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Rock mass characteristics of the Fagfog Quartzite along the Kalu Pandey Highway, Central Nepal Lesser Himalaya

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Abstract

The Fagfog Quartzite, a prominent lithostratigraphic unit of the Lower Nawakot Group, Lesser Himalaya, is extensively exposed along the Kalu Pandey Highway, Central Nepal. Rock mass characterization was carried out at fifteen road-cut slope sites (F1–F15) using the Rock Mass Rating (RMR). Five parameters were systematically assessed: uniaxial compressive strength (UCS), Rock Quality Designation (RQD), discontinuity spacing, condition of discontinuities, and groundwater condition. RMR values ranged from 72 to 85, classifying the rock mass as Class II Good Rock at nine sites and Class I Very Good Rock at six sites. UCS ranged from 50 MPa to >200 MPa; RQD was uniformly excellent (89–100%). Three discontinuity sets trend NW–SE; discontinuity spacing (R3) and condition (R4) were the dominant controls on RMR variability. Groundwater was completely dry during dry-season fieldwork; monsoon-season conditions may reduce RMR by up to 8–10 points. The dataset provides a geotechnical baseline for the Fagfog Quartzite and supports future kinematic failure analysis and Slope Mass Rating (SMR) assessment for highway slope stability management.

Keywords: Fagfog Quartzite; Rock mass rating (RMR); Stratigraphic column; Route mapping; Lesser Himalaya.

1. Introduction

Rock mass characterization is a fundamental component of geotechnical engineering, providing essential data for design and stability assessment of infrastructure projects such as highway excavations, slopes, and mining works [9, 6]. The RMR system [5, 6] evaluates rock mass quality using five principal parameters: UCS of intact rock, Rock Quality Designation (RQD), discontinuity spacing, condition of discontinuities, and groundwater conditions summed to give RMR = R1+R2+R3+R4+R5. A sixth parameter (orientation adjustment) is applied separately in tunneling design; for slope characterization, orientation effects are evaluated through SMR [17]. The RMR system has been validated in over 351 case studies globally [14] and is widely applied for road and highway slope assessment [4, 22].

The RMR system has demonstrated its versatility across varied geological settings, with palmstrom2006 noting its successful application in over 351 case studies [14]. Its utility extends to tunneling, excavation planning, and even underground mining, where adaptations like Laubscher's Mining Rock Mass Rating (MRMR) have been developed [13]. The integration of RMR with numerical modeling has further augmented its capabilities in contemporary geotechnical design. For instance, barton2002 [3] highlighted the critical role of RMR values in deriving rock mass deformation moduli for finite element analyses, while aksoy2008 [2] established strong correlations between RMR classifications and the observed performance of rock slopes, thereby validating its predictive capacity. Recent advancements include the RMR14 system, which offers more realistic support assessments in challenging rock conditions [12], and methods for continuous rating and back analysis to refine support design in tunneling [16].

For slope stability evaluations, particularly concerning highway cuts, the Slope Mass Rating (SMR) system, an extension of RMR developed by romana1985 [17], is widely employed. SMR incorporates adjustment factors related to the orientation of discontinuities relative to the slope face, making it highly effective for such assessments [18]. Enhancements to SMR include graphical approaches using stereographic projection to simplify the determination of correction factors [26], and its reliability has been confirmed through validation studies on highway cut slopes [19].

Despite the engineering significance of the Fagfog Quartzite along the Kalu Pandey Highway, no systematic RMR-based rock mass characterization of this unit has been published. Previous work established intact rock strength and durability [20, 21], but rock mass quality data at cut-slope scale were absent. This study addresses that gap. The specific objectives are: (i) to systematically characterize rock mass quality at fifteen road-cut slope sites using the RMR system [6]; (ii) to assess spatial variability in RMR and its controlling parameters along the highway; and (iii) to establish a geotechnical baseline for the Fagfog Quartzite supporting future SMR and kinematic slope stability analyses.

2. Study area

The study area lies in the Kalu Pandey Highway in Central Nepal Himalaya (Figure 1). Geographically, it lies between 27° 51′ 00.69″ N latitude and 84° 51′ 20.10″ E longitude. This region is part of the Mahabharat Range, characterized by steep slopes. The Fagfog Quartzite is prominent Precambrian to Lower Paleozoic metamorphic rock that prominently forms ridges reflecting a distinct high relief and steep slopes [23]. The geomorphology reflects active tectonic uplift and intense fluvial erosion. Slope orientations vary due to complex topography with dominant south-facing slopes. North-facing slopes are prone to rockfalls.

The subtropical climate exhibits pronounced wet (monsoon: June–September) and dry (October–May) seasons. Cyclic wetting and drying promotes progressive weathering along discontinuity

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surfaces, degrading joint condition over time. Elevations along the studied section range from 422 to 468 m above sea level. The Kalu Pandey Highway connects the Prithvi Highway at Malekhu to Kathmandu via the Mahabharat Range, traversing approximately 4.2 km of continuous Fagfog Quartzite exposure between Kalidaha Bazar and Malekhu. This section was selected for study because: (a) the Fagfog Quartzite is the sole lithology exposed along this reach; (b) road-cut slopes of 4 to 30 m height provide fresh, accessible exposures for systematic RMR assessment; and (c) recurrent slope instability including rockfalls and planar sliding along joint surfaces causes frequent highway maintenance requirements. Rock mass characterization using RMR is therefore of direct practical importance for this highway corridor.

