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ORIGINAL ARTICLE

Study of Freeze-thaw Induced Damage Characteristic for Himalayan Schist

A.K. Verma[1]*, Sahil Sardana[2] and Amit Jaiswal[3]
[1]Department of Civil and Environmental Engineering, Indian Institute of Technology Patna, Patna - 801 106, India
[2]Department of Mining Engineering, Indian Institute of Technology (Banaras Hindu University) Varanasi - 221 005, India
[3]Department of Mining Engineering, Indian Institute of Technology (Indian School of Mines) Dhanbad - 826 004 India
***E-mail:** *amitvermaism@gmail.com*

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ABSTRACT

The freeze-thaw (F-T) induced deterioration in rocks affects their durability, leading to various landslides, rockslides, and avalanches. The study focuses on estimating loss in rock strength using mineralogical properties under the influence of multiple F-T cycles. The rock samples were collected from F-T affected north Indian Himalayan region. The rock specimens were subjected to multiple F-T conditioning (0th, 10th, 20th and 30th F-T cycles). The mineralogical properties (such as mineralogical indices and textural indices) and mechanical properties (such as uniaxial compressive strength; UCS and Brazilian tensile strength; BTS) were calculated before and after F-T conditioning. A correlation was developed among the various strength properties and mineralogical properties. The result shows a strong relationship between the UCS and BTS with mean grain size. Further, results were used to develop a mathematical model, based on mineralogical parameter and decay function, to predict the rock strength under the influence of multiple F-T cycles.

INTRODUCTION

The rock slopes in Himalayan regions are exposed to different climatic conditions. At high altitudes, extreme temperature variation is encountered by rocks. The temporal variation and climatic conditions result in physical weathering of rocks that accelerates the rock to break apart. The cyclic freezing and thawing (F-T) cause rocks to disintegrate, resulting in the instability of rocks. In the course of the freezing and thawing process, the transition of water to ice causes 9% volume expansion (Davision and Nye 1985; Park et al. 2020). Deterioration in rocks because of F-T conditioning might cause quick change in their strength and therefore, the durability gets limited with time (Tan et al. 2011; Jamshidi et al. 2017; Chen et al.2021; Ito et al.2021). In natural conditions, most substance does not disintegrate because of single FT cycle, but repeated FT cycles (Deprez et al. 2020).

In the past two decades, numerous investigation has been carried out on the mechanical and physical properties, along with durability of several rocks exposed to F–T (Mutluturk et al. 2004; Yavuz et al. 2006; Yavuz 2011; Jamshidi et al. 2017; Du et al. 2017; Hashemi et al. 2018; Torabi-kaveh et al. 2019; Wang et al. 2020). Some of the studies have been discussed below.

Nicholson et al. (2000) examined the influence of F-T cycle on ten different types of sedimentary rocks having primary fissures and cracks. They suggested that four types of damage were caused by F-T cycle. The outcomes of the study investigated by Mutluturk et al. (2004) showed a declining trend and proposed a decay model to estimate the Brazilian tensile strength (BTS), point load strength index (PLSI) and uniaxial compressive strength (UCS) of the volcanic rock sample (Isparta ignimbrite) following repeated F–T cycle. Similarly, Bayram (2012) also predicted the loss in UCS value based on statistical analysis for different limestone rock post F-T cycle. Jamshidi et al. (2017) evaluated the strength of travertine stones under F-T setting and proposed a physico-mechanical model to determine UCS, BTS and PLSI. Mousavi et al. (2020) investigated the degradation of Iranian Schist under multiple F-T. Recently, Jamshidi (2021) proposed another model to predict the UCS and BTS using petrographic properties influenced under F-T conditioned.

Most of the proposed studies relied on the physico-mechanical properties to examine the strength of rocks after repeated F-T cycle. Whereas, there is scarce literature concerning estimation of the rock strength using petro-mechanical properties. This parallel study may provide more reliable and stronger evidence of rock weathering and n its strength weakening. Therefore, in the present study, an attempt has been made to evaluate the durability of metamorphic rock subjected to multiple F-T cycles involving petrographical and physico-mechanical approaches in the laboratory. The petrographic analysis includes both textural and mineralogical parameters. Efforts have also been made to establish the correlation between physico-mechanical parameters with petrographical parameters.

