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Durability of sandstones from Sub-Himalaya of central Nepal

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ABSTRACT

The Sub-Himalaya of Nepal experiences sub-tropical climate where geologically young and delicate sedimentary rocks are prone to chemical and physical weathering and consequent erosion. The main aim of this study is to identify and evaluate the durability characteristics of some sandstones against slaking, freezing-thawing and abrasion. Lithosomes were characterized in the field. The following laboratory tests included measurements of dry density, specific gravity, water absorption, Slake Durability Index (SDI), Sulphate Soundness (SS), and Los Angles Abrasion (LAA). Sandstones from the Lower Siwalik Subgroup (LSS) are massive to cross-stratified, very fine- to medium-grained, and occasionally calcareous, whereas the sandstone from the Middle Siwalik Subgroup (MSS) are mostly cross-stratified to few massive, medium- to coarse-grained with salt-and-pepper appearance, and uncommonly calcareous. Sandstones have four different types of deterioration and had high to extremely high SDI. The majority of the sandstones have displayed similar slaking tendencies. Under the five-cycle SS test, the majority of sandstones from LSS and MSS have experienced low final weight loss (below 10%). However, two from LSS and three from MSS have experienced greater final weight loss. The LAA values range from 29.66% to 99.14%, and except two sandstones from LSS, rest of the samples have exceeded 45% abrasion showing they were incompetent in terms of abrasion test, and are highly susceptible to abrasion. The uniformity factor ranges from 0.21 to 0.44 indicating that all the sandstones were of non-uniform hardness. Correlation among physical parameter and durability indices was weak to moderate probably because of varied nature of sandstones.

Keywords: Sub-Himalaya, Slake Durability Index, Los Angeles Abrasion, Sulphate Soundness

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INTRODUCTION

The Siwalik Group of rocks is the thick accretion of Neogene foreland in the foothills of the rising Himalaya (Tokuoka et al., 1986; Kizaki, 1994). It is prone to weathering and consequent mass wasting (Tamrakar and Yokota, 2008; Tamrakar et al., 2021). Landsliding often takes place because of weakness and poor durability of slope-forming rocks (Regues et al., 1995). Interbedding of relatively softer mudrocks and stiffer sandstones characterize the lower to the middle parts of the Siwalik Group (Tamrakar and Yokota, 2008). Mudrocks and sandstones weather in different rates, yielding protuberance of stiffer and more durable sandstones against soft and less durable mudrocks, which form vicinity of gullies that develop along the bedding. Tamrakar and Yokota (2008) and Tamrakar and Karki (2019) considered such gullies as bedding structure-controlled gullies formed due to differential weathering of rocks.

The sandstones of the Siwalik Group range from ones of poorly cemented but well packed to those of well-cemented and stiff nature (Tamrakar et al., 2000, 2002). Pore space in the sandstones has close and direct relationship with effective porosity. At the state of loose packing, the rate in which fluids move in aggravating various weathering processes also increases (Demarco et al., 2007).

Physico-mechanical properties of rocks are significantly influenced by composition, texture and microstructures (Shakoor and Bonelli, 1991; Ulusay et al., 1994; Akesson et al., 2001; Al Harthi, 2001; Přikryl, 2001; Tamrakar et al., 2002; Tamrakar et al., 2007; Sabatakakis, 2008; Gupta and Sharma, 2012; Yilmaz et al., 2011; Tondon and Gupta, 2013). Tests on LAA, SDI and SS are widely adopted for evaluating physical changes and behavior of rock durability as a result of abrasion, wetting-drying, and freeze thaw weathering, respectively (Gökçeoğluet al., 2000; Erguler and Ulusay, 2009; Gautam and Shakoor, 2013). Rock durability is perhaps important factor in degradation of rocks in slopes (Miščević and Vlastelica, 2014). Sandstones of the Siwalik Group have various stiffness and durability, which are of much concern to slope movement processes along the riverbanks and highway road cut slopes. Slope movement phenomena are caused by poor durability of rocks in the Siwaliks of mid-western Nepal (Tamrakar, 2012; Tamrakar and Yokota, 2008). Therefore, the main aims of the present study are to access the stiffness and durability characteristics of sandstones from the Siwalik Group of central Nepal Sub-Himalaya.

The study area lies in the Makawanpur and the Bara Districts, central Nepal (Fig. 1). The Rapati Nadi (river), which flows across in the northern Siwalik Range and terminates westward in Hetauda, is the major drainage from the Lesser Himalaya. The major axial drainage, the Karra Khola makes a confluence at this point of turning of the Rapati Nadi. Besides the Karra Khola, the Samari Khola and the Kisedi Khola also contribute the Rapati Nadi in Suparitar. The Chure Khola and the Dudhaura Khola form another prominent drainage, which originate in the Churiya Hills and flow towards south to the Indo-Gangetic Plain.