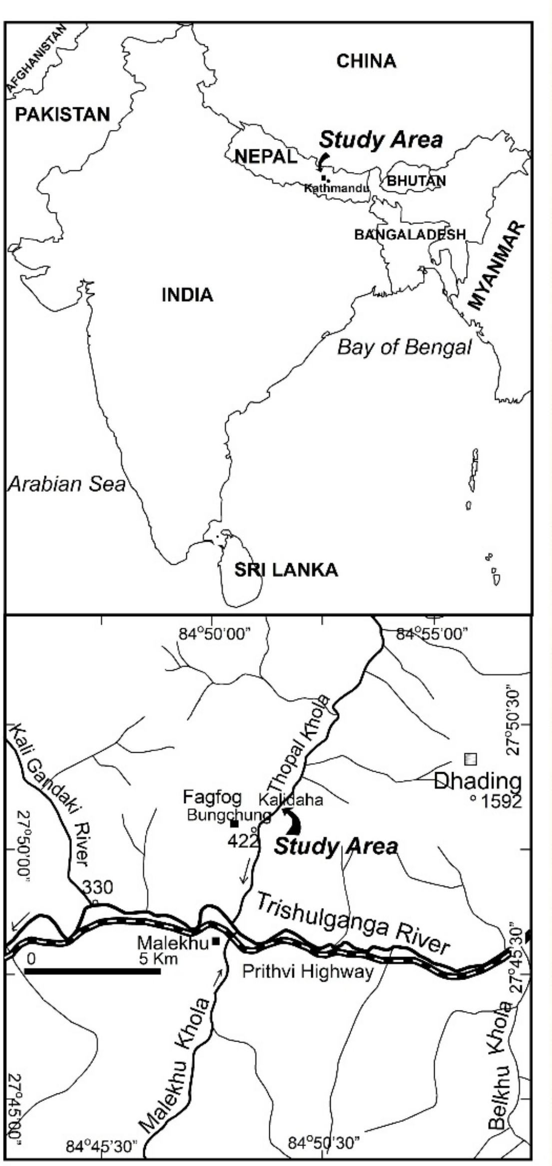

Figure 1: Location map of study area.

2.1. Geological setting

The study area lies within the Lower Nawakot Group of the Nawakot Complex, Lesser Himalaya (Figure 2), composed predominantly of Proterozoic to Paleozoic metamorphic rocks [24, 27]. The stratigraphic sequence exposed along the highway, from structurally lower to upper, comprises: (i) Kuncha Formation phyllite (weaker unit, lower intact strength, prone to weathering); (ii) Fagfog Quartzite (dominant, strongest unit); and (iii) Dandagaon Phyllite (weaker upper unit). The mechanical contrast between the strong quartzite and weaker bounding phyllites creates differential slope stability conditions at formation contacts, where slope failures are most frequent. Beds of the Fagfog Quartzite generally strike NW–SE and dip at moderate angles to the NE (representative attitude: N50°W/40°NE). Overturned sequences are locally observed, consistent with large-scale recumbent folding associated with the Lesser Himalayan Duplex [15, 8]. Three principal discontinuity sets (J1: bedding-parallel; J2 and J3: conjugate cross-cutting) are consistently present at all fifteen sites, produced by Himalayan tectonic deformation. These joint sets, in combination with the NW–SE bed attitude and highway-cut slope geometry, create conditions potentially favorable for planar sliding (J1), wedge failure (J1–J2 or J1–J3 intersections), and toppling (J2 or J3 where steep and slope-parallel). No detailed geotechnical study of the Fagfog Quartzite along this highway existed prior to this work; only preliminary geological mapping by bista2017 [7] covers this section.

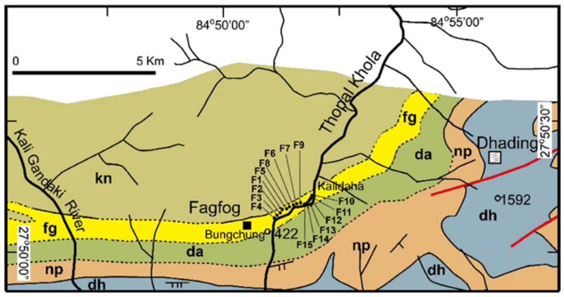

Figure 2: Regional geological map of the study area. *kn*=Kuncha Formation, *fg*=Fagfog Quartzite, *da*=Dandagaon Phyllite, *np*=Nourpur Formation, *dh*=Dhading Dolomite (after stocklin1977 [24]), F1 to F15 are sample sites.

3. Methodology

A systematic methodology was followed to assess the rock mass characteristics along the Kalu Pandey Highway in the Lesser Himalayan region. Pre-field preparations involved the review of existing topographic sheets and geological maps to delineate the study area and define lithological boundaries. The Quartzite unit was systematically divided into 15 vertical sections from the bottom to the top along the highway alignment. A route map and columnar section were prepared to acquire more detailed information on the lithology of the sampling sequence. Fieldwork focused on section-wise rock mass characterization of each of 15 sites. RMR parameters were systematically collected at representative outcrops or road cuts.

RMR was calculated as the sum of ratings for five principal parameters following bieniawski1989 [6]:

$$\text{RMR} = R1 + R2 + R3 + R4 + R5 \tag{1}$$

It is important to clarify that the standard RMR system [6] includes a sixth parameter — an orientation of discontinuities adjustment — which is applied specifically in tunneling and underground excavation support design. In the present study, RMR was applied for surface slope characterization and rock mass quality assessment of highway cut slopes, not for tunnel support. For slope applications, discontinuity orientation effects are evaluated separately through kinematic analysis or the SMR system [17], and are therefore not incorporated into the basic five-parameter RMR summation used here. This approach is consistent with standard practice for slope geotechnical investigations [6, 17, 4].