STUDY AREA

Location of the Area

The study area is part of the northwest Himalayas, with an average elevation ranging from 2666m to 2780 m. The studied portion incorporates four locations located on the roadside from Manali to Atal Tunnel, Himachal Pradesh (India). The latitude and longitude of location are N32°20'2.1" to N32°17'26.29" and E77° 8'42.61" to E77°10'48.98", respectively. The area comes under a toposheet number of Survey of India is 143X3. The rock slopes of the studied area have sharp variation in dip amount in the area i.e. 70° to almost vertical and prone to avalanche (Verma et al. 2018). Figure 1 shows the locality of the studied area. During the field visit of the study area, the average attitude of bedding observed was (125°/20° SW). Three major types of joint sets were observed having attitude —joint J1 (060° /50° SE), joint J2 (002°/85° E) and joint J3 (265° /70° N). The portions of beds

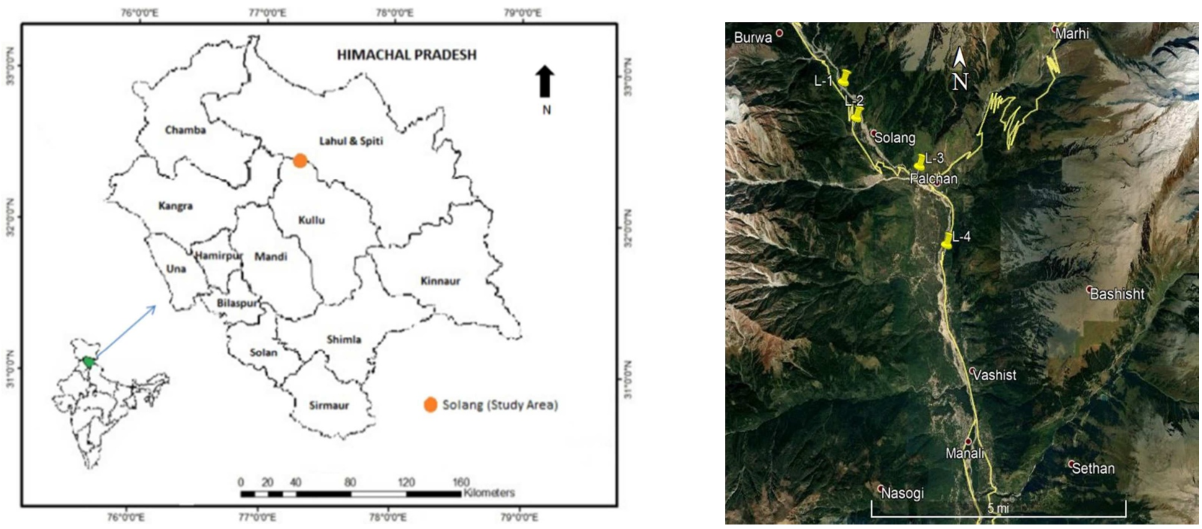

Fig.1. Location of the study area.

exposed along the roadside are moderate to highly weathered, whereas upper parts of the beds are unweathered. The major rock type encountered during field traverse was medium grade schist. The temperature variation of the study area is between minimum -15 ºC to maximum of +15 ºC.

Geology of the Area

The geological background of the study area consists of four major tectonostratigraphic units along Beas river valley (Thakur ,1992; Misra and Tiwari, 1988; Yin, 2006; Webb et al. 2011) and is present as Larji–Rampur window Group, Chail Group, Jutogh Group and Vaikrita Group; from south to north respectively. The tectonic division between Larji-Rampur window Group and Chail Group is known as the Chail thrust. The Chail Group is tectonically overlain by rocks of Jutogh Group and the tectonic contact between both groups marked by the Jutogh thrust which is considered to be a continuation of the MCT. The rocks of Jutogh Group are low- to medium-grade metamorphics comprising of biotite-chlorite schist, mica schist, gneisses and with intrusive granites of Proterozoic to Paleozoic ages. The high-grade metamorphics and migmatites rock of Vaikrita Group is overthrusted on Jutogh Group in north. The glacier originated river Beas in the higher Himalaya, cut across the topography and formations are well exposed along the river. The formation of the study area is tectonically deformed and mylonitized. Various other types of rock formation that are exposed in and around the study area are foliated micaceous quartzite, quartz-biotite schist, biotite porphyroblast schist and fined grained banded gneisses.

METHODOLOGY

In the present study, Biotite Schist from Solang Valley and the nearby area, have been subjected to multiple F-T conditioning to anaylse the petrographical parameters and its comparison with different physicomechanical properties have been conducted.

