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Field-based assessment of rock discontinuity and geological attributes of rock mass for stones for various engineering applications

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ABSTRACT

Because of the occurrence of various rock types within the short span of areas, the Malekhu Khola area is one of the most promising areas where scope of stones is high. This paper presents recognition of the most promising rock types in terms of their geology and discontinuity for evaluating suitability for building stones. The research focuses on the assessment of nine different rock types allocated along the Malekhu Khola, central Nepal. Geological parameters, rock mass characterization and discontinuity analysis were carried out in each of allocated sites. During field study, rock masses were categorised based on different geological parameters, and on number of joint set, tentative block shape, size and volume. Field-based data were tabulated, analysed, and finally identified for the block size and geometry, and rock mass quality for stones. The number of major joint set ranges from one to four with random joint sets. The study shows that the outcrop condition of rock is faintly to slightly weathered and strongly indurated. The study shows that the rock types depending on the Rock Mass Rating (RMR) system vary from poor to very good. The block types that could be extracted are flat, long and compact. The probable end uses of these rock types could be armourstone, interior and exterior paving, cladding and foundation.

Keywords: Natural stones, Joint volume, Discontinuity analysis, Geological attribute, Malekhu River

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INTRODUCTION

Natural stones are naturally occurring rock types used for various purposes such as walling, paving, or roofing materials in construction after different procedure of cutting or shaping. The use and demand of natural stones for various engineering purposes have been increased with urbanization in the remote areas of Nepal. Various studies have been carried out for the recognition of various rock types for dimension stones in Nepal (Ghimire and Napit, 2008; Shrestha and Napit, 2003; Singh and Tamrakar, 2013). However, the study of the most promising and prospective rock types is still lacking. Currently, a number of methods are being used for the assessment of discontinuity analysis (Palmström, 2001; Wang et al., 2003; Smith, 2004). In reference to research problem, this study is a kind of support to explore the rock types and their characteristics based on discontinuity analysis and geological attributes.

The study area belongs to the part of the Malekhu Khola watershed that is bounded by latitudes 27°44' N to 27°52' N and longitudes 84°48' E to 84°59'E, respectively (Fig. 1). Stratigraphically, the study area lies within the Lesser Himalaya of central Nepal (Stöcklin and Bhattarai, 1980). The study area extends across the strike of the major formations, which comprise of various rock types such as limestone, quartzite, amphibolite, marble, metasandstone, augen gneiss, granite etc. Because of occurrence of various rock types within the short span of areas, the Malekhu Khola area is one of the most promising areas where opportunity of stones is high. Preliminary field based study was used to assess the dimension, shape and size of rock mass. Most of the same rock types found within the same rock units along the Malekhu river corridor have varying characteristics because of their varying rock mass characteristics, mineralogical composition etc. which ultimately affects their suitability in engineering purposes.

Rock mass condition helps to know about the condition of rock, number of joint sets, persistency and their joint condition (Bieniawski, 1973). Joint set signifies the actual block shape for extraction (Elci and Tuck, 2014). Discontinuity analysis develops an idea on providing block volume, block size and finally helps to identify the economic zones for quarrying (Palmström, 1995). The block volume is an important parameter to estimate resource and enhance economical production for larger industries. Geology, rock mass characteristics and discontinuities help to identify and evaluate rock mass for probable engineering applications. Therefore, the objectives of the research were to explore rock types, their characteristics based on field-based geological assessment and discontinuity, and finally differentiate and evaluate rocks suitable for various engineering applications.