Where:

- $R1$ = Uniaxial Compressive Strength (UCS) of the rock material. Reflects the strength of the intact rock, typically measured in MPa.
- $R2$ = Rock Quality Designation. Indicates the degree of fracturing, expressed as a percentage of core pieces longer than 10 cm in a drill core.
- $R3$ = Spacing of Discontinuities. Describes the distance between joints or fractures in the rock mass.
- $R4$ = Condition of Discontinuities. Includes factors such as roughness, weathering, infilling material, and continuity of the joints.
- $R5$ = Groundwater Conditions. Evaluates the influence of water, such as dampness, seepage, or flow, which can affect rock mass behavior.

Uniaxial Compressive Strength was estimated using a Schmidt hammer. RQD was determined by measuring joint spacing following ISRM [11] guidelines. Joint conditions were assessed by visual inspection of persistence, roughness, infillings, weathering and groundwater conditions. Joint orientations were measured relative to the slope or excavation face.

For each site, RMR was calculated following bieniawski1989 [6]. Individual ratings were assigned to UCS (R1: 0–15), RQD (R2: 3–20), discontinuity spacing (R3: 5–20), condition of discontinuities (R4: 0–30), and groundwater condition (R5: 0–15) using Bieniawski's (1989) rating tables (Table 1). Each site was classified into one of the five rock mass classes of bieniawski1989 [6] based on total RMR (Table 1). Field UCS was classified using the hoek1997 [10] field strength scheme: $>$250 MPa Extremely Strong; 100–250 MPa Very Strong; 50–100 MPa Strong; 25–50 MPa Moderately Strong.

Table 1: Classification of Rock mass rating system.

Class	Rock Quality	RMR Range	Description
I	Very Good Rock	81–100	Intact, strong, very favorable for engineering purposes.
II	Good Rock	61–80	Slightly fractured, good conditions, suitable for most designs.
III	Fair Rock	41–60	Moderately fractured, requires some support.
IV	Poor Rock	21–40	Heavily fractured, weak zones, needs significant support.
V	Very Poor Rock	$<$20	Very weak, highly fractured, unsuitable without reinforcement.

All field data were compiled into a route map, integrating lithological and structural details with corresponding RMR profiles.

4. Results

The Fagfog Quartzite is a lithostratigraphic unit in the central Nepal Himalaya. Well-developed sequence of quartzite beds is typically massive, white in color [23]. The Fagfog Quartzite is a part of the Nawakot Group of Proterozoic age, reflecting a high-energy depositional environment, likely shallow marine or fluvial in origin [23].

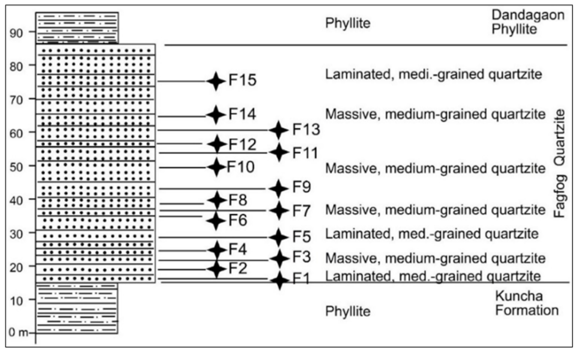

Figure 3: Graphic log of the Fagfog Quartzite as exposed at the Kalu Pandey Highway.

The Fagfog Quartzite (Figure 3) displays a rhythmic alternation of laminated and massive medium-grained quartzite, indicating fluctuating depositional energy in a shallow marine, rift-related Proterozoic setting. This cyclicity distinguishes it from the finer-grained Kuncha Formation below and the overlying Dandagaon Phyllite.

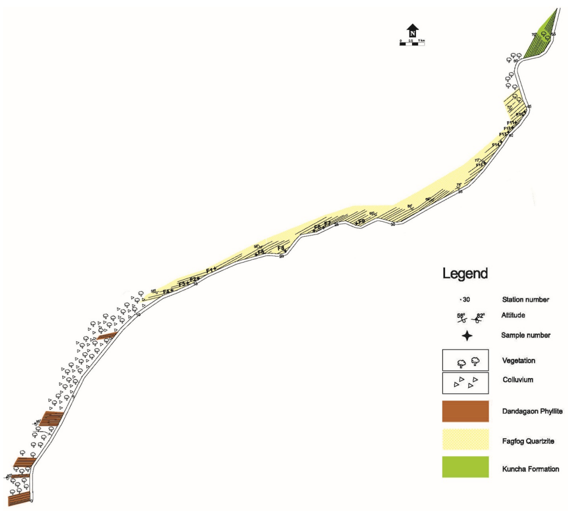

Figure 4: The geological route mapping showing the spatial distribution of the Kuncha Formation, Fagfog Quartzite, and Dandagaon Phyllite.

The Fagfog Quartzite forms the dominant lithology and is exposed extensively between the underlying phyllite of the Kuncha Formation and the overlying Dandagaon Phyllite (Figure 4). It displays alternating laminated and massive units, suggesting varied depositional energy and structural complexity. Frequent faults and fractures observed along the section indicate a tectonically active setting, influencing slope geometry and stability. Colluvium deposits and vegetation reflect surface processes and terrain characteristics relevant to geotechnical and engineering assessments.

Fifteen quartzite samples were collected from road-cut slopes in the central Nepal Himalaya (Table 2), specifically within the Fagfog Quartzite. The samples, taken from elevations ranging between 422 m and 466 m, consistently show medium-grained textures and vary in color from white and milky white to light grey. Bed thicknesses range from 2 to 10 meters, with no associated rock units observed at any of the sites. Exposure heights vary from 3 to 30 meters, and vegetation cover ranges from 5 to 35%, indicating varying degrees of surface exposure and preservation conditions.