Freeze-thaw Testing of Rock Specimens in laboratory

NX size cylindrical core and lumped shaped small-sized rock specimens were treated with multiple F-T cycles in the laboratory according to ASTM (2013) standard. The temperature and duration of freezing/thawing are important parameters in F-T testing. Therefore, the range of these parameters was selected by considering the ASTM standard and the field conditions. All the rock specimens were saturated for 72 h prior to the F-T testing in the water-filled container. The container was then transferred to the freezer maintained at -20ºC for 12h. After that, frozen specimens were shifted to the water bath maintained at +30ºC for 12h. Figure 2 shows the frozen rock specimens. The F-T was repeated for 30 cycles and specimens were taken out to conduct mineralogical and physio-mechanical testing.

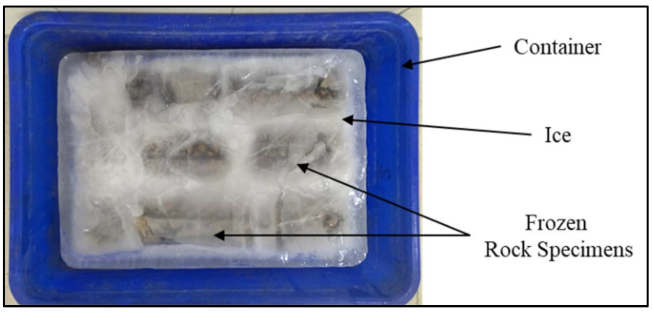

Fig. 2. Frozen rock specimens from the freezer at -20ºC.

Petrographic Analysis and SEM

The petrographic investigation was performed on macroscopic and microscopic scales for mineralogical and textural parameters. Two polished thin-section were prepared in the laboratory from rock samples of every 10^{th} cycles of F-T for studying under a petrological microscope. Thin sections were also examined under scanning electron microscope (SEM) for observing porosity change through widening of cracks and voids, fragmentation of rock into smaller pieces and change in structures of minerals present in rock.

Petrographic Analysis

The petrographic attributes include estimation of textural and mineralogical parameters using thin sections. According to Middleton et al (1985), it is necessary to have at least two thin sections to calculate the requisite indices. Generally, 50 to 200 grains are taken to analyse a single thin section adequately. In this study, about 280-300 grains from each thin section were analysed to conclude the result. Petrological microscope was used to determine mineralogical and textural indices under both plane-polarized and cross-polarized luminescence. The image processing was performed using software Image J v1.8.0 developed by Wayne Rasband of the National Institute of Health, USA. The steps involved in image processing are given in the flowchart (Fig. 3). In first step image was captured from a digital camera mounted on the microscope, then image processing was done with the help of segmentation and threshold setting and then mineral

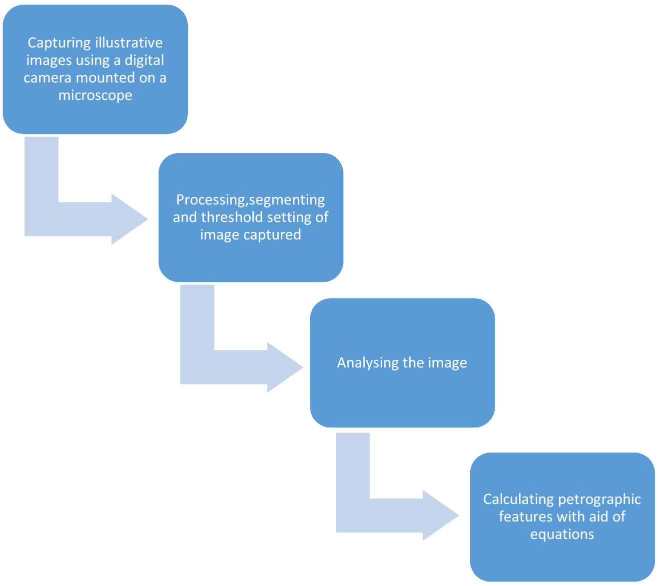

Fig. 3. Steps involved in image processing.

identification and modal percentage calculation was carried out.

For the study of mineralogical indices, average quantitative mineralogical data (modal concentration of minerals) were calculated. The mineralogical indices, namely, Feldspathic Index (IF), Quartz-Feldspar Index (IQF) and Colouration Index (IC), and textural indices namely, Mean Grain Size (MGS) and grain morphometry through Aspect Ratio (AR), were calculated using thin sections conditioned with 0^{th}, 10^{th}, 20^{th} and 30^{th} F-T cycle.