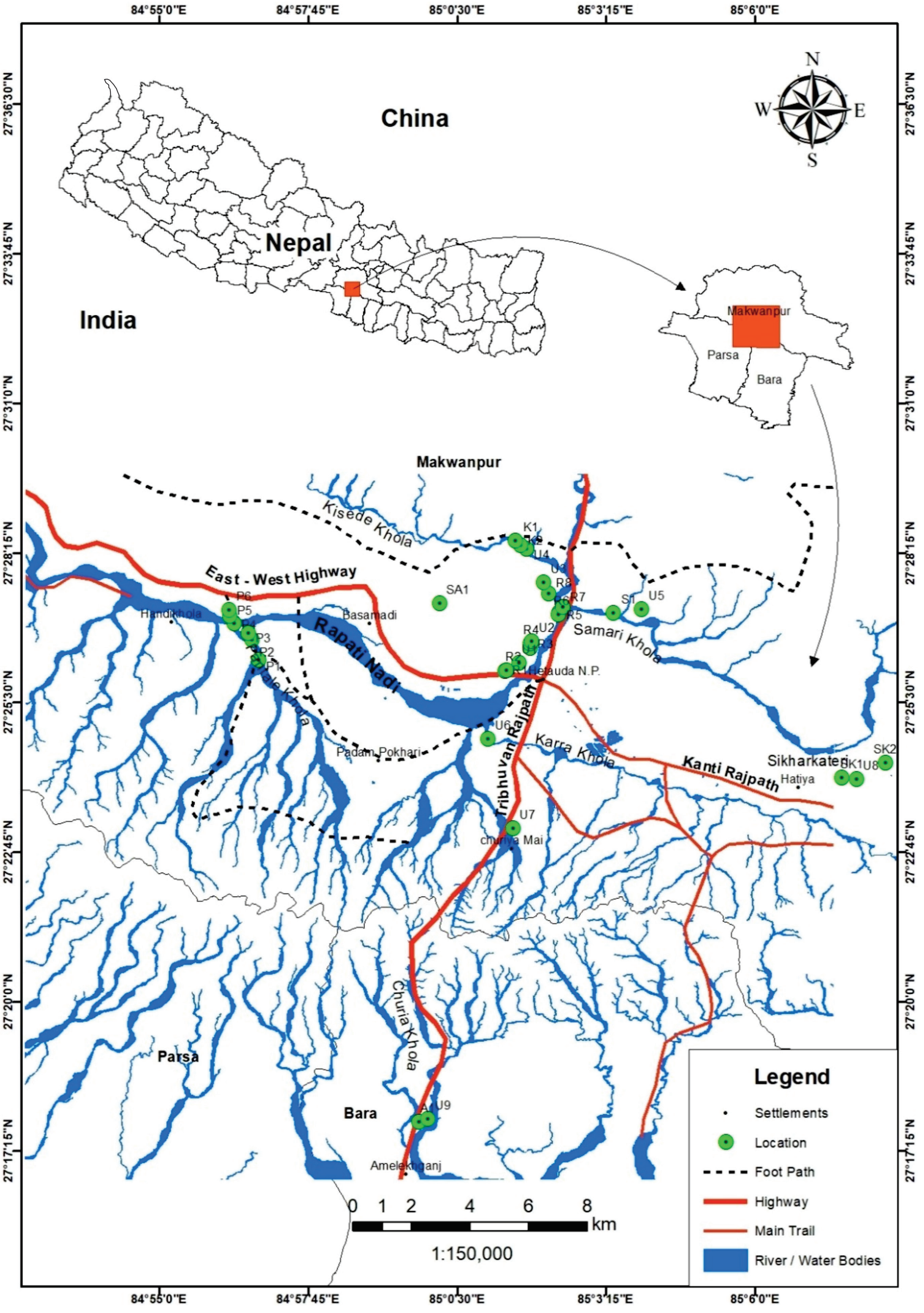


Fig. 1: Location of study area and sampling points.

Geological setting

The synorogenic sediments of the foreland basin fringe the Himalayan range extending from Assam, India to western Pakistan (Kizaki, 1994). Currently, the Sub-Himalayan Range (Siwalik foothills) represents the deformed fringe of this foreland basin and approaches maximum elevation of around 1500 m.

The Siwalik Group, a thick fluvial accumulation (Ulak and Nakayama, 1998), is bounded between two major thrusts, the Main Frontal Thrust (MFT) in the south and the Main Boundary Thrust (MBT) in the north, respectively distinguishing the group from the Lesser Himalayan metasediments (or the Midland Group meta-sediments) in the north and the Indo-Gangetic Plain in the south (Schelling et al., 1991; Kizaki, 1994; Kimura, 1995).The Siwalik is divisible into three subgroups based on the change of the lithology and increasing grain size of the sediments viz. the Lower Siwalik Subgroup (LSS), the Middle Siwalik Subgroup (MSS) and the Upper Siwalik Subgroup (USS). In the Hetauda-Amlekhganj section, the LSS succession is minimum of 1,500 m thick. The LSS is composed primarily of variegated mudstones, silt-shales, clay-shales, siltstone, sandstone beds (often <10 m thick) and some impure limestones (Auden, 1935; Sah et al., 1994; Dhital et al., 1995; Ulak and Nakayama, 1998; Tamrakar et al., 2000). Sandstones of the LSS are frequently fine- to medium-grained, ferruginous to calcareous concreted. The MSS is approximately 2,000 m thick and consists principally of mica-rich, cross-bedded sandstones with occasional mudrock and pebble-conglomerate beds. Individual sandstone sequences within the MSS are recurrently many tens of meters thick. From the lower to the upper part of the MSS, repeated interbedding of mudrocks and salt-and-pepper appeared sandstones passes to pebbly coarse-grained sandstones and pebble conglomerates via thick-bedded, coarse-grained salt-and-pepper appeared sandstones and slightly pebbly to pebbly salt-and-pepper appeared sandstones. The USS comprises of matrix- to clast-supported, massive loosely consolidated cobble-pebble conglomerate in the lower part and matrix-supported, massive loosely consolidated cobble-boulder conglomerate in the upper part. Few mudrock beds and sandstone flashers occur with conglomerates.

In the Amlekhganj-Suparitar region, the Siwalik belt is divisible in to the southern and the northern belts partitioned (Fig. 2) by the Main Dun Thrust (MDT) (Schelling et al., 1991). The MDT separates the footwall of the Upper Siwalik Subgroup from the hanging wall of the Lower Siwalik Subgroup, between Hetauda and the Churiya Hills (Schelling et al., 1991; Ulak and Nakayama, 1998; Tamrakar and Karki, 2019). The Siwalik foothills is a system of mainly imbricate thrust faults (Schelling et al., 1991; Chalaron et al., 1995; Powers et al., 1997) with synclines and anticlines in both northern and southern belts (Schelling et al., 1991; Sah et al., 1994; Kimura, 1995; Ulak and Nakayama, 1998; Tamrakar et al., 2002; Tamrakar and Karki, 2019).