Table 2: Description of sample location and outcrop of the Fagfog Quartzite.

Sample	Latitude/Longitude	Elv. (m)	Description of location	Outcrop description
F1	27.8502°N 84.8509°E	466	2.64 km from Kalidaha Bazar towards Malekhu, right side cut slope. Exposure H: 5–8 m, L: 5–7 m. Vegetation: 10–20%.	Ripple laminated, med.-grained quartzite. Bed thickness: 4–6 m.
F2	27.8502°N 84.8509°E	464	2.670 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 8–10 m, L: 5–7 m. Vegetation: 20–25%.	Ripple marks med.-grained quartzite. Bed thickness: 3–5 m.
F3	27.8500°N 84.8504°E	462	2.685 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 10–12 m, L: 8–10 m. Vegetation: 20–25%.	Ripple marks med.-grained quartzite. Bed thickness: 3–5 m.
F4	27.8500°N 84.8502°E	461	2.720 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 8–10 m, L: 3–4 m. Vegetation: 15–20%.	Ripple marks med.-grained quartzite. Bed thickness: 4–6 m.
F5	27.8503°N 84.8518°E	468	2.590 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 4–5 m, L: 8–10 m. Vegetation: 5%.	Ripple marks med.-grained quartzite. Bed thickness: 3–5 m.
F6	27.8507°N 84.8533°E	452	2.470 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 5–7 m, L: 5–7 m. Vegetation: 10–15%.	Ripple marks med.-grained quartzite. Bed thickness: 4–5 m.
F7	27.8510°N 84.8527°E	461	2.460 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 4–6 m, L: 8–10 m. Vegetation: 25%.	Ripple marks med.-grained quartzite. Bed thickness: 8–10 m.
F8	27.8504°N 84.8521°E	453	2.540 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 10 m, L: 8–10 m.	Ripple marks med.-grained quartzite. Bed thickness: 3–5 m.
F9	27.8506°N 84.8587°E	441	2.540 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 4–6 m, L: 20 m. Vegetation: 10–20%.	Ripple marks med.-grained quartzite. Bed thickness: 3–5 m.
F10	27.8522°N 84.8563°E	424	2.06 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 20–25 m, L: 2–6 m. Vegetation: 5–10%.	Ripple marks med.-grained quartzite. Bed thickness: 3–6 m.
F11	27.8519°N 84.8561°E	423	2.085 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 15–20 m, L: 5–7 m. Vegetation: ∼10%.	Ripple marks med.-grained quartzite. Bed thickness: 2–4 m.
F12	27.8518°N 84.8561°E	422	2.095 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 15–20 m, L: 5–7 m. Vegetation: 15–20%.	Ripple marks med.-grained quartzite. Bed thickness: 2–4 m.
F13	27.8518°N 84.8562°E	422	2.100 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 20–30 m, L: 5–7 m. Vegetation: ∼20%.	Ripple marks med.-grained quartzite. Bed thickness: 3–4 m.
F14	27.8518°N 84.8560°E	422	2.150 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 5–7 m, L: 3–5 m. Vegetation: 10%.	Ripple marks med.-grained quartzite. Bed thickness: 2–3 m.
F15	27.8512°N 84.8556°E	427	2.350 km from Kalidaha Bazar towards Malekhu, right side. Exposure H: 5–7 m, L: 3–5 m. Vegetation: 30–35%.	Ripple marks med.-grained quartzite. Bed thickness: 3–5 m.

4.1. Site descriptions

Location F1

The rock mass at this location has a UCS ranging from 100–200 MPa, indicating strong rock. RQD is 95%, which signifies excellent rock quality. The rock contains three joint sets with spacing ranging from 0.001 to 1.20 m, indicating moderately to widely spaced joints. Discontinuities show persistency greater than 3 meters with apertures up to 6 mm, varying from rough to smooth surfaces, and include clay-mud infilling. The rock is slightly to moderately weathered and completely dry, which enhances stability. With an RMR value of 72, the rock mass is classified as Class II – Good rock.

Location F2

The rock mass shows UCS of 50–100 MPa, classifying it as strong. RQD is 100%, indicating excellent quality. It contains three joint sets, with joint spacing between 0.02 to 2.0 m, ranging from moderately to widely spaced. Discontinuities are persistent over 3 meters with apertures up to 12 mm, surface conditions are mostly rough to smooth, and infillings include clay. The rock is slightly weathered and groundwater condition is completely dry. The RMR value of 74 classifies it as Class II – Good rock.

Location F3

This site has a UCS of >200 MPa, indicating very strong rock [10]. RQD is 100%, which is excellent. It has three joint sets with joint spacing ranging from 0.01 to 3.0 m, and discontinuities with persistency 1–2 m and apertures up to 8 mm. Surfaces are rough and slightly weathered, with silty-clay infill. With an RMR of 82, it is classified as Class I – Very good rock.

Location F4

At this location, the UCS ranges from 100–200 MPa, indicating very strong rock [10]. RQD is 100%, still within excellent quality. Three joint sets are present, with joint spacing between 0.02 to 2.0 m. Discontinuities show persistency up to 2 m with apertures of 10 mm. Joint surfaces are slightly rough with clay filling. The RMR value is 76, classifying it as Class II – Good rock.

Table 3: Field UCS, joint spacing, discontinuities, groundwater condition and rock mass classification of the Fagfog Quartzite.

