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Slake durability indices and slaking characteristics of mudrocks of the Siwalik Group, Central Nepal

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ABSTRACT
The Siwalik Group consists of sedimentary rocks like mudrocks, sandstones and conglomerates. Mudrocks are notably found in the Lower Siwalik Subgroup and the Middle Siwalik Subgroup. It is necessary to study mudrock weathering characteristics because weathering of mudrock weakens rock masses and contributes in gully formation and subsequent landsliding. This work presents results obtained in a study aiming at identifying degradation processes responsible for erosion and slope movements of rocks in the Siwaliks of Nepal. Mudrocks under investigation were obtained from the Lower and the Middle Siwalik Subgroups of Hetauda-Amlekhganj area, Central Nepal. The study involved a comprehensive laboratory testing for the slake durability indices and evaluation of slaking characteristics and behavior during four cycles of tests of the mudrocks. Usually, mudrocks are prone to slaking, but some mudrocks with calcareous binding materials are relatively more durable compared to non-calcareous ones. Altogether nine types of degradation curves have been identified.
***Keywords* -** Siwaliks, Slake durability test, Sedimentary rocks, Mudrocks, Slaking behavior

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I. INTRODUCTION

Slake durability of rock is the resistance of the rock against slaking, i.e. disintegration under cyclic wetting and drying processes. Slake durability index (SDI) is an index calculated and expressed in percentage of mass retained after second cycle of wetting and drying of the test specimens of rock [1]. SDI test is conducted in laboratory to estimate qualitatively the durability of weak rocks in the service environment [2]. The aim of the slake durability test is to provide an index that is related to resistance of rock against degradation when subjected to two standard cycles of wetting and drying.

Many researchers in the past and recent have carried out an experimental and theoretical research on the slake durability test of weak rocks [3, 4, 5, 6, 7, 8]. The Slake Durability Index (SDI) was devised by [1] to assess the durability or weatherability of clastic sedimentary rocks such as mudstone, claystone and shale, and is particularly useful for rocks with significant clay content [3, 4, 9]. The test has been standardized and reapproved by ASTM D 4644-87 in 1992, thus providing technical guidance and procedures that are employed determining the slake durability index of weathered rocks. Some researchers claim that the standard second cycle index value is not sufficient to characterize the durability behavior of mudrocks and hence suggested that the index values at the end of fourth cycle should be taken as a basis [4, 10, 11].

SDI test is widely used to determine the disintegration characteristic of the weak and clay-bearing rocks in geo-engineering problems [10, 12], and characterizing rocks for building stones [13]. Over a given period of time, rocks with higher clay contents slake more rapidly and extensively under natural climatic conditions than those with lower clay content. Soft rocks and expansive soils are most often associated with non-durability, foundation problems and structural failures [14]. [15] showed that slake durability index of completely weathered mudstone differ drastically from the moderately weathered mudstone, showing that SDI reduces with respect to increased degree of weathering. Rapid slaking of the mudstones on exposure to wetting and drying environments has given rise to slope stability problems [16]. As a recent example, Hattian landslide dam formed by the 2005 Kashmir earthquake, Pakistan, breached in 2010 during moderate rainfall. It was reported that the breaching of the dam was induced by the slaking of the dam body which was composed of crushed mudstone [17]. The 2009 Suruga Bay earthquake caused a slope failure at the highway embankment in Shizuoka Prefecture, Japan. [18] reported that the major reason for the failure as the destabilization of the embankment due to the slaking of filled crushed mudstone.

The Siwaliks extend throughout the East-West of the foothills of the Himalayas, and represent the youngest mountain belt of the Himalayas [19]. The Lower and the Middle Siwalik Subgroups are composed mainly of mudrocks and sandstones in the interbedding successions. The inter-bedding between Sandstones and mudrocks reflects differentially weathered outcrops, in which mudrocks weather more commonly by slaking and exfoliation, in faster rate creating spacing between sandstone inter-bedding and kinematically unstable slopes. The mudrocks that interbed with sandstones are of various types, and with variation of their types, slake durability is thought to be varied. This study therefore aims to understand the disintegration characteristics and durability behavior of various types of mudrocks under slaking.