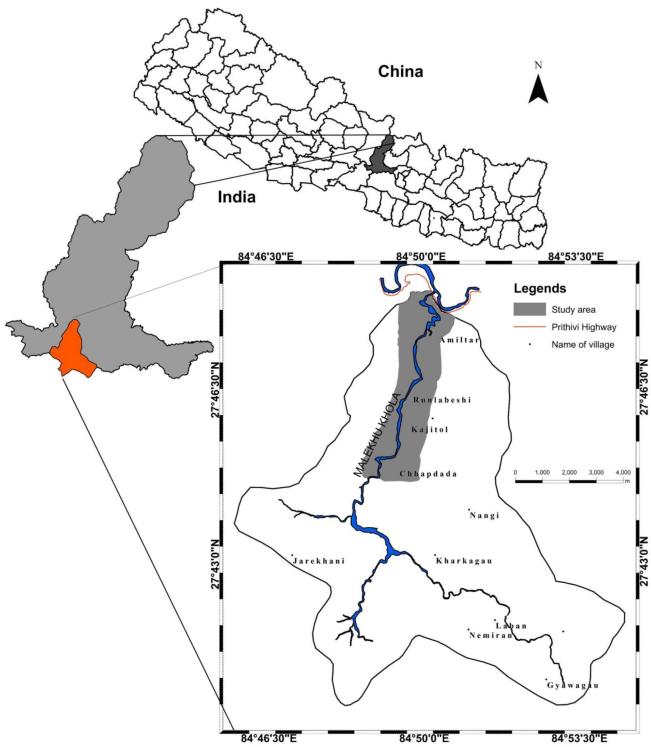

Fig. 1: Location map of the study area

METHODOLOGY

Reconnaissance survey was carried out using 1:25,000 scale maps traversing along the river corridor, gravel roads and trails. Nine locations were assigned for the field investigation depending on their probable rock types, outcrop extension and condition, topography, morphology, outcrop extension, rock quality and characteristics, socio-environmental consideration, etc. Geological attributes, geotechnical properties and discontinuity analysis are three indispensable properties that help to find the suitability of rock sample for engineering applications. Geological attributes focus on promising rock type, large vertical and lateral extension of rock mass, stratigraphical position in the Lesser Himalayan rock unit, whereas geotechnical studies help to find out the tentative rock mass quality, strength of rock mass and their characteristics. Finally, discontinuity analysis focuses on amount of block volume, block shape and size that could be extracted in a specified rock exposure. The attributes assessed during this studies were as below:

1. Geological attributes: Geological parameters mainly included outcrop, morphology, topography, dimension, structure, metamorphic grade, stratigraphy and lithology. Physical properties, texture, minor structures and even geographic situation determine the suitability of rock formation to exploitation.

2. Geotechnical studies: Rock mass rating (RMR) system was measured in accordance to Bieniawski (1989). Strength of intact rock, Rock Quality Designation (RQD), spacing of discontinuities, joint condition and groundwater condition were measured to calculate the Rock Mass Rating (RMR) system. Strength of intact rock was determined by hammering the rock exposure and their strength in response to hammer was correlated to Brown (1891). Finally, the RMR class was found to be the addition of above five parameters i.e.

$$RMR = R1 + R2 + R3 + R4 + R5 \quad (1)$$

where, R1 is the rating for strength of intact rock (UCS), R2 is the rating for Rock Quality Designation (RQD), R3 is the rating for spacing of discontinuities, R4 is the rating for joint condition and R5 is the rating for groundwater condition.

RQD % was found in reference to the Palmström (2005) as:

$$RQD\ (\%) = 110 - 3.5\ J_v \quad (2)$$

Joint volume (Jv) was calculated from average relation to joint frequency, where average joint frequency was determined from joint spacings measured perpendicular distance between two major joint sets, and using the following equation:

$$J_v = 1/S_1 + 1/S_2 + 1/S_3 \quad (3)$$

where, S_1: Maximum joint spacing, S_2: Intermediate joint spacing and S_3: Minimum joint spacing (Fig. 2).

3. Discontinuity analysis: The discontinuity analysis included joint spacing, joint frequency, joint density, joint volume, joint size, joint shape and block quality designation (BQD). The measurement and characterization of rock mass jointing was done in reference to Palmström (2005) which discusses on joint conditions of rock:- Joint roughness, Joint alteration, Joint size, and termination. Palmström (1995) assessed the block size (expressed as block volume, V_b in m^3) of the rock mass from the equation:

$$V_b = \beta \times J_v^{-3} \quad (4)$$

where, β is a block shape factor, which was determined in accordance with the jointing pattern (from Palmström, 1995, using the following relation:

$$\beta = (\alpha_2 + \alpha_2 \times \alpha_3 + \alpha_2)^3/(\alpha_2 \times \alpha_3)^2) \quad (5)$$

where, $\alpha_2 = S_2/S_1$, $\alpha_3 = S_3/S_1$. For the assessment of the rock mass analysis, Block Quality Designation (BQD) was determined in accordance with Elci and Turk (2014) as follows:

$$BQD\% = (Ls/L) \times 100 \quad (6)$$

where, Ls = Sum total scanline length of joint sets more than 1 m) and L = Total length of the scan line.

Finally, nine different sites were evaluated for probable end uses for engineering purposes based on their weathering grade, induration, BQD, Joint volume, Joint shape and Strength of intact rock.