Mineralogical Indices

Feldspathic Index (IF) represents the ratio of the amount of (Or) orthoclase to the added amount of orthoclase and (Pl) plagioclase. Colouration Index (IC) represents the total amount of the coloured or dark minerals present in the rock. Quartz-Feldspar Index (IQF) represents the proportion of the amount of (Qz) Quartz to the added amount of orthoclase and plagioclase. The mineralogical indices, IF, IC, and IQF can be estimated using Eq. 1-3 respectively.

$$IF = Or\% /((Or + Pl)\%) \quad (1)$$

$$IC = 100 - (Qz + Or + Pl)\% \quad (2)$$

$$IQF = Qz\% / ((Or + Pl)\%) \quad (3)$$

Textural Indices

Mean grain size (MGS) index represents the measure for the mean grain size of minerals present in rock. Aspect ratio represents the elongation of individual grains and is defined as the ratio of length to the width of individual grains. In the case of circular grain, the aspect ratio is 1 and increases as individual grains start becoming elongated. The textural indices, MGS and AR, can be estimated using Eq. 4-5 respectively.

$$MGS = 1/n \, \Sigma_1^n \, ECD_i \quad (4)$$

$$AR = L_i / W_i \quad (5)$$

Where n is total number of grains measured and ECD_i is diameter of a circle having equal area as the individual grain have, L_i is length of individual grain and W_i is width of individual grain.

Physico-mechanical Properties of Rock

The rock specimens conditioned with multiple F-T cycles were subjected for determination of variation in the tensile strength and compressive strength (Fig. 4). Brazilian tensile strength (BTS) and uniaxial compressive strength (UCS) have been determined as per the ISRM suggested method (ISRM, 1981) using NX size rock specimens. The load at a constant stress rate was applied until the specimen failed.

Fig. 4. F-T conditioned rock specimens NX size rock specimens for **(a)** UCS and **(b)** BTS.

RESULT AND DISCUSSION

Microscopic Analysis

The petrographical studies of biotite schist samples have exhibited various mineralogical compositions and textural attributes. Microscopic observations of average quantitative mineralogical data (modal concentration of minerals), mineralogical parameter and textural parameter of F-T conditioned rock samples are shown in Table 1. Rock sample mainly consists of quartz, orthoclase, biotite and plagioclase. Some opaque minerals are accessory constituents in few samples. Microphotographs of samples from polished thin-sections (Fig. 5) show plagioclase exhibiting two set cleavage in plane polarized light and lamellar twining under cross-polarized light. Biotite looks like as brown-coloured flaky mineral in plane-polarized light. K-feldspar appears as a colourless mineral with two set cleavages and moderate relief under plane polarized light, while quartz is also colourless but has low relief with no cleavage present.

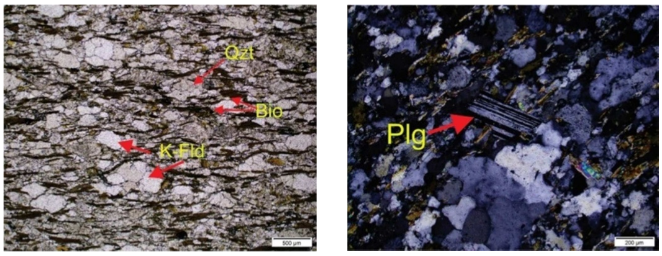

Fig.5. Rock forming minerals with their diagnostic properties under microscope in **(a)** PPL and **(b)** XPL.

The comparison of petrographical characteristics has shown that values of individual mineralogical indices remain unchanged before and after 10, 20 and 30 freeze and thaw cycles. Whereas textural indices have shown some changes as AR increases and MGS decreases after every 10^{th} cycle of F–T. The reduction in MGS indicates the physical weathering process, as depicted in Fig. 6. During petrography, it was observed that the schistose structure of rock samples is highly susceptible and gets destroyed after every cycle of F-T. Fig. 7 shows the alignment of biotite and other minerals getting randomized after the F-T cycle. Initially, there was an abundance of elongated minerals, which on progressive F-T cycle get converted into elliptical to circular grains. The aspect ratio of grain indicates that the grains with AR>2 get decrease from 21.49 % to 20 %, and grains with AR≤2 increase from 78.5% to 79.94% with the progressive cycle of F-T. The majority of elongated grains were composed of biotite which gets weathered first during weathering cycle. A cumulative decrease in the number of

Table 1. Petrographic analysis of rock specimens under different F-T conditioning