METHODOLOGY

The sandstone samples of about 10 kg were selectively gathered from each of 20 different sites, ten from the LSS and ten from the MSS (Fig. 3). They were brought to the material testing laboratory for testing physical properties, strength and durability. Density, specific gravity and water absorption tests were conducted in accordance with ASTM C127. The SDI test was carried out using the standard test method according to ASTM D4644-87 and the test was conducted for four cycles to obtain deformation behaviour. The total weight of the sample taken was 450 to 550 g. After the test, the percent loss of weight at each cycle was calculated. For reporting the Slake Durability Index, the second cycle slake durability (I_{d2}) was considered and was obtained using the following Equation 1:

$$I_{d2} = (\text{wt. loss/initial wt.})\ 100\% \qquad (1)$$

Sulphate Soundness (SS) test was carried out on the aggregate samples after ASTM C88-05 to determine the durability of aggregate against physical weathering. The SS value (SSV) was obtained as (Eq. 2):

$$SSV = \{(W1–W2)/W1\}\ 100\% \qquad (2)$$

where, W1 = initial weight of the sample and W2 = weight retained on 10 mm after the test. Minimum allowance of SSV for coarse aggregate is 10% for concrete (ASTM 1978).

LAA was carried out for test sample (Grade B) in accordance with ASTM C131 (2006). Uniformity factor and wear of gravel were determined by Los Angeles test (ASTM C131-89 1989). Los Angeles abrasion value was calculated as (Eq. 3, 4):

$$W_{r100} = \{(W–W_{100})/W\}.100\% \qquad (3)$$

$$W_{r500} = \{(W–W_{500})/W\}.100\% \qquad (4)$$

where, W_{r100} = % wear at 100 revolutions, W_{r500} = %wear at 500 revolutions, W = initial wt. of sample, and W_{100} and W_{500} are respectively the wt. of samples retained on 1.7 mm after 100 and 500 revolutions. Uniformity factor (UF) was obtained as (Eq. 5):

$$UF = (W–W_{100})/\ (W–W_{500}) \qquad (5)$$

The test results of physical properties, strength and durability were analysed and correlated applying bivariate analysis to see if one variable can explain well the other variable.

RESULTS AND DISCUSSIONS

The samples were located and their litholosomes, including structure, texture and weathering grades were recorded (Table 1). Among the 20 samples, ten were from the LSS and the remaining ten from the MSS. The Lower Siwalik Subgroup samples were from the Rapati Nadi, Saraswati Nagar located west of Hetauda, and the Pantale Khola, a tributary of the Rapti Nadi south of Bastipur. The MSS samples were from the Rapti Nadi, Kisedi Khola, Shikharkateri, Makawanpur Gadhi and Amlekhganj. The sandstones from the LSS were massive to cross-laminated, very fine- to medium-grained, and were slight to moderately weathered. The sandstones from the Pantale Khola were mostly of calcareous cemented. The sandstones from the MSS were mostly of massive to cross-laminated, medium- to coarse- grained salt-and-pepper appeared, and were infrequently calcareous cemented. Few sandstones from the Rapati Nadi and the Kisedi Khola were very fine- to medium-grained, and light grey to white.

Dry Density, Specific Gravity and Water Absorption

The dry density of the sandstones from the LSS varies from 2080-2600 kg/m^3 (Table 2), and that of the MSS varies from