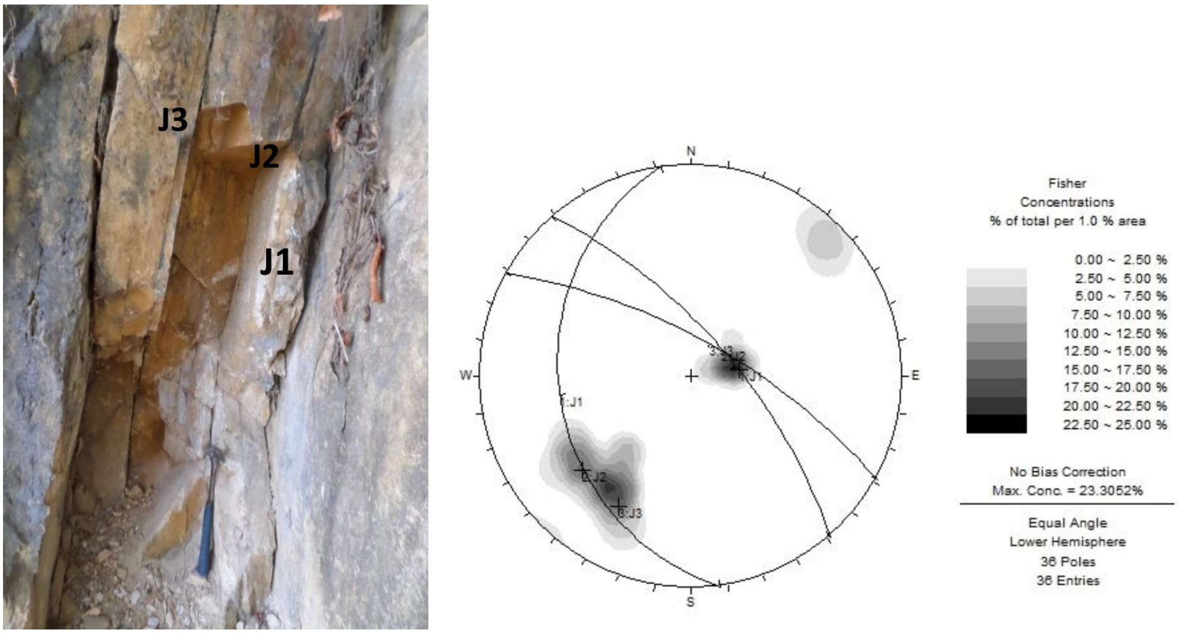

Fig. 2: Rock exposure showing their (a) major joint set (b) stereoplot of given sample (sample: BM-M1)

GEOLOGICAL SETTING

The stratigraphy of the study area is discussed under the Nawakot complex and the Kathmandu Complex as shown in Table 1 (Stöcklin and Bhattarai, 1977; Stöcklin, 1980). The Nawakot Complex comprises the Lower Nawakot Group and the Upper Nawakot Group (Precambrian age). The Kathmandu Complex is divided into the Bhimphedi Group (older-precambrian age) and the Phulchauki Group (younger Paleozoic age). The study area comprises the Upper Nawakot Group, the Bhimphedi Group and the Phulchauki Group (Tistung Formation) (Table 1, Fig. 3).

Table 1: Stratigraphic succession of Central Nepal (After Stöcklin and Bhattarai, 1997, and Stöcklin, 1980)

Unit		Formation	Main Lithology	Apparent Thickness (m)	Age
Kathmandu Complex	Phulchauki Group	Godavari Limestone	Limestone, dolomite	300	Devonian
		Chitlang Formation	Slate	1,000	Silurian
		Chandagiri Limestone	Limestone	2,000	Cambro – Ordovician
		Sopyang Formation	Calc-phyllite, slate	200	Cambrian
		Tistung Formation	Metasandstone, phyllite	3,000	Late Precambrian
			Transitional Contact		
	Bhimphedi Group	Markhu Formation	Marble, schist	1,000	Late Precambrian
		Kulikhani Formation	Quartzite, schist	2,000	Precambrian
		Chisapani Quartzite	White quartzite	400	Precambrian
		Kalitar Formation	Schist, quartzite	2,000	Precambrian
		Bhainsedobhan Marble	Marble	800	Precambrian
		Raduwa Formation	Garnetiferrous schist	1,000	Precambrian
			Mahabharat Thrust (MT)		
Nawakot Complex	Upper Nawakot Group	Robang Formation	Phyllite, quartzite	200 – 1,000	Paleozoic
		Malekhu Limestone	Limestone, Dolomite	800	Paleozoic
		Benighat Slate	Slate, argillaceous dolomite	500 – 3,000	Paleozoic
			Unconformity (?)		
	Lower Nawakot Group	Dhading Dolomite	Stromatolitic dolomite	500 – 1,000	Late Precambrian
		Nourpul Formation	Phyllite, quartzite, dolomite	800	Late Precambrian
		Dandagaon Phyllite	Phyllite	1,000	Late Precambrian
		Fagfog Quartzite	White quartzite	400	Late Precambrian
		Kuncha Formation	Phyllite, quartzite, Conglomerate, gritstone	5,000	Late Precambrian
			Main Boundary Thrust (MBT)		
Siwalik Group			Conglomerate, sandstone, mudstone,	Several Kilometers	Neogene