Sample	UCS (MPa)	RQD (%)	Joint Spacing	Condition of Discontinuities	GW	RMR	Class
F1	100–200R1=12	95 R2=20	J1: 0.004–1.20 m; J2: 0.003–1.00 m; J3: 0.001–0.80 m R3=13	Persist. >3 m; Apt: J1: <4 mm, J2: 2–5 mm, J3: 1–6 mm; Rough/smooth; Clay-mud infill; Sl.–mod. weathered R4=12	DryR5=15	72	II, Good
F2	50–100 R1=7	100R2=20	J1: 0.02–1.20 m; J2: 0.03–1.50 m; J3: 0.04–2.00 m R3=15	Persist. 1–3 m; Apt: J1: <10 mm, J2: 0.2–12 mm, J3: <10 mm; Rough/smooth; Clay infill; Sl. weathered R4=17	DryR5=15	74	II, Good
F3	>200 R1=12	100R2=20	J1: 0.02–2.00 m; J2: 0.03–3.00 m; J3: 0.01–0.90 m R3=17	Persist. 1–2 m; Apt: J1: 0–1 mm, J2: 0–22 mm, J3: 0–8 mm; Rough; Clay-mud infill; Sl. weathered R4=18	DryR5=15	82	I, V. Good
F4	100–200R1=12	100R2=20	J1: 0.05–1.19 m; J2: 0.05–2.00 m; J3: 0.02–1.19 m R3=15	Persist. >2 m; Apt: J1: <5 mm, J2: <10 mm, J3: 10 mm; Rough; Clay infill; Sl.–mod. weathered R4=14	DryR5=15	76	II, Good
F5	100–200R1=12	94 R2=20	J1: 0.005–1.20 m; J2: 0.004–0.90 m; J3: 0.03–0.80 m R3=15	Persist. 1–3 m; Apt: J1: <5 mm, J2: 0–20 mm, J3: 0–40 mm; Rough; Clay infill; Sl.–mod. weathered R4=16	DryR5=15	78	II, Good
F6	>200 R1=12	99 R2=20	J1: 0.20–1.10 m; J2: 0.10–0.90 m; J3: 0.25–1.40 m R3=15	Persist. >2 m; Apt: J1: 0–2 mm, J2: 0–2 mm, J3: <4 mm; Rough; Sl. weathered R4=17	DryR5=15	79	II, Good
F7	>200 R1=12	89 R2=17	J1: 0.02–0.30 m; J2: 0.50–0.80 m; J3: 0.04–0.75 m R3=13	Persist. 3–10 m; Apt: J1: 0–2 mm, J2: 0–2 mm, J3: <3 mm; Rough; Sl. weathered R4=15	DryR5=15	72	II, Good
F8	100–200R1=12	95 R2=20	J1: 0.002–1.60 m; J2: 0.003–0.80 m; J3: 0.002–0.90 m R3=15	Persist. 0–3 m; Apt: J1: <5 mm, J2: 0–20 mm, J3: 0–20 mm; Rough; Clay-mud infill; Sl. weathered R4=16	DryR5=15	78	II, Good
F9	>200 R1=12	100R2=20	J1: 0.04–1.32 m; J2: 1.00–1.20 m; J3: 0.01–3.00 m R3=17	Persist. 1–2 m; Apt: J1: none, J2: 1–3 mm, J3: 1–4 mm; Rough; Mud-rock; Sl. weathered R4=19	DryR5=15	83	I, V. Good
F10	100–200R1=12	100R2=20	J1: 0.40–2.00 m; J2: 1.00–5.00 m; J3: 0.50–3.00 m R3=18	Persist. 0–2 m; Apt: J1: 0–2 mm, J2: 0–5 mm, J3: 0–5 mm; Rough to v. rough; Sl. weathered R4=18	DryR5=15	83	I, V. Good
F11	>200 R1=12	100R2=20	J1: 0.03–2.00 m; J2: 0.10–6.00 m; J3: 0.50–3.00 m R3=18	Persist. 1 m; Apt: J1: 0–2 mm, J2: 0–5 mm, J3: 0–5 mm; Rough to v. rough; Sl. weathered R4=18	DryR5=15	83	I, V. Good
F12	>200 R1=12	100R2=20	J1: 0.05–2.50 m; J2: 0.10–8.00 m; J3: 0.50–4.00 m R3=20	Persist. 1 m; Apt: J1: 0–2 mm, J2: 0–5 mm, J3: 0–5 mm; Rough to v. rough; Sl. weathered R4=18	DryR5=15	85	I, V. Good
F13	>200 R1=12	100R2=20	J1: 0.05–2.00 m; J2: 0.10–10.00 m; J3: 0.50–3.00 m R3=18	Persist. 1–2 m; Apt: J1: 0–2 mm, J2: 0–5 mm, J3: 0–5 mm; Rough to v. rough; Mud infill; Sl. weathered R4=18	DryR5=15	83	I, V. Good
F14	>200 R1=12	90 R2=20	J1: 0.07–0.60 m; J2: 0.07–0.90 m; J3: 0.04–0.75 m R3=13	Persist. 3–5 m; Apt: J1: 1–3 mm, J2: 1–3 mm, J3: 1–3 mm; Rough; Mud infill; Sl. weathered R4=15	DryR5=15	75	II, Good
F15	100–200R1=12	100R2=20	J1: 0.05–2.00 m; J2: 0.05–1.50 m; J3: 0.015–1.50 m R3=15	Persist. 0–3 m; Apt: J1: 1–20 mm, J2: 1–100 mm, J3: 1–30 mm; Rough to v. rough; Thick clay infill; Sl.–mod. weathered R4=14	DryR5=15	76	II, Good

Location F5

The rock shows UCS of 100–200 MPa, indicating very strong rock [10]. RQD is 94%, indicating excellent quality. It has three joint sets with spacing between 0.03 to 1.20 m. Discontinuities have persistency up to 3 m and apertures around 30 mm. Joint surfaces are rough with clay filling. The RMR value is 78, classifying it as Class II – Good rock.

