and elongation indices also remained moderate, ensuring aggregate shape suitability.
5. Group A (Tanawal) samples demonstrated the lowest porosity and best overall mechanical performance, while Group B (Plura) and Group C (Oghi) showed slightly higher values, yet still within acceptable engineering standards.
6. Petrographic analysis confirmed the absence of reactive silica phases, with plagioclase (30–60 %), clinopyroxene (20–40 %), and low quartz (0–3 %), suggesting low petrographic ASR potential; this should be confirmed by ASTM C1260 and/or ASTM C1293/C1293M where required for qualification of HPC/hydraulic structures, unlike many other commonly used aggregates in dam and infrastructure projects. However, direct confirmation in the final concrete product requires compressive strength testing of standardized concrete mixes prepared with each aggregate group (A–C), which is recommended as future work.
7. The presence of coarse-grained ophitic textures, porphyritic structures, and consistent modal mineralogy indicate slow cooling and strong crystalline bonding, enhancing long-term durability.
8. Due to its excellent strength, low absorption, and low petrographic ASR potential (subject to confirmation by ASTM C1260/C1293 where required), Mansehra Dolerite is well-suited, Mansehra Dolerite is ideally suited for use in dam structures, high-strength concrete pavements, and other long-life civil engineering projects.

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