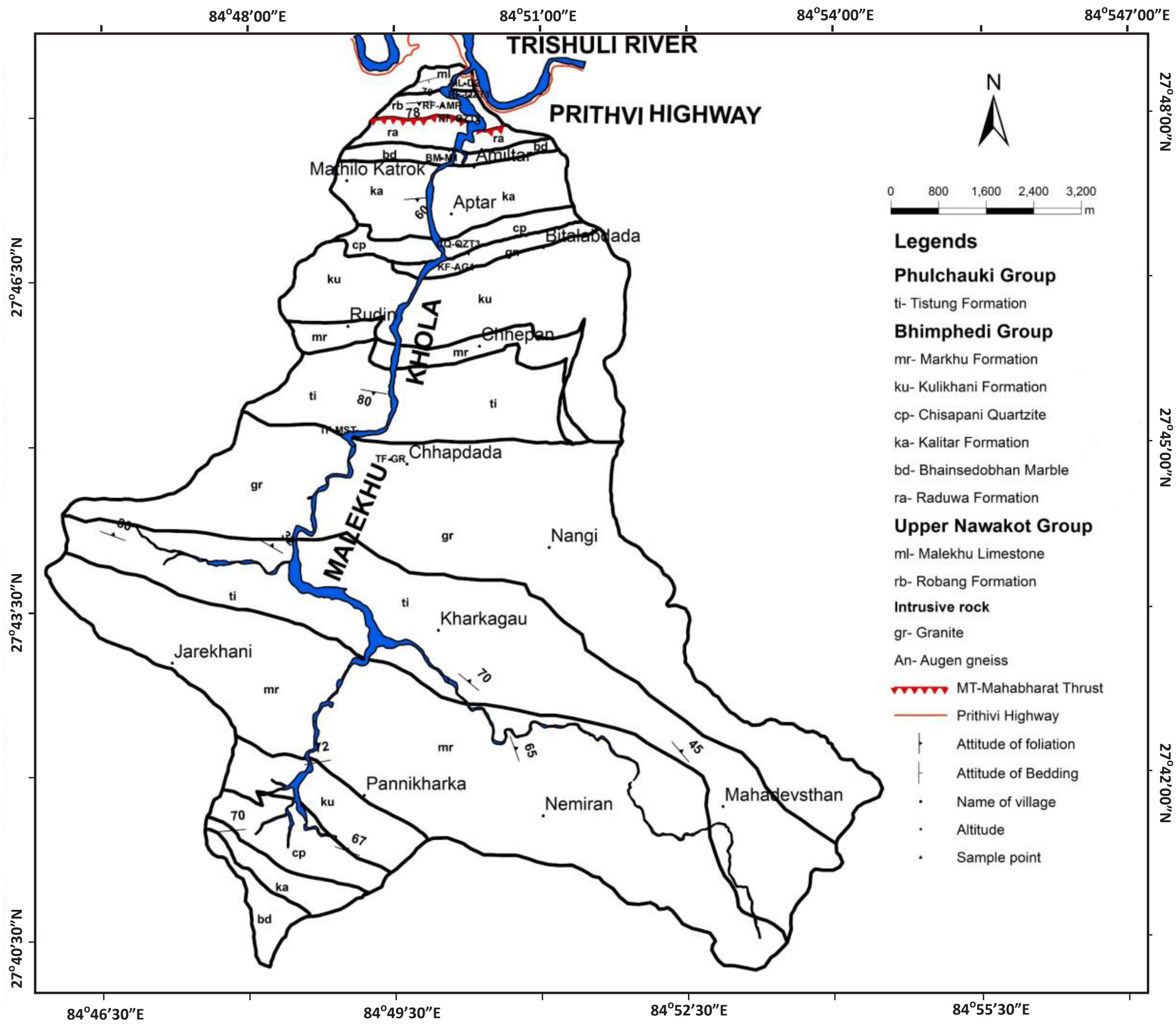

Fig. 3: Geological map of the study area (Stöcklin and Bhattarai, 1977 and Stöcklin, 1980)

The granitic intrusion exists at the middle stretch of the Malekhu Khola that comprises south dipping northern limb. The upstream stretch comprises of north dipping southern limb indicating the core of the Mahabharat Syncline.