Location F6

This location presents a UCS of >200 MPa, indicating very strong rock [10]. RQD is 99%, indicating excellent quality. The rock has three joint sets, joint spacing between 0.10 to 1.40 m. Discontinuities have persistency up to 2.5 m with 0 to 4 mm apertures. Surfaces are rough with clay-silt infilling. The RMR is 79, classifying it as Class II – Good rock.

Location F7

The rock has a UCS of >200 MPa, indicating very strong rock [10]. RQD is 89%, indicating excellent quality. It has three joint sets with spacing from 0.02 to 3.0 m. Discontinuities have persistence 3 to 10 m, with apertures around 3 mm. Joint surfaces are rough with some silt-clay filling. The RMR is 72, classifying it as Class II – Good rock.

Location F8

Here, UCS ranges between 100–200 MPa, indicating very strong rock [10]. RQD is 95%, classifying it as excellent quality. The rock shows three joint sets, with spacing from 0.002 to 1.60 m. Discontinuities are persistent up to 3 m, apertures up to 20 mm, and clay-mud infilling is common. RMR value is 78, classifying it as Class II – Good rock.

Location F9

This rock mass has UCS of >200 MPa, indicating very strong rock [10]. RQD is 100%, suggesting excellent quality. There are three joint sets, with joint spacing from 0.01 to 3.0 m. Discontinuities have persistence 1 to 2 m, apertures of 1 to 4 mm, and surfaces are rough with clay-mud infilling. The RMR value is 83, classifying it as Class I – Very good rock.

Location F10

UCS at this site is 100–200 MPa, indicating very strong rock [10]. RQD is 100%, suggesting excellent rock quality. Three joint sets exist with spacing from 0.400 to 3.00 m. Discontinuities have persistency up to 2 m, aperture is 5 mm, and clay infilling. Surfaces are very rough. The RMR value is 83, classifying it as Class I – Very good rock.

Location F11

Here, UCS is >200 MPa, indicating very strong rock [10]. RQD is 100%, indicating excellent quality. Three joint sets are observed, with spacing from 0.03 to 6.00 m. Discontinuities are persistent (1–2 m), aperture is 5 mm, and surfaces are very rough with clay infilling. RMR value is 83, classifying it as Class I – Very good rock.

Location F12

The rock has a UCS >200 MPa (very strong). RQD is 100%, indicating excellent quality. It has three joint sets, with spacing from 0.05 to 8.00 m. Discontinuities have persistence 2 m, apertures of 5 mm, very rough surfaces with clay-silt infilling. The RMR value is 85, classifying it as Class I – Very good rock.

Location F13

The rock has a UCS >200 MPa (very strong), and RQD is 100%, indicating excellent quality. The rock contains three joint sets with spacing from 0.05 to 3.00 m. Discontinuities have persistency 1 to 2 m, apertures of 5 mm, surfaces are very rough with mud infilling. RMR value is 83, classifying it as Class I – Very good rock.

Location F14

This location shows UCS >200 MPa and RQD is 90%; the rock is very strong and of excellent quality. It has three joint sets, spacing from 0.04 to 0.90 m. Discontinuities have persistence 3 to 5 m, with apertures around 3 mm, rough surface with clay infilling. RMR value is 75, classifying it as Class II – Good rock.

Location F15

This location shows UCS 100–200 MPa and RQD is 100%. It has three joint sets, spacing from 0.015 to 2.00 m. Discontinuities are persistent 1 to 3 m, apertures >20 mm, and surfaces are very rough with thick clay infilling. RMR value is 76, classifying it as Class II – Good rock.

4.2. Statistical summary and parameter analysis

To synthesize the site-wise rock mass data and identify the parameters controlling rock mass quality, statistical analysis was performed on the total RMR values and individual parameter ratings (R1–R5) obtained at all fifteen sites (F1–F15). The results are presented in Table 4 and illustrated graphically in Figures 5, 6, and 7. Pearson's correlation analysis was further applied to quantify the relationship between total RMR and each parameter rating, enabling objective identification of the dominant controlling variables.

Table 4: Statistical summary of RMR and parameter ratings across fifteen sites (F1–F15), Fagfog Quartzite, Kalu Pandey Highway.

Parameter	Mean	Min	Max	SD
RMR (Total)	78.6	72	85	4.4
R1 – UCS Rating	11.8	7	12	1.3
R2 – RQD Rating	19.8	17	20	0.8
R3 – Spacing Rating	15.8	13	20	2.1
R4 – Joint Cond.	16.3	12	19	2.0
R5 – Groundwater	15.0	15	15	0.0
RQD (%)	97.5	89	100	3.9

Total RMR values ranged from 72 to 85, with a mean of 78.6 and a standard deviation of 4.4 (Table 4; Figure 5). Based on the classification of bieniawski1989 [6], sites F3, F9, F10, F11, F12, and F13 were classified as Class I Very Good Rock (RMR 81–100), while the remaining sites F1, F2, F4, F5, F6, F7, F8, F14, and F15 fell within Class II Good Rock (RMR 61–80). The Fagfog Quartzite is consistently competent along the entire studied highway section. The relatively low standard deviation (4.4) indicates moderate spatial variability in rock mass quality, with the spread primarily governed by local discontinuity characteristics rather than changes in intact rock properties.