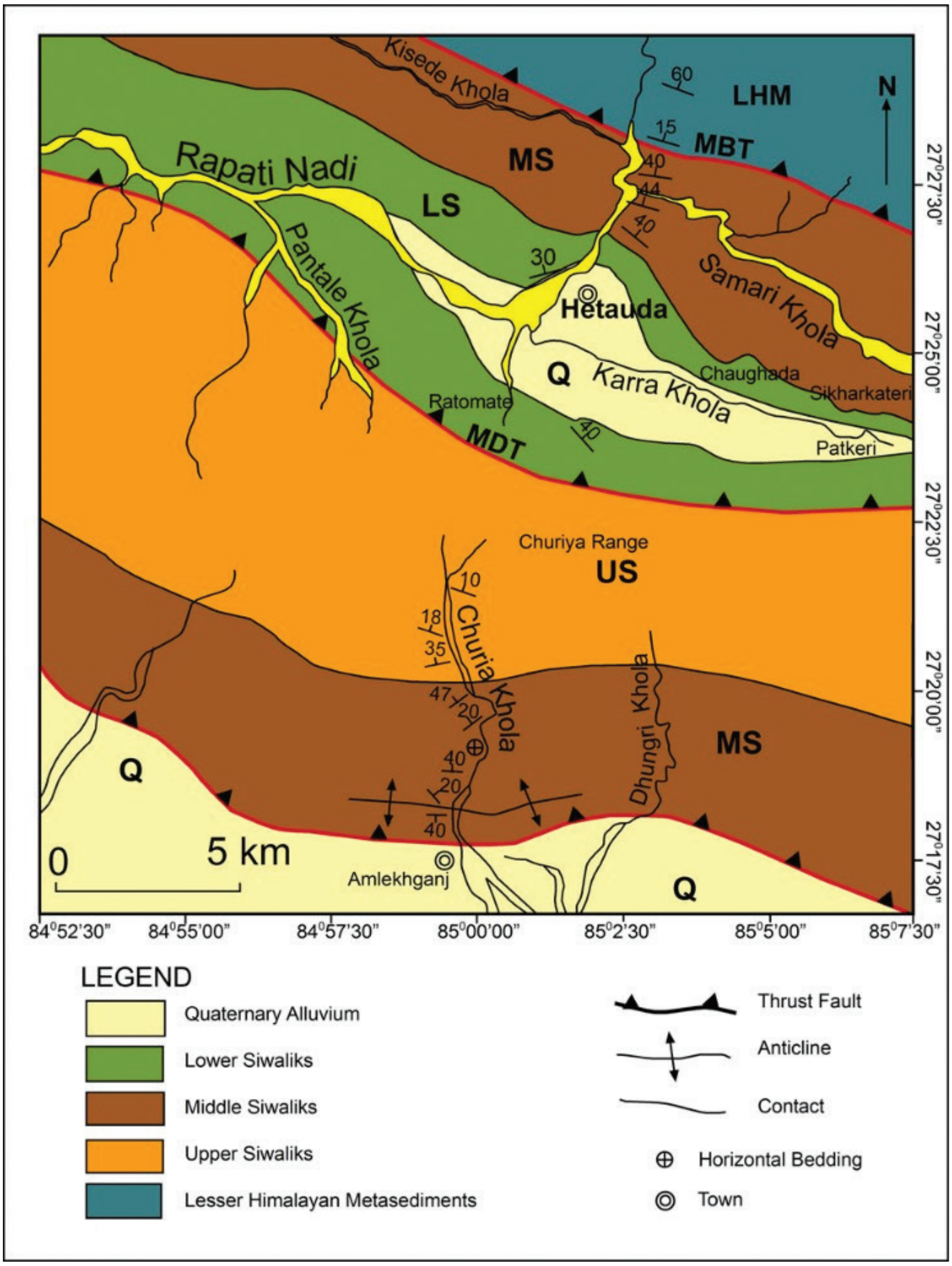


Fig. 2: Geological map of the study area (after Schelling et al., 1991).

1860 to 2680 kg/m^3. The specific gravity of sandstones vary from 2.18 to 2.69 (LSS), and 2.45–2.72 (MSS), showing that they lie in low to normal relative densities (ASTM C 128). The water absorption value (WAV) ranges from 0.99 to 3.18% (LSS) and from 1.26 to 5.36% (MSS). Physical parameters thus determined vary within narrow ranges but WAV is somewhat higher in sandstones from the MSS than in those from the LSS.

Slake Durability Index

The breakdown of a material mass into smaller fragments due to the effect of abrasion and cyclic process of wetting and drying conditions for a period of time was determined as percentage of material retained at the end of each of the four cycles. Slake Durability Index (I_{d2}) of the sandstones from the LSS ranges from 86.13% (high) to 98.49% (extremely high) (Table 3). Out of ten samples from the LSS, seven belong to extremely high, two belong to very high and one to high category. Eight samples deteriorated showing type I category of deterioration, whereas two samples deteriorated showing type II category.

I_{d2} of the sandstones from the MSS varies from 90.72% (very high) to 99.14 (extremely high) (Table 3). Out of ten samples seven show extremely high and three show very high I_{d2}. Seven samples show type I and three show type II deterioration pattern. The samples undergoing type I deterioration pattern exhibit retention of the same number of pieces of samples fed during the test, and deteriorate from the surface abrasion and partial reduction of size. The samples undergoing type II

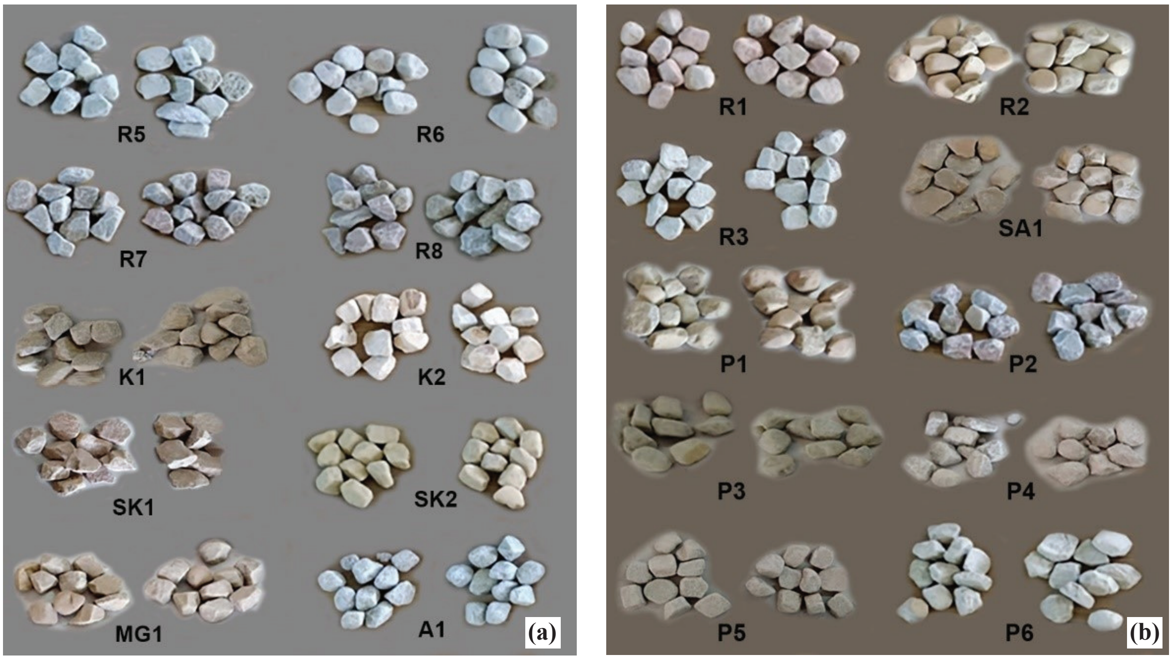


Fig. 3: Sandstone samples after four cycles of slake durability test. (a) Samples from the Lower Siwalik Subgroup and (b) Samples from the Middle Siwalik Subgroup.

Table 1: Location and description of samples.