RESULTS

Nine different desirable sites were categorized into three classes based on their rock types, lithology and compositions.

1.Finely crystalline argillaceous dolomite (ML-D2),

2.Foliated, medium to coarsely crystalline, white to light grey quartzite (RF-QZT1, RF-QZT2 & CQ-QZT3), massive, coarsely crystalline white marble (BM-M1) and coarsely crystalline and dark grey augen gneiss (KF-AG1), and

3.Foliated, medium crystalline and green amphibolite (RF-AMP) and massive, coarsely crystalline granite (TF-GR).

Geological attributes

The limestone (ML-D2) of the Malekhu Limestone has dark grey to bluish grey, finely crystalline, argillaceous parting, laminated, intercalation of crenulated phyllite with quartz vein in few portions. Quartzite samples of the Robang Formation (RF-QZT1 and RF-QZT2) has light grey to dark grey, fine to medium grained, crystalline and laminated (Figs. 4a and b). But quartzite of the Chisapani Quartzite is dark grey medium to coarsely crystalline (Fig. 4c). The marble rock mass of the

Fig. 4: Dark grey to grey quartzite samples: (a) Serricite quartzite, RF-QZT1, (b) Quartzite RF-QZT2, and (c) Dark grey medium-grained quartzite CQ-QZT3

Bhainsedobhan Marble (BM-M1) has white, fine to medium crystalline texture. The Augen gneiss rock mass of the Kulikhani Formation (KF-AG1) is dark grey coarsely crystalline texture. The metasandstone is dark grey and granite of the Tistung Formation (TF-GR) has coarse crystalline textue. All the sample sites contain well developed foliation having three to four major joint sets with varying random joint sets. Besides rock of granite, all the samples have medium grade of metamorphism. Weathering condition and induration range from slightly to moderately weathered and strongly to very strongly indurated, respectively.

Most of the sites have precipitous topography with 65^0 hillslope angle while the site TF-MST on the left bank of the Malekhu Khola has steep hill slope (45^0). The site of quartzite of the Robang Formation has a cliffed hillslope that falls under 85^0. The outcrop dimension is the largest in granite with 300×100 m^2 and smallest in quartzite of the Robang Formation (Dhunga Quartzite member: RF-QZT2) with 80×30 m^2. The extension of the rock exposure is found to be continuous and extends laterally and vertically by more than 100 m.

Geotechnical studies

RMR system proposed by Bieniawski, 1989 shows rock sample falls between fair to very good rock, the quartzite of the Robang Formation being fair and the augen gneiss of the Kulikhani Formation falls under very good (Table 3). Rest of the sample falls under good rock type. For the quality of block extraction, the Block Quality Designation (BQD) value ranges from very poor to good type (Table 3). Very good rock types are of dolomite, quartzite (ML-D2, RF-QZT1 & RF-QZT2) and good rock types are of augen gneiss and amphibolite (KF-AG1 & RF-AMP).

Discontinuity analysis

Average joint frequency of rock varies from 4.28 to 30.39. The block volume that could be extracted from nine different sample sites ranges from 0.1 to 12.68 m^3. The block shape factor β ranges from nine different rock types ranges from 21.66 to 124.81 m^3 (Table 4). Tentative block shape was determined based on Palmström (1995) where samples ML-D2