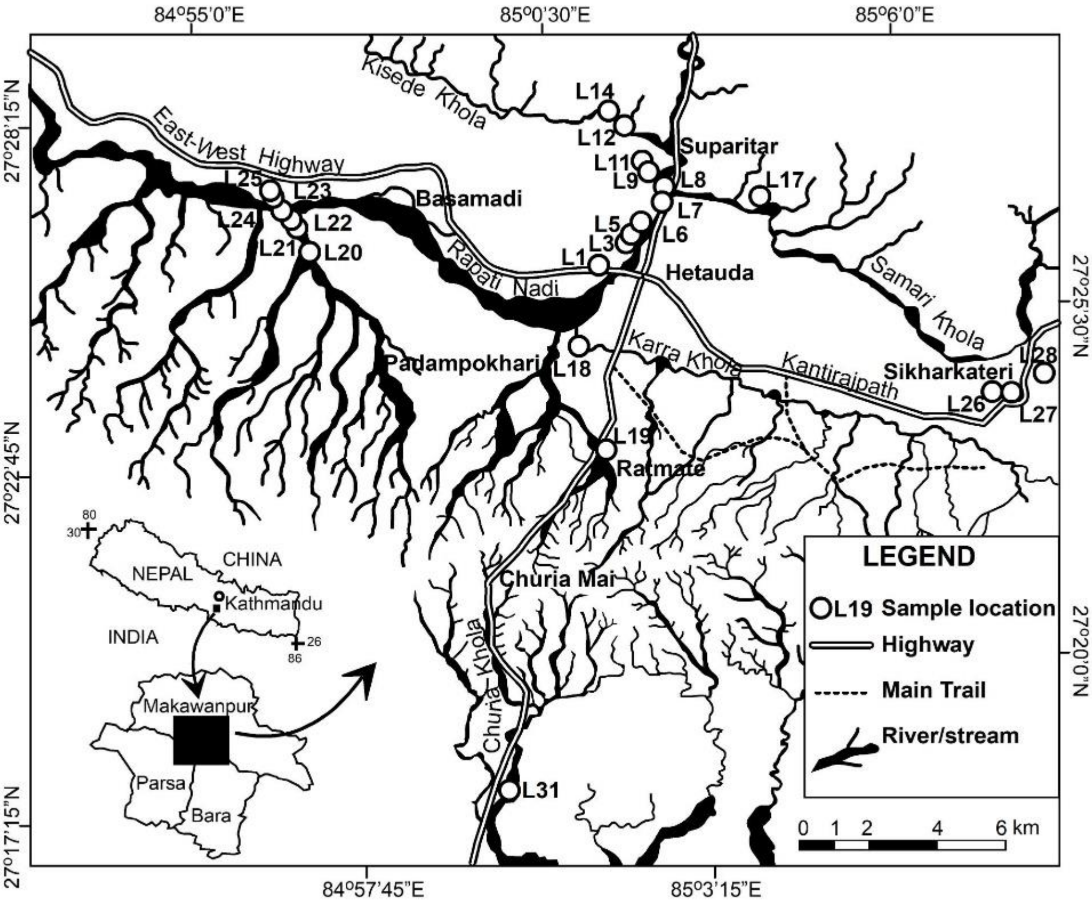

Fig. 1 Location Map of the Study area

II. GEOLOGICAL SETTING

The study site is located in the Hetauda-Amlekhganj area partly covering the Makawanpur and the Bara Districts of central Nepal Sub-Himalaya (Fig. 1). The Siwalik Group is a thick sedimentary sequence, which extends throughout the East-West of the foothills of the Himalayas, is bounded by the Main Boundary Thrust (MBT) in the north and the Main Frontal Thrust (MFT) in the south, and represents the foreland sedimentary succession of mid Miocene to early Pleistocene age (Tokuoka et al. 1986; Sah et al. 1994; Kizaki 1994; Gautam and Rosler 1999). The Siwalik Group is divided into three Subgroups viz. the Lower Siwalik Subgroup, the Middle Siwalik Subgroup and the Upper Siwalik Subgroup (Schelling et al. 1991) (Fig. 2). In the Hetauda-Amlekhganj region, the Lower Siwalik Subgroup is of approximately 2700 m thick, and is composed primarily of fine-medium-grained sandstones, and mudrocks (mudstone, siltstone, silt-shale and clay-shale). The Middle Siwalik Subgroup is approximately 2000 m thick, and consists primarily of cross-bedded, medium to coarse-grained, micaceous sandstones with occasional mudrock layers and pebble-conglomerate beds. Individual sandstone sequences within the Middle Siwalik Subgroup are frequently many tens of meters thick. The upper Siwalik Subgroup comprises mainly conglomerate and subordinately sandstones and mudrocks, and is more than 1500 m thick.