Conditions	Locations	Minerals				Mineralogical Indices			Textural Indices		
		Qz	Or	Plg	Bt	IF	IC	IQF	MGS	ARd”2	AR>2
FT-0	L1	56.2	22	2.5	19	0.898	19.3	2.29	44.8	78.43	21.57
	L2	54.0	23.6	2.7	19	0.897	19.7	2.05	53.43	78.5	21.5
	L3	54.7	21.6	3.0	20	0.878	20.7	2.22	35.38	78.58	21.42
	L4	53.8	23.6	2.4	20	0.908	20.2	2.07	48.05	78.84	21.16
FT-10	L1	56.2	22	2.5	19	0.898	19.3	2.29	33.71	79.41	20.59
	L2	54.0	23.6	2.7	19	0.897	19.7	2.05	39.16	79.85	20.15
	L3	54.7	21.6	3.0	20	0.878	20.7	2.22	29.12	79.88	20.12
	L4	53.8	23.6	2.4	20	0.908	20.2	2.07	36.95	80.05	19.95
FT-20	L1	56.2	22	2.5	19	0.898	19.3	2.29	30.56	79.53	20.47
	L2	54.0	23.6	2.7	19	0.897	19.7	2.05	35.44	79.94	20.06
	L3	54.7	21.6	3.0	20	0.878	20.7	2.22	27.47	79.98	20.02
	L4	53.8	23.6	2.4	20	0.908	20.2	2.07	32.91	80.17	19.83
FT-30	L1	56.2	22	2.5	19	0.898	19.3	2.29	29.27	79.6	20.4
	L2	54.0	23.6	2.7	19	0.897	19.7	2.05	33.32	79.99	20.01
	L3	54.7	21.6	3.0	20	0.878	20.7	2.22	25.06	80.18	19.82
	L4	53.8	23.6	2.4	20	0.908	20.2	2.07	30.18	80.29	19.71

Quartz: Qz, Orthoclase: Or, Plagioclase: Plg, Biotite:Bt

elongated grains (AR>2) and an increase in circular to elliptical grains (AR≤2) have also been well observed under the microscope and shown in Fig. 7.

Scanning electron microscopy (SEM) was employed to investigate the effect of F-T cycling on the microstructure of biotite grains, pores and cracks present in rock samples. Without treatment, the structures of a mineral specimen were more compact and microcracks were of small size than those exposed to F-T treatment. A comparison of microstructures of biotite grain suggests that grains get gradually separated along their basal cleavage and become less compact after 30th cycle of F-T (Fig. 8). The size of micropores and cracks also got enlarged, resulting in an increase in rock porosity after multiple F-T cycles (Fig. 9). Rock fragmentation into smaller pieces was observed in SEM images of F-T treated samples than that of untreated samples Fig. 10.

Strength Estimation under the Influence of F-T Cycles

The compressive and tensile rock strengths were estimated for specimens conditioned with 0th, 10th, 20th and 30th F-T cycles. The calculated values for all tests are given in Table 2. Laboratory investigation shows a loss in both compressive and tensile strength, increasing the number of F-T cycles for all four locations. A reduction of about 26 to 38 % in UCS and 30 to 41 % in BTS was observed for the rock specimens treated with 10 to 30 cycles of F-T. Fig. 11 shows an exponential decrease in UCS and BTS when subjected to higher F-T cycles. However, the decrement rate varied from 0.010 to 0.017 for UCS and 0.012 to 0.018 for BTS. As the four locations belong to the same rock group, the average decrement rate of 0.013 and 0.015 for UCS and BTS should be considered. The study conducted by Mutlutuk et al. (2004) and Yavuz et al. (2006) also showed an exponential decrement for carbonate and diabase.

Strength Estimation Post F-T Conditioning using Petrological as well as Mechanical Properties

The strength of the rock is achieved by its mineral composition and textural behaviour. The F-T induced variation in mineralogical indices and textural indices affects rock durability. Therefore, an attempt was made to correlate the strength properties with the mineralogical properties of the rock. Simple regression study was conducted to correlate the rock strength properties (BTS and UCS)