Table 2: Overall geological attributes of nine different sites

Sample no	ML-D2	RF-QZT1	RF-AMP	RF-QZT2	BM-M1	CQ-QZT3	KF-AG1	TF-MST	TF-GR
Topography	Precipitous hill slope, 65°			Cliffed hill slope, 85°	Precipitous hill slope, 65°			Steep hill slope, 45°	Precipitous hill slope, 65°
Outcrop dimension (m²)	22.5*12.5	75*42.5	32.5*17.5	80*30	12.5*9.5	45.5*17.5	67.5*15.5	45.5*12.5	300*100
Stratigraphy	Malekhu limestone	Robang formation			Bhainsedobhan marble	Chisapani quartzite	Kulikhani formation	Tistung formation	
Morphology	Continuous, more than 100 m lateral and vertical extension								
Structure	Foliation, 4 set joint		Foliation, 3 set joint	Foliation, 4 set joint,	Foliation, 3 set joint,	Foliation, 4 set joint	Foliation, 3 set joint,	Random joint,	Foliation, 3 set joint,
Metamorphic grade	Medium grade								Medium grade
Lithology	Dolomite, white, fine, crystalline			Quartzite, dark grey, fine-medium, crystalline.	Marble, white, fine - medium, crystalline.	Quartzite, dark grey, coarse, crystalline	Augen gneiss, dark grey, crystalline, coarse.	Granite, dark grey, coarse, crystalline	Metasand-stone, dark grey, fine-medium.
Weathering grade	IB			II	II	IB	IB-II	II	II
Induration	H4 – H5			H4	H5	H4	H4	H4 –H5	H4-H5

Induration: H5 = Very Strongly Indurated, H4 = Strongly Indurated Larsen et al. (1995); * Weathering grade: IB = faintly weathered II= slightly weathered GSL (1977).

Table 3: Rock mass rating category of the studied sample

Sample no	Rock Mass Rating parameters					RMR value	RMR category
	R1	R2	R3	R4	R5		
ML-D2	7	17	9	20	15	68	Good rock
RF-QZT1	12	8	12	20	15	67	Good rock
RF-AMP	15	17	13	14	15	74	Good rock
RF-QZT2	12	3	9	17	15	56	Fair rock
BM-M1	12	20	14	13	15	74	Good rock
CQ-QZT3	15	13	12	17	15	72	Good rock
KF-AG1	12	20	18	16	15	81	Very good rock
TF-GR	12	20	13	8	15	60	Fair rock
TF-MST	12	20	13	20	7	74	Good rock

*R1, Unconfined Compressive Strength (UCS); R2, Rock Quality Designation (RQD); R3, Joint condition; R4, Joint roughness; R5, Groundwater Conditions

Table 4: Table showing discontinuity analysis of the study sites

Sample no		ML-D2	RF-QZT1	RF-AMP	RF-QZT2	BM-M1	CQ-QZT3	KF-AG1	TF-GR	TF-MST
JOINT DENSITY	Total freq.	8.9–27.74	3.45–58.34	1.39–20.20	3.25–75.35	3.33–24.30	4.33–28.36	1.08– 5.70	2.28 – 12.0	1.60 – 18.10
	Av .Freq (Jv)	18.3	30.4	11	36.94	13.82	16.33	4.28	7.7	10.54
Block size (V_b, m³)		5.67	0.56	4.1	0.8	1.26	0.1	12.68	2.3	0.23
Block shape factor (β)		217	36.8	27	28.33	75.21	123.8	28.79	39	31.86
Block type		Long and flat	Flat	Compact	Compact	Flat	Long	Compact	Flat	Compact