Sample	Elevation (m)/Latitude/Longitude		Rock type	Weathering grade
Lower Siwalik Subgroup				
R1	384/27.4343/85.0232	Rapati Nadi	massive, fine-grained, greenish grey sandstone	II
R2	383/27.4346/85.0236		massive, fine-grained, light grey sandstone	II
R3	393/27.4415/85.0309		Cross-laminated, medium-grained, grey sst.	II
SA1	621/27.4551/85.0029	Saraswati Nagar	laminated, fine-grained, light grey sandstone	III
P1	332/27.4378/84.9472	Pantale Khola	massive, very fine-grained light grey calc sandstone	III
P2	348/27.444/84.9452		Cross-laminated, very fine-grained light grey calc sst.	II
P3	340/27.4459/84.944		Massive, fine-to medium-grained light grey, calc sst.	II
P4	337/27.4491/84.9397		Cross-laminated, medium grained, light grey sst.	III
P5	293/27.4513/84.9383		Cross-laminated, fine-to medium-grained, light grey sst.	III
P6	319/27.453/84.938		Laminated, fine- to medium-grained, light grey sst.	III
Middle Siwalik Subgroup				
R5	405/27.4523/85.0398	Rapati Nadi	Massive, coarse-grained,salt-and-pepper textured sst.	II
R6	437/27.4517/85.0395		Massive, very fine-grained, light grey sst.	III
R7	402/27.454/85.0409		Laminated, medium-grained, light grey sst.	II
R8	428/27.4582/85.0366		Massive, medium-grained, grey sst.	II
K1	444/27.4744/85.0264	Kisede Khola	Laminated, fine- to medium-grained light grey sst.	II
K2	443/27.4729/85.0278		massive, medium-grained, white sandstone	III
SK1	645/27.4018/85.1268	Shikharkateri	cross-laminated, medium-grained salt-and- pepper textured sandstone	II
SK2	775/27.4063/85.1403		massive, medium-grained, yellowish grey salt-and-peper textured sandstone	III
MG1	820/27.4103/85.1487	Makawanpur Gadhi	massive, fine- to coarse-grained, salt-and-pepper textured sandstone	II
A1	294/27.2962/84.9965	Chure Khola	massive, coarse-grained salt-and-pepper textured sandstone	II

Table 2: Physical properties of sandstones from the Siwalik Group.

Sample	Oven dry wt., g (A)	SSD wt., g (B)	Saturated submerged wt., g (C)	Dry bulk density, g/cm^3	Specific gravity	WAV (%)
Lower Siwalik Subgroup						
R1	980	1011.170	585.660	2300	2.49	3.18
R2	980	1001.860	598.150	2430	2.57	2.23
R3	980	996.578	598.159	2460	2.57	1.69
SA1	980	1005.540	615.700	2510	2.69	2.60
P1	970	988.406	606.850	2540	2.67	1.89
P2	960	969.523	600.470	2600	2.67	0.99
P3	980	1004.980	615.640	2520	2.69	2.54
P4	990	1012.170	536.570	2080	2.18	2.24
P5	990	1012.360	612.380	2480	2.62	2.25
P6	950	975.333	578.000	2390	2.55	2.66
Middle Siwalik Subgroup						
R5	990	1043.070	615.270	2310	2.64	5.36
R6	980	992.405	609.740	2560	2.65	1.26
R7	970	985.068	601.970	2530	2.64	1.55
R8	990	1152.560	620.870	1860	2.68	1.76
K1	960	979.701	600.050	2530	2.67	2.05
K2	990	1005.110	610.700	2510	2.61	1.52
SK1	990	1006.870	620.120	2560	2.68	1.70
SK2	990	1030.940	585.950	2220	2.45	4.13
MG1	990	995.787	625.710	2680	2.72	2.65
A1	990	1014.140	622.230	2530	2.69	2.43

Table 3: Slake durability indices of sandstones from the Siwalik Group.

Sample	SDI (%) in each cycle				Durability	Type
	I_{d1}	I_{d2}	I_{d3}	I_{d4}		
Lower Siwalik Subgroup						
R1	98.52	97.67	96.72	95.98	Extremely high	I
R2	98.98	98.54	98.09	97.09	Extremely high	I
R3	98.89	98.49	97.92	97.53	Extremely high	I
SA1	98.82	98.25	97.48	97.10	Extremely high	I
P1	96.68	95.16	93.63	92.44	Very high	I
P2	99.15	98.80	98.37	98.07	Extremely high	I
P3	95.56	91.47	88.92	85.91	Very high	II
P4	92.04	86.13	79.75	75.00	High	II
P5	98.04	97.05	95.84	94.99	Extremely high	I
P6	98.43	97.48	96.68	96.06	Extremely high	I
Middle Siwalik Subgroup						
R5	96.38	93.63	91.90	89.53	Very high	II
R6	99.22	98.85	98.43	98.23	Extremely high	I
R7	99.00	98.28	97.67	97.10	Extremely high	II
R8	94.76	90.72	87.68	85.00	Very high	II
K1	98.4	97.60	96.75	96.21	Extremely high	I
K2	99.41	99.14	98.86	98.69	Extremely high	I
SK1	99.05	98.80	98.35	98.18	Extremely high	I
SK2	98.19	96.94	95.87	94.96	Extremely high	I
MG1	98.76	97.71	96.65	95.89	Extremely high	I
A1	96.11	92.93	90.16	87.48	Very high	II

deterioration pattern show deterioration by abrasion on the surface and by fragmentation into small number of pieces. Under the test, majority of the samples show partial surface worn out, thus are strong enough to withstand slaking under the weathering environment.