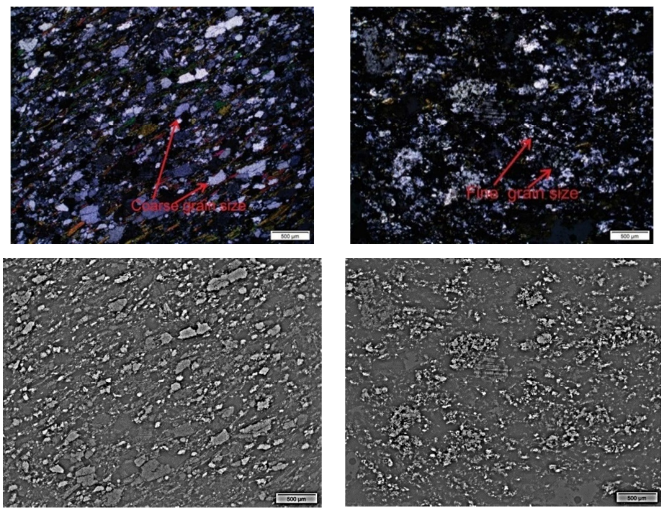

Fig. 6. Original and processed image for grain size at 0th F-T cycle and 30th F-T cycle.

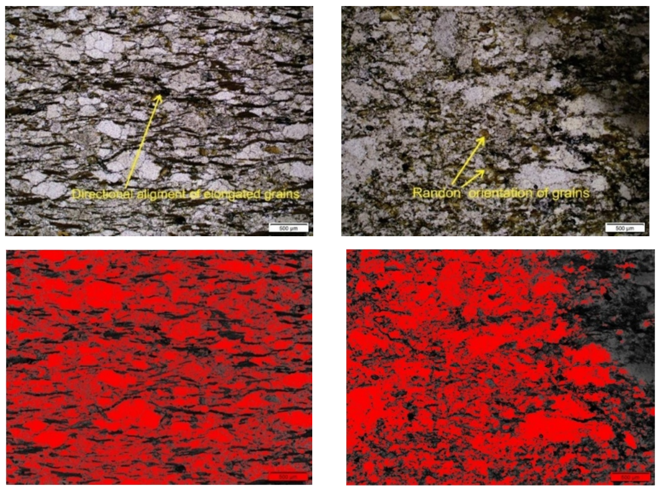

Fig. 7. Elongated biotite grains aligned in a particular direction before F-T get randomly aligned with more circular grains of biotite after 30 cycle of F-T.

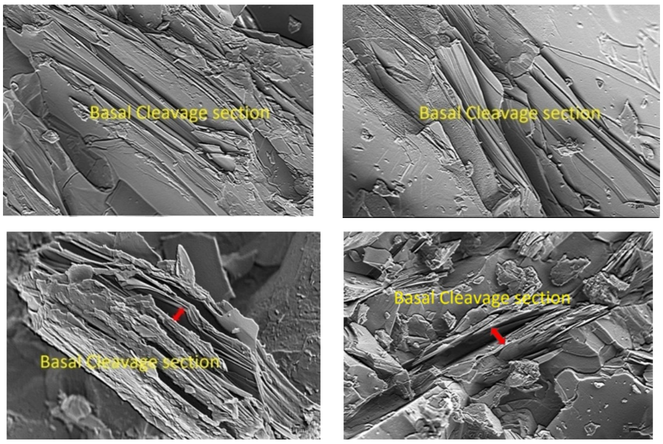

Fig. 8. Biotite mineral splitting along their basal cleavage plane and becoming less compacted. Spacing between two sheets increased after every cycle.

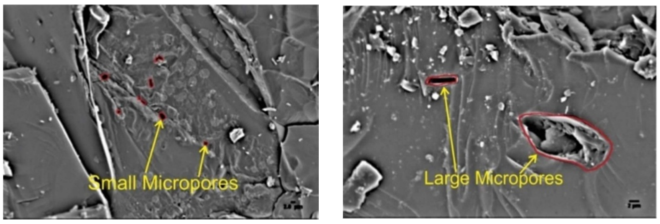

Fig. 9. Mircopore size increased after 30 F-T cycle (a) before F-T cycle (b) after 30th cycle of F-T.

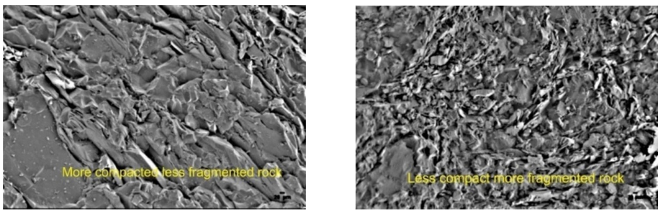

Fig. 10. Fragmentation of grains observed after 30 cycle of F-T under SEM image (a) before F-T cycle and (b) after 30 F-T cycle.

with the mineralogical properties (mineralogical indices and textural indices). The correlations were investigated using exponential, linear, power and logarithmic regression analysis. The correlation coefficient (R^2) values for strength properties with the mineralogical properties are shown in Fig. 12.