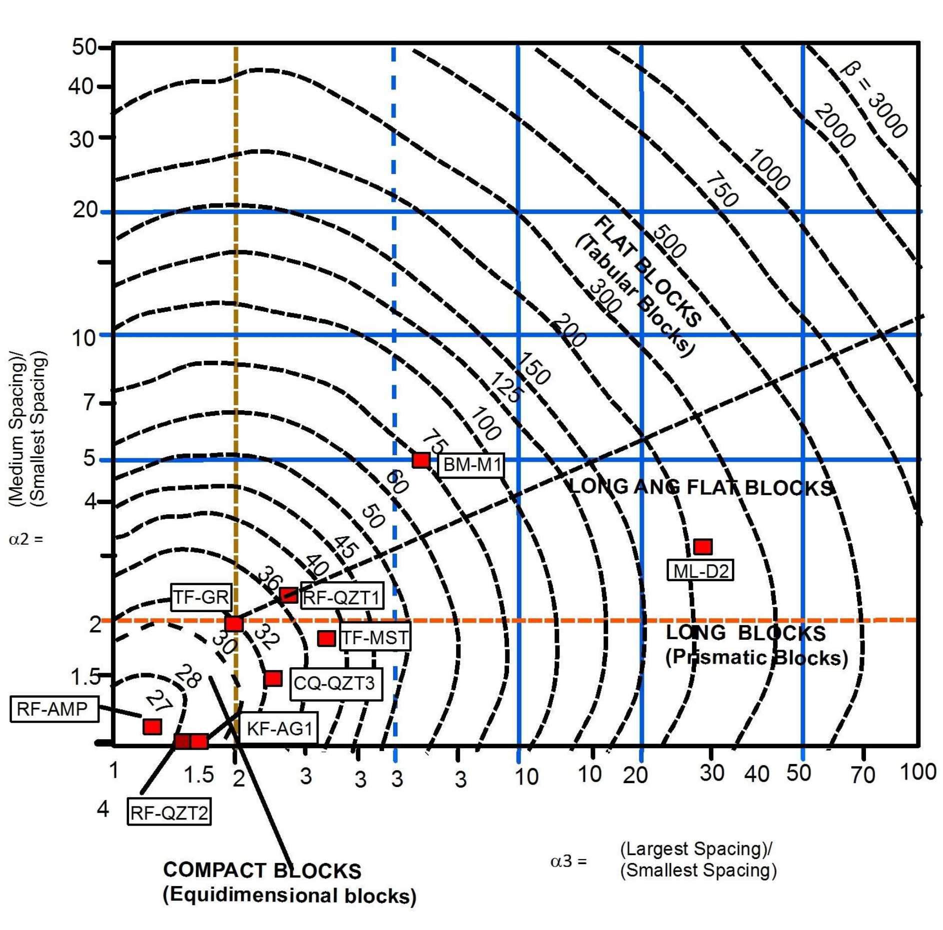

Fig. 5: Block types characterized by the block shape factor of the studied samples

Table 5: Summarized table for interpretation (Armourstone)

Sample	ML-D2	RF-QZT1	RF-AMP	RF-QZT2	BM-M1	CQ-QZT3	KF-AG1	TF-GR	TF-MST
Lithology	Dolomite	Quartzite	Amphibolite	Quartzite	Marble	Quartzite	Augen gneiss	Granite	Metasandstone
BQD category	Poor	Very Poor	Good	Very Poor	Poor	Very Poor	Good	Poor	Fair
Volumetric Joint	18.3	30.4	11.4	36.9	13.8	16.33	4.3	7.7	10.54
volume(Jv) m^3	SB	VSB	SB	VSB	SB	SB	MB	MB	MB
UCS, Mpa	50-100	100-250	> 250	100-250	100-250	> 250	100-250	100-250	100-250
	M	G-E	E	G-E	G-E	E	G-E	G-E	G-E
Evaluation for armourstone	M	M	G	M	G	G	G	G	G

UCS value (Excellent, E > 192 Mpa, Good, G = 96-192 Mpa, Marginal, M = 36 - 96 Mpa, Poor, P = < 36 Mpa (CIRIR/CUR, 1996); ISRM, 1978, Jv : VLB <1 ; LB = 1 – 3; MB = 3 – 10; SB = 10 – 30; VSB > 30 m³;; (Estimated probable use G = Good & M = Moderate) has long and flat blocks, RF-AMP and KF-AG1 have compact blocks, RF-QZT1, TF-GR and BM-M1 have flat blocks, and the other samples have long block shape (Fig. 5).

Volumetric joint count (J_V) ranges from 4.3 m^3 (moderate blocks) to 36.9 m^3 (very small blocks) in accordance with ISRM (1978) and Toyos et al. (1994). BQD ranges from very poor in quartzite samples to good in amphibolite and augen gneiss, respectively.

EVALUATION OF STONES FOR VARIOUS ENGINEERING APPLICATIONS

Nine different sites were evaluated for armourstone and stone masonry based on their rock mass characteristics, discontinuity properties and unconfined compressive strength. Rock types analysed for evaluation were dolomite, sericite quartzite, amphibolite, marble, quartzite, augen gneiss, granite, metasandstone etc. Weathering grade and induration range from faintly to slightly weathered and strongly to very strongly indurated, respectively. These can be used for both armourstone and stone masonry.

Armourstone

Quartzite (RF-QZT1 and RF-QZT2) of the Robang Formation can be used moderately for armourstone because of very poor BQD, very small block shape and strength value that ranges from 100–250 MPa. Another quartzite sample (CQ-QZT3) has similar properties with two other quartzite samples but have higher strength value, which indicates that this rock type can be used for armourstone. Dolomite and amphibolite have similar properties having poor BQD and small block shape but amphibolite has higher strength value compared to the former two rock types and indicates that amphibolite can be used for armourstone (Table 5). Granite sample being poor in BQD % value, it has moderate block shape with wide range of strength values, and therefore can be used for armourstone. Being fair in rock type, moderate block size and wide range of UCS value, metasandstone can be used for armourstone (Table 5).