Under the four-cycle test, samples showed gradual diminishing of their weight in the successive cycles. The sandstones from the LSS deteriorate showing three characteristic patterns, A (samples P1, P2, P5, P6, SA1 and R3), F (sample P4) and J (sample P3) (Fig. 4a), whereas those of the MSS deteriorate giving characteristic patterns of A (samples R6, R7, K1, K2, MG1, SK1 and SK2), J (sample R5), and F (samples A1 and R8) (Fig. 4b). According to Tamrakar et al. (2021), the pattern A exhibits little progressive diminish or no significant change in durability from the beginning to the end of the 4th cycles. The pattern F exhibits progressive deterioration up to 3rd cycle and then negligible up to 4th cycle down to high durability (concave curve). The deterioration pattern J identified here exhibits the progressive diminish of durability but the durability between the second and the third cycles diminishes little compared to those in between other cycles showing more or less C-type pattern of Tamrakar et al. (2021). The deterioration pattern K is more or less similar to the pattern F of Tamrakar et al. (2021), but its I_{d2} goes down from very high durability to the high durability in the I_{d3} and I_{d4}. Samples showing the pattern A are strong against slaking. Samples showing deterioration patterns F (sample P4), J (samples P3 and R5) and K (samples A1 and R8) are relatively prone to slaking in the long run as their durability diminishes down from very high or high to high durability. Therefore, sandstones from both LSS and MSS give both strong and relatively weak patterns of slaking characteristics, in which sandstones exhibit more or less similar slaking characteristics A and J, except for few samples possessing slaking characteristics F and K.

Sulphate Soundness

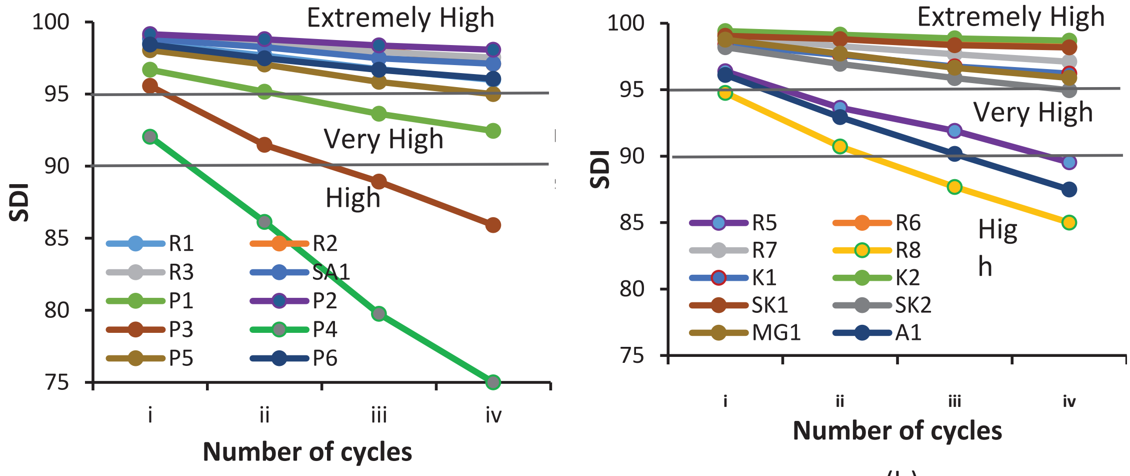
Sulphate Soundness refers to measure of resistance of aggregates to crystallization of salts within the pores and disintegration resulting due to alternate cycles of wet and dry conditions. Five-cycle test results show that Sulphate Soundness Value (SSV) of sandstones from the LSS varies between 0.02% and 20.15%, and that of sandstones from the MSS varies between 0.91% and 21.59% (Table 4). Two sandstones (P1 and P4) from the LSS and three from the MSS (R5, SK2, and A1) exceed critical SSV of 10% (ASTM, 1978). Therefore, majority of the sandstones from the Siwalik Group are sound against frost weathering.

The graphical representation of weight loss in the first to the last cycle indicates that some sandstones from the LSS experience narrow range of weight loss below 1%, whereas four of the ten sandstones experience relatively higher weight loss either in the first cycle (sample P6) or in the second cycle (samples P1 and R3) or in the third cycle (sample P4) (Fig. 5a). Similarly, seven of the ten sandstones experience narrow range of weight loss within 1%, and three remaining samples experience somewhat wider range (Fig. 5b). The samples SK2 and R8 show high weight loss in the second cycle and then show reduced loss in the successive cycles. The sample A1 shows high loss in the third cycle and then shows diminished weight loss in the successive cycles. The samples SK2 and A1 experience high weight loss at the end of the test, and their SSV exceeds 10%, but the sample R8 gives low weight loss below 1% at the end of the fifth cycle.

Los Angles Abrasion Value

Los Angles Abrasion test was done after the completion of sieve analysis test retained on 9.5 mm and 12.5 mm (Grade B test sample) for the determination of degree of wear and tear due to relative rubbing between the balls and aggregates. The percent retained on w_{r100} and w_{r500} were recorded and Los Angeles Abrasion values were determined (Table 5).

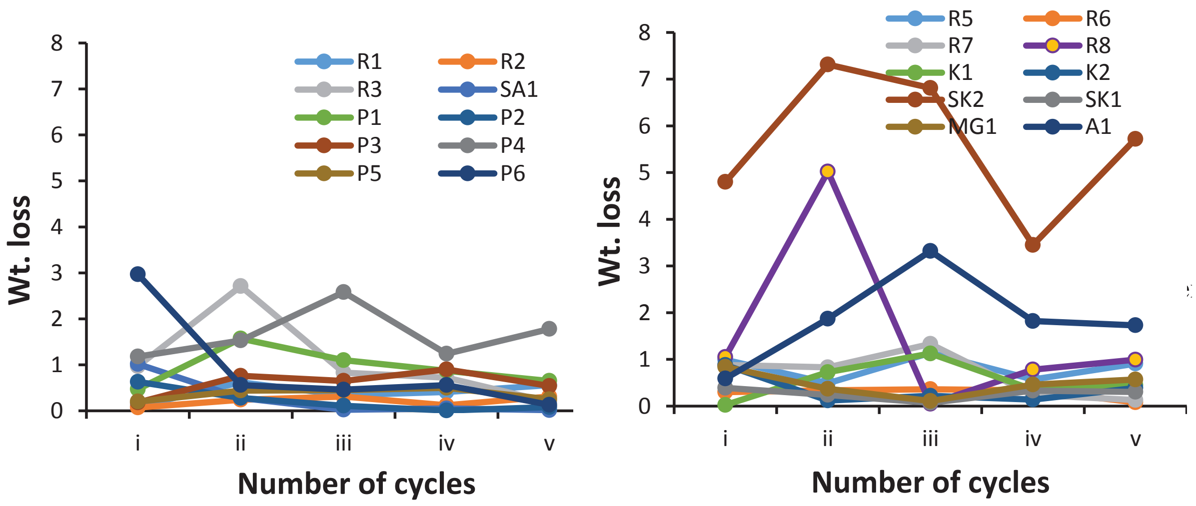
The LAA value w_{r500} ranges from 29.66% to 99.14% (LSS samples), and from 45.40% to 99.08% (MSS samples) (Table 5). Besides, two sandstone samples (SA1 and P2) from the LSS, rest of the sandstones give LAA values of more than