Table 2. Rock strength properties under the influence of multiple F-T cycles

Conditions	Locations	UCS (MPa)	BTS (MPa)
FT-0	L1	85.6	12.55
	L2	99.57	13.1
	L3	83.72	12.48
	L4	88.58	14.05
FT-10	L1	79.9	11.36
	L2	89.83	10.84
	L3	68.61	10.31
	L4	77.7	12.23
FT-20	L1	70.14	9.67
	L2	78.7	9.85
	L3	65.71	8.24
	L4	62.9	11.34
FT-30	L1	63.27	8.76
	L2	71.92	7.89
	L3	55.96	7.26
	L4	54.54	9.21

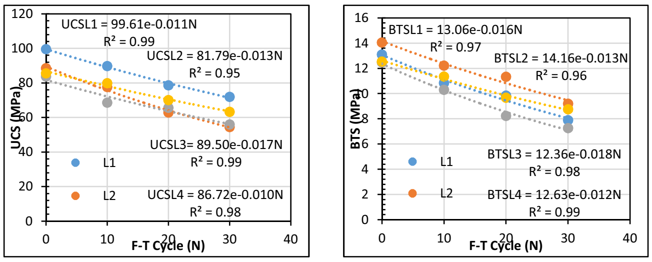

Fig. 11. Loss in **(a)** compressive strength and **(b)** tensile strength with an increase in F-T cycles

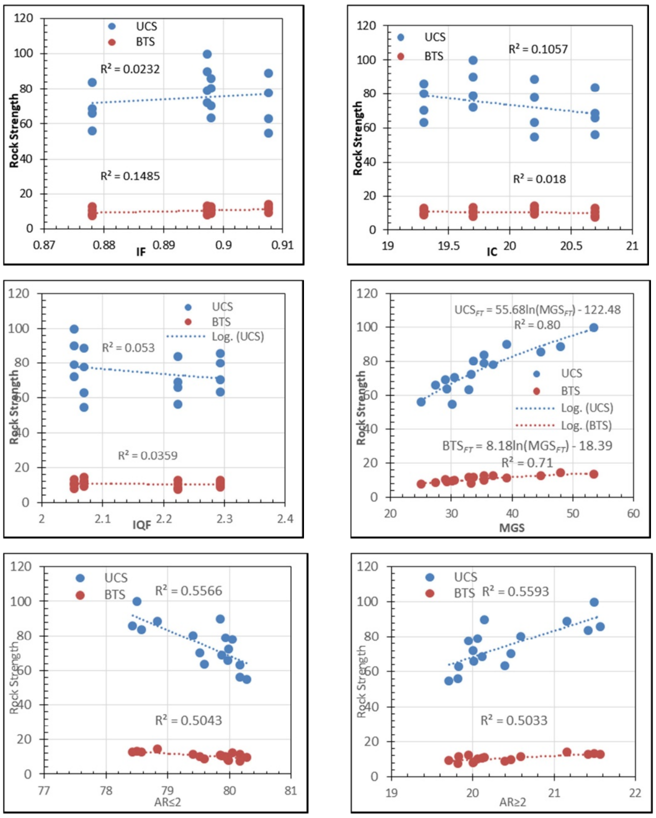

Fig. 12. Correlation of rock strength (UCS and BTS) with the mineral indices (IF, IC and IQF) and textural indices (MGS and AR)

In the analysis, mineralogical indices were found to be unaffected due to multiple F-T cycles. Therefore, a very weak correlation was observed for UCS and BTS with the mineralogical indices i.e. IF, IC and IQF. The correlation between rock strength properties and textural indices showed medium to strong bonding. The UCS-MGS and BTS-MGS correlation values were found to 0.80 and 0.71 respectively, where the correlations for UCS and BTS with AR were observed to be 0.56 and 0.50 respectively. MGS showed the best and strong bonding among all mineralogical properties with the rock strength. Both UCS-MGS and BTS-MGS showed a logarithmic relation (Fig. 12d). Therefore, the relation between the rock strength with the MGS can be expressed in a generalized equation, as given in Eq. 6.

$$l_{FT} = a \times \ln (MGS_{FT}) - b \quad (6)$$

where, a and b are the constants. l_{FT} and MGS_{FT} are the rock strength (compressive or tensile) and mean grain size of rock specimen conditioned with the similar number of *FT* cycles.