Examination of the individual parameter ratings (Table 4; Figure 6) shows that R1 (UCS rating) was uniformly high, recording a value of 12 at fourteen of fifteen samples (UCS 100–>200 MPa; very strong rock, hoek1997 [10]) and 7 at F2 (UCS 50–100 MPa), contributing negligibly to inter-site RMR variability. Similarly, R2 (RQD rating) was consistently near-maximum (mean 19.8, range 17–20), reflecting the excellent fracture condition of the quartzite throughout the studied section. R5 (groundwater rating) was 15 at all samples, as fieldwork was conducted during the dry season. These three parameters (R1, R2, R5) therefore contribute a near-constant combined value of approximately 47 to total RMR at all samples, and their role in driving RMR variability is minimal. In contrast, R3 (discontinuity spacing rating, mean 15.8, range 13–20) and R4 (condition of discontinuities rating, mean 16.3, range 12–19) show the greatest variation across sites (Figure 6) and are clearly the dominant controls on total RMR. Sites with the highest R3 and R4 ratings — F3, F9, F10, F11, F12, and F13 — consistently record Class I rock mass quality, whereas sites with the lowest R3 and R4 values — F1, F7, F14, and F15 — fall within the lower range of Class II.

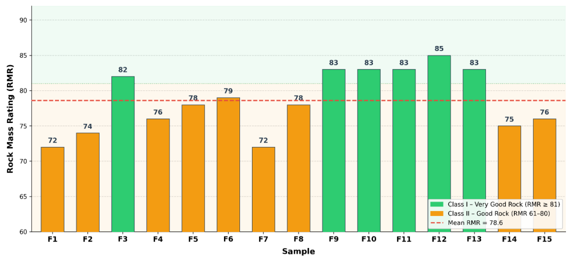

Figure 5: RMR values of Fagfog Quartzite.

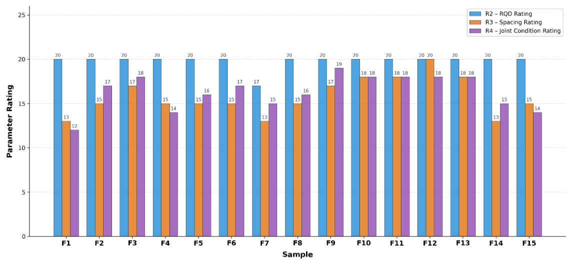

Figure 6: Parameter ratings R2, R3, R4 of Fagfog Quartzite.

Pearson's correlation analysis between total RMR and individual parameter ratings (Figure 7) confirms the qualitative observations above. R3 (discontinuity spacing) shows the strongest positive correlation with total RMR ($r = 0.938$), indicating that variation in joint spacing is the single most influential factor governing rock mass quality at the site scale. R4 (condition of discontinuities) also shows a strong positive correlation ($r = 0.841$), reflecting the significant influence of joint surface roughness, infilling material, aperture, and persistence on overall RMR. Together, R3 and R4 account for virtually all RMR variability observed across the fifteen samples. R2 (RQD rating) shows a moderate correlation ($r = 0.419$), which is attributable to its limited range (17–20) rather than a weak relationship. R1 (UCS rating) shows the weakest correlation ($r = 0.312$), consistent with the near-constant UCS across sites. These findings confirm that in the Fagfog Quartzite, the inherently high intact rock strength does not govern rock mass quality; rather, it is the geometry and condition of the discontinuity network — specifically joint spacing and joint surface characteristics — that determine engineering rock mass behavior.

Spatially, RMR values exhibit a recognizable trend along the highway alignment (Figure 5). Samples F1 and F2 show relatively low RMR values of 72 and 74 respectively, associated with closely spaced joints and clay-mud infilling. Moving along the highway, RMR increases progressively through the mid-section sites. The highest RMR values (82–85) are concentrated at samples F3 and F9–F13, where joint spacing is widest, surfaces are rough to very rough, and infilling is absent to minimal. Samples F7 and F14 are notable low-RMR outliers within the lower section (RMR 72 and 75 respectively), attributable to locally closer joint spacing (R3 = 13), lower RQD (F7: 89%), and clay-mud infilling (R4 = 15). Sample F12 records the maximum RMR of 85 in the entire dataset, characterized by the widest joint spacing (0.05–8.00 m), giving R3 = 20,