(a)

(b)

Fig. 4: Slaking behavior of the sandstones under four-cycle slake durability test. (a) Sandstones from the Lower Siwalik Subgroup and (b) Sandstones from the Middle Siwalik Subgroup.



(a)

(b)

Fig. 5: Weight loss in each of the five cycles of sulphate soundness test. (a) Sandstones from the Lower Siwalik Subgroup, and (b) Sandstones from the Middle Siwalik Subgroup.

Table 4: Sodium Sulphate Soundness values of the sandstones from the Siwalik Group.

Sample	Initial wt., g	Oven dried wt., g	% wt. loss in each cycle					After washing in $BaCl_2$	
			1st	2nd	3rd	4th	5th	wt., g	SSV, %
Lower Siwalik Subgroup									
R1	330	315.92	0.09	0.62	0.34	0.41	0.56	297.78	5.74
R2	330	319.30	0.07	0.24	0.31	0.12	0.31	309.76	2.99
R3	330	311.87	0.97	2.71	0.83	0.72	0.19	294.99	5.41
SA1	330	320.50	1.02	0.28	0.02	0.05	0.02	320.42	0.02
P1	330	320.98	0.47	1.57	1.10	0.87	0.65	270.73	15.66
P2	330	321.19	0.63	0.28	0.11	0.01	0.08	316.28	1.53
P3	330	319.88	0.18	0.76	0.65	0.90	0.54	295.94	7.48
P4	330	319.93	1.18	1.53	2.58	1.24	1.78	273.54	14.50
P5	330	319.69	0.20	0.44	0.45	0.50	0.25	298.28	6.70
P6	330	330.29	2.97	0.56	0.46	0.56	0.13	309.33	6.35
Middle Siwalik Subgroup									
R5	330	322.13	0.99	0.49	1.14	0.57	0.91	253.99	21.15
R6	330	324.50	0.30	0.34	0.36	0.34	0.08	319.54	1.53
R7	330	322.01	0.88	0.83	1.33	0.24	0.13	310.41	3.60
R8	330	312.50	1.05	5.02	0.05	0.78	0.99	284.51	8.96
K1	330	320.88	0.02	0.73	1.13	0.35	0.45	300.19	6.45
K2	330	322.14	0.88	0.12	0.22	0.14	0.39	319.20	0.91
SK1	330	320.26	0.39	0.24	0.07	0.33	0.30	317.04	1.01
SK2	330	316.00	4.80	7.31	6.81	3.45	5.72	247.77	21.59
MG1	330	320.60	0.84	0.37	0.11	0.46	0.57	304.88	4.90
A1	330	322.70	0.59	1.87	3.32	1.82	1.73	264.22	18.12

45%, the loose threshold taken for construction purpose by DoR (2016). The sandstones from the Siwalik Group are not tough enough to withstand abrasion and impact under the Los Angeles Abrasion test, with few exceptions.

The uniformity factor (UF) ranges from 0.21 to 0.44 for sandstones from the LSS, and from 0.24 to 0.37 for sandstones from the MSS (Table 5). This indicates that the sandstones have non-uniform hardness (ASTM, 1989).

Correlations

Physical parameter such as water absorption is correlated with all the durability indices (Fig. 6a,b,c). Also, durability indices are correlated among themselves (Fig. 6d,e,f). Water absorption (WA) correlates very weakly with I_{d2}, and moderately with SSV and LAA value (LAAV). The latter two durability indices tend to increase when WA increases. The correlation between I_{d2} and LAAV is very weak. SSV correlates in moderate