Random rubble masonry

Considering UCS values, all samples except metasandstone (TF-MST) have excellent UCS values in accordance with CPWD (2009) (Table 6). Being very small in block shape, very poor in BQD and having a wider range of strength value, quartzite samples of the Robang Formations are moderately suitable for stone masonry. While other quartzite sample CQ-QZT3 of the Chisapani Quartzite can be used for stone masonry because of its higher strength value. Dolomite and marble have poor BQD and small block shape indicating their usefulness for stone masonry due to higher strength values. Both the samples amphibolite and augen gneiss have excellent UCS values and good BQD. Among these rock types, amphibolite can be used moderately for stone masonry and augen gneiss is good enough to use because of its small and moderate block shape. Granite and metasandstone can be used for stone masonry because of their excellent UCS value and moderate block shape.

DISCUSSIONS

Quartzite samples of the Robang Formation (RF-QZT1 and RF-QZT2) and of the Chisapani Quartzite (CQ-QZT3) have more or less similar mineralogical composition but they have varying strength values due to their textural characteristics (Kheirelseed et al., 2008; Bista and Tamrakar, 2015). RF-QZT1 and RF-QZT2 differ in textural properties but these samples have same strength range due to presence of sericite minerals in RF-QZT1. Sample KF-AG1 and TF-GR require blasting during excavation because of massive structure, few joint sets with large persistency, high BQD %, high strength value and low weathering grade. Agra granite of the Malekhu Khola and Ipa granite of the Makawanpur (Ghimire and Dhakal, 2007) are comparable to each other based on their strength value. Weathering grade ranges from slightly to moderately weathered indicating rock types slightly altered but not decomposed into clay minerals (Geological Society of London, 1977). Induration of most of the rock types ranges from strongly to very strongly indurated which indicates that rock types are stiff enough and have strong strength (Larsen et al., 1995). Most of the samples

Table 6: Summarized table for interpretation (Random Rubble Masonry)

Sample	ML-D2	RF-QZT1	RF-AMP	RF-QZT2	BM-M1	CQ-QZT3	KF-AG1	TF-GR	TF-MST
Lithology	Dolomite	Quartzite	Amphibolite	Quartzite	Marble	Quartzite	Augen gneiss	Granite	Metasandstone
BQD category	Poor	Very Poor	Good	Very Poor	Poor	Very Poor	Good	Poor	Fair
Volumetric	18.3	30.39	11	36.94	14	16.3	4.28	8	11
Joint volume (Jv)	SB	VSB	SB	VSB	SB	SB	MB	MB	MB
UCS, Mpa	50-100	100-250	> 250	100-250	100-250	> 250	100-250	100-250	100-250
	E	E	E	E	E	E	E	E	G-E
Evaluation for stone masonry	G	M	G	M	G	G	E	G	E

** 98 Mpa granite; 20 Mpa Limestone; 80 Mpa Quartzite; 50 Mpa Marble (CPWD, 2009) except quartzite samples of the Robang Formation show high RQD values correspond to good to very good rock types. Augen gneiss, granite and amphibolite can be used for economical production for quarries. These rock sites are considered as suitable. The use of rock types may vary with the implication of their uses in field of building construction. Generally, the long and flat block can be used for slabbing and paving in outdoor use. The compact blocks can be used for foundation, retaining walls and stone masonry. The elongate blocks can be used as curb stones.

CONCLUSIONS

From the assessment of nine different rock types, the quality of rock masses was found to be fair to very good. From discontinuity analysis, BQD % was found to be very poor to good (0–81%). Block volume ranges from 21.789 (Malekhu limestone) to 123.81 m^3 (Chisapani quartzite). Block shape was found to be long, flat and compact.

From the study, it can be concluded that the engineering applications for the same rock types can be different due to variation in the number of block size, weathering condition, block shape, induration, strength etc. Generally, dolomite, marble, augen gneiss, quartzite, metasandstone and granite can be used for both armourstone and random rubble masonry. End-use for same rock type is influenced by discontinuity, quality, block shape and how it breaks. Generally, the long and flat block can be used for slabbing, paving in outdoor use. The compact blocks can be used as foundation, retaining walls and stone masonry.

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