DEVELOPMENT OF MATHEMATICAL MODEL USING PETRO-MECHANICAL PROPERTIES

A mathematical model has been developed to estimate the compressive and tensile strength of the rock using mineralogical and mechanical properties with the decay function model. Mutlutuk et al. (2004) proposed a decay function model (Eq. 7) to predict the disintegration of rock under the influence of F-T cycles. The integrity of rock at 'N' number of F-T cycle (I_N) can be estimated using the integrity of rock at the beginning (I_0) and disintegration rate (λ). Thereafter, several authors predicted F-T induced damage based on exponential, logarithmic and linear equations using physico-mechanical properties (Yavuz et al. 2006; Momeni et al. 2015; Jamshidi et al. 2017). Further, Jamshedi et al. (2021) attempted to predict the damage using petro-mechanical parameters. However, in the present study, the decay function model has been modified by incorporating petro-mechanical properties. According to the decay function equation, the rock integrity can be estimated as

$$I_N = I_0 \times exp^{-\lambda N} \quad (7)$$

A general correlation determined between petro-mechanical properties (Eq. 6), for $FT = 0$, can be rewritten as

$$I_0 = a \times \ln(MGS_0) - b \quad (8)$$

After incorporate Eq. 8 into Eq. 7, it becomes

$$I_N = (a \times \ln(MGS_0) - b) \times exp^{-\lambda N} \quad (9)$$

Further, the developed equation has been validated for predicting compressive and tensile strength of rock by incorporating the values of disintegration rate (λ) and constants and from Fig. 11 and 12d. Therefore, Eq. 9 can be written as

$$UCS_N = (55.68 \times \ln(MGS_0) - 122.48) \times exp^{-0.013N} \quad (0 \geq N \leq 30) \quad (10)$$

$$BTS_N = (8.18 \times \ln(MGS_0) - 18.39) \times exp^{-0.015N} \quad (0 \geq N \leq 30) \quad (11)$$

Figure 13 shows validation of predicted strength values from Eq. 12-13 with calculated strength values in the laboratory. A correlation coefficient of $R^2 = 0.83$ and $R^2 = 0.84$ observed from Fig. 13a-b indicates a strong relationship between predicted and calculated compressive and tensile strength values respectively. Therefore, Eq. 11, a petro-mechanical equation, is appropriate for predicting compressive and tensile rock strength using mineralogical properties under the influence of 'N' number of F-T cycles.

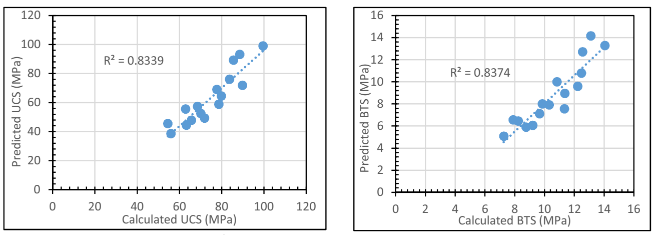

Fig. 13 Validation of predicted values with the calculated values for **(a)** compressive strength and **(b)** tensile strength.

CONCLUSION

The study investigated the phase analysis and mechanical behaviour of Himalayan schist under multiple F-T cycles (i.e. upto 30 F-T) at micro and macroscopic levels. The conditioned rock specimens undergo several analyses such as mineral modal composition, grain size distribution, aspect ratio, SEM imaging, porosity, BTS and UCS for the 0^{th}, 10^{th}, 20^{th} and 30^{th} F-T cycle.

The petrographic analysis has shown that the overall modal composition of rocks remains unaltered after F-T condition until 30^{th} cycle. The decrease in MGS after every 10^{th} cycle of F-T represents weathering in rocks. MGS shows a reduction of 17-27 %, 22-34 % and 29-38 % after 10^{th}, 20^{th} and 30^{th} cycle of F-T. SEM image depicts that pore size increases with F-T conditioning while in biotite grains, the spacing of two basal cleavage planes increases and grain splits along that plane, which increases rock fragmentation. An exponential decrease was observed in rock strength i.e. 26-38 % in UCS and 30-41 % in BTS after 30^{th} cycle of F-T. Further, MGS represents a strong correlation with both UCS and BTS, among various mineralogical and mechanical properties. Therefore, an attempt was made to incorporate MGS into the decay function model to predict the UCS and BTS. The proposed model shows good accuracy for predicting rock strength, thus recommended for assessing rock durability under multiple F-T cycles.

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