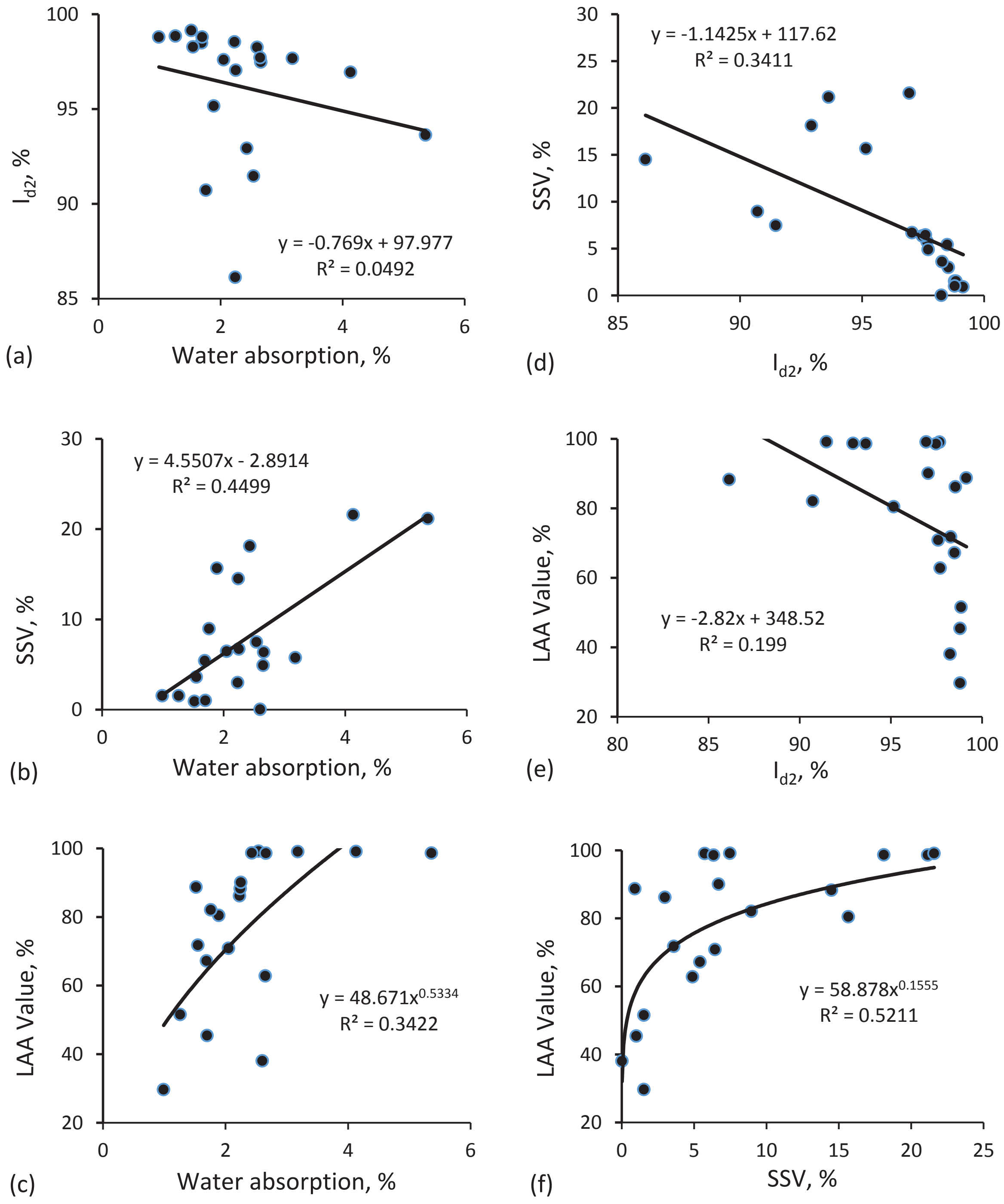


Fig. 6: Correlations between (a) WA and Id2, (b) WA and SSV, (c) WA and LAA value, (d) Id2 and SSV, (e) Id2 and LAA value, and (f) SSV and LAA value.

Table 5: Los Angeles Abrasion value of sandstones from the Siwalik Group.

Sample	Total weight of Specimen W, kg	Wt. of sample retained on 1.7 mm, kg (W_{100})	Abrasion value, after (W_{r100}), %	Wt. of sample retained on 1.7 mm, kg (W_{500})	Abrasion value after (W_{r500}), %	Uniformity factor (UF)
Lower Siwalik Subgroup						
R1	5	3.19	36.2	0.04	99.04	0.36
R2	5	4.03	19.34	0.69	86.16	0.23
R3	5	4.01	19.66	1.64	67.18	0.29
SA1	5	4.52	9.52	3.09	38.04	0.25
P1	5	3.99	20.12	0.97	80.44	0.25
P2	5	4.69	6.1	3.51	29.66	0.21
P3	5	3.45	30.96	0.04	99.14	0.31
P4	5	3.37	32.56	0.58	88.26	0.37
P5	5	3.02	39.5	0.49	90.06	0.44
P6	5	3.39	32.2	0.07	98.56	0.33
Middle Siwalik Subgroup						
R5	5	3.2	35.98	0.07	98.60	0.37
R6	5	4.39	12.14	2.42	51.54	0.24
R7	5	3.9	20.4	1.41	71.74	0.31
R8	5	3.75	24.88	0.89	82.04	0.30
K1	5	4.01	19.7	1.45	70.84	0.28
K2	5	3.81	23.74	0.56	88.70	0.27
SK1	5	4.4	11.92	2.73	45.40	0.26
SK2	5	3.2	35.82	0.04	99.08	0.36
MG1	5	3.98	20.4	1.86	62.78	0.32
A1	5	3.17	36.6	0.06	98.66	0.37

degree with LAAV and I_{d2} (Fig. 6b), showing that when SSV increases LAAV tends to increase, and I_{d2} tends to diminish. The correlations among the parameters are not very strong probably owing to variation in types and nature of sandstones.

CONCLUSIONS

Development of tensile, shear and compressive stresses in the Siwalik sandstone beds has created the tensional cracks, fissures and joints in them, which have become the crucial cause of the rock failure and mass wasting. Physical parameters thus determined vary within narrow ranges but WAV is somewhat higher in sandstones from the MSS than in those from the LSS. Slake Durability Index (I_{d2}) of the sandstones from the LSS varies from very high to extremely high showing type I to II deterioration categories, whereas those from the MSS from high to extremely high showing type I to II categories. Sandstones from both LSS and MSS give both strong and relatively weak patterns of slaking characteristics, in which sandstones exhibit more or less similar slaking characteristics A and J, except for few samples possessing slaking characteristics F and K. After fifth cycle test of Sulphate Soundness, some 60% samples from the LSS and 70% from the MSS experienced narrow weight loss below 1%, whereas the remaining sandstones possessed higher weight loss exceeding 10% showing unsound nature against chemical weathering and frost resistance. Besides, except for 20% of sandstones from the LSS, the LAA of the rest of the sandstones exceed 45% showing that they are not tough enough to withstand abrasion and impact. SSV and LAA tend to increase with increased WA. The correlation between I_{d2} and LAAV is very weak. SSV correlates in moderate degree with LAAV and I_{d2}. The correlations among the parameters are not very strong probably owing to variation in types and nature of sandstones.

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