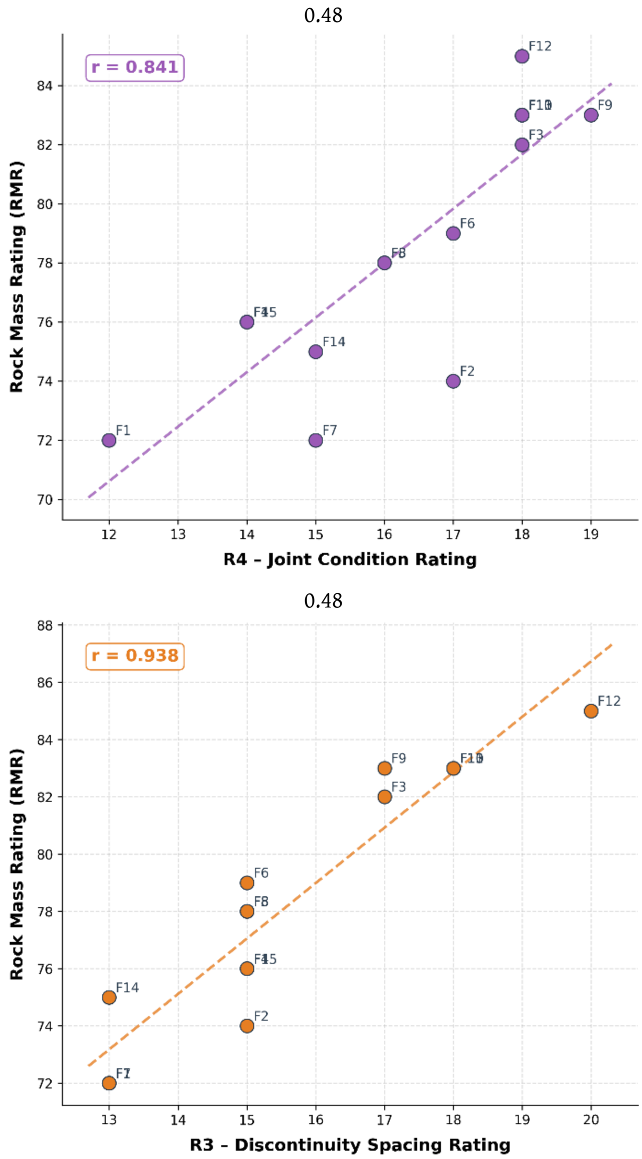

Figure 7: RMR vs. dominant parameters of the Fagfog Quartzite.

combined with a high joint condition rating (R4 = 18). This spatial pattern suggests that local structural controls — particularly variation in tectonic joint intensity along the NW–SE trending beds — are the primary driver of rock mass quality differences within the Fagfog Quartzite along this 4.2 km highway section.

5. Discussion

The investigation of fifteen sites (F1–F15) within the Fagfog Quartzite along the Kalu Pandey Highway reveals heterogeneity in rock mass quality across a 4.2 km reach. RMR values ranged from 72 to 85 (mean = 79.5, SD = 3.8), classifying nine sites as Class II Good Rock and six sites (F3, F9–F13) as Class I Very Good Rock [6]. Although UCS of the intact quartzite was high (100–>200 MPa; very strong rock, hoek1997 [10]) at 14 of 15 sites, UCS alone did not determine rock mass class. Discontinuity spacing (R3: 13–20) and condition of discontinuities (R4: 12–19) were the dominant controls on RMR variability (Table 3). Sites with wider joint spacing and rough, minimally infilled surfaces (R3: 17–20, R4: 17–19 at F3, F9–F13) consistently achieved Very Good rock quality. Sites with closer spacing and clay-mud infilled, persistent joints (R3: 13–15, R4: 12–15 at F1, F7, F14) yielded the lowest RMR values (72–75).

This confirms that discontinuity characteristics govern rock mass behavior, overriding the inherent strength of the quartzite matrix [6, 10]. RQD was uniformly excellent (89–100%) and contributed minimally to inter-site RMR variability. Groundwater conditions were completely dry at all sites during fieldwork (R5 $= 15$); however, monsoon-season infiltration is expected to reduce R5 from 15 to 7–10 (moist–damp), potentially lowering RMR by 5–8 points at susceptible sites and reclassifying some Class I sites to Class II. This seasonal effect on slope stability should be considered in highway maintenance planning.

Comparison with previous studies in the Himalayan region confirms broad consistency. tamrakar2013 [25] reported RMR values of 36–82 for quartzite formations in the Thopal–Malekhu River area, central Nepal. The higher minimum RMR (72 vs. 36) in the present study reflects the dominance of massive, unvaulted quartzite without significant shear zones. abbas2023 [1] documented comparable RMR distributions in Proterozoic quartzites in the Garhwal Himalaya, supporting regional consistency in geotechnical behavior of this rock type. The three discontinuity sets (J1 bedding-parallel NW–SE/NE; J2 and J3 conjugate) identified at all sites have direct implications for slope failure modes on the NE-facing cut slopes. J1, dipping $\sim 40^\circ$NE into the cut face, creates planar sliding potential where cut-slope angle exceeds joint dip. J1–J2 or J1–J3 intersections define wedge failure geometries. Steep J2 or J3 sets, where approximately parallel to the slope face, create toppling potential. A full kinematic analysis using stereographic projection and the SMR system [17, 26] is recommended to quantify failure mode probabilities at each site. The RMR data established here provide the necessary foundation for that analysis and for evidence-based slope maintenance prioritization along the Kalu Pandey Highway.

6. Conclusion and Future Work

1. RMR values of the Fagfog Quartzite ranged from 72 to 85 (mean 79.5), classifying nine sites as Class II Good Rock and six sites as Class I Very Good Rock [6]. No site fell below Class II, confirming the geotechnical competence of this unit.

2. Discontinuity spacing (R3) and condition of discontinuities (R4) were the dominant controls on RMR variability. Sites with wider spacing and rough, minimally infilled joints (F9–F13) achieved RMR 83–85; sites with closer spacing and clay-mud infilling (F1, F7, F14) yielded RMR 72–75.

3. UCS ranged from 50 MPa (strong) to $>$200 MPa (very strong; hoek1997 [10]); RQD was uniformly excellent (89–100%) at all sites. High intact strength did not solely determine rock mass class — discontinuity characteristics were the governing factor.

4. Three discontinuity sets (J1: bedding-parallel NW–SE/NE; J2, J3: conjugate) create potential for planar sliding, wedge failure, and toppling on highway cut slopes. Kinematic SMR analysis is recommended as the immediate follow-up study.

5. Groundwater was completely dry during dry-season fieldwork (R5 $= 15$). Monsoon-season infiltration may reduce R5 to 7–10, lowering RMR by up to 8 points. Seasonal RMR monitoring is recommended for slope hazard management.

6. This study provides the first systematic RMR dataset for the Fagfog Quartzite along the Kalu Pandey Highway, establishing a geotechnical baseline for slope stability management and SMR-based kinematic analysis.

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