The Siwalik Group of the Amlekhganj-Hetauda region are cut by three major thrust faults (Fig. 2), the Main Boundary Thrust, the Main Dun Thrust and the Main Frontal Thrust. North of Hetauda lies the Main Boundary Thrust (MBT) along which Lesser Himalayan Meta-sediments have been thrust over the non-metamorphosed Siwalik Group. The MBT trends approximately N70W. The footwall of the MBT contains the Middle Siwalik Subgroup. The Main Dun Thrust (MDT), which trends roughly N80W, with local variations, contains Lower Siwalik mudstones in its hanging wall and the Upper Siwalik conglomerates in its footwall. The Upper Siwalik conglomerates, well exposed at the Churia Pass south of Hetauda along the Hetauda-Amlekhganj road, form the main ridge of the Churia Hills that lie between the Hetauda Dun to the north and the Ganges Plain to the south.

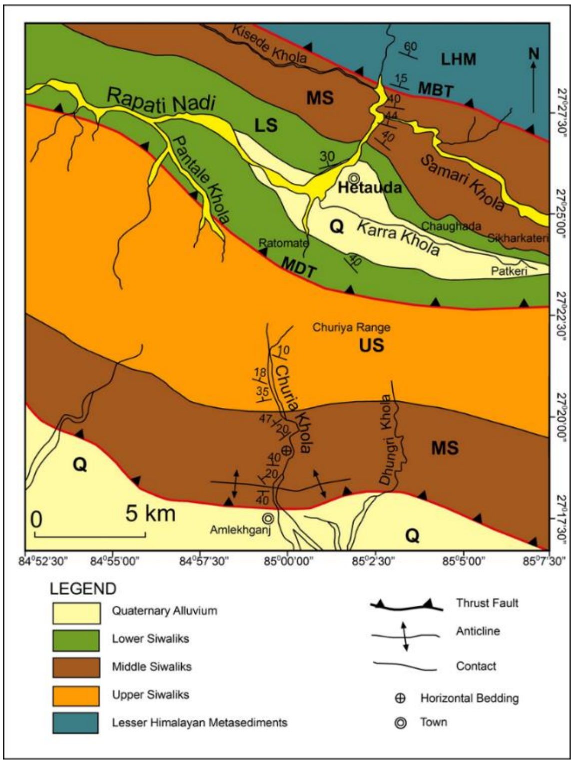

Fig. 2 Regional Geological map of Hetauda-Amlekhganj region of the Central Nepal Siwalik Hills (after Schelling et al. 1991).

III. MATERIALS AND METHODS

3.1 Samples

The samples used in the experiment for this study were collected from the different locations of the Siwalik Group i.e. the Lower Siwalik Subgroup and the Middle Siwalik Subgroup of Hetauda-Amlekhjang area (Fig. 2). Sampling sites are mainly located along the rivers and road cuts. Sampling of mudrocks is a tough job as mudrocks are very fragile in nature. However, with high care and patience five types of 38 mudrocks viz. siltstone (17), mudstone (11), claystone (3), silt-shale (5) and clay-shale (2) from 23 location points were collected (Fig.1; Table 1). Mudrocks whose petrographic description was based on megascopic examination, had massive to laminated structure, varied coloured and calcareous to non-calcareous binders. They were moderate to highly weathered in the rock masses, however, the intact samples were little more fresh than the whole rock masses.Mudrocks were broken carefully into smaller pieces with the help of hammer such that each piece weighed up to 50 g to 60 g and were wrapped into soft paper and put into the plastic bag. The good care was also taken for its moisture content. The collected samples were cleaned by brush and sharp corners were worn before they were taken for the slake durability test.

3.2 Methods

The standard operating procedure was based on ASTM D 4644-87 (Reapproved 1992) Standard Test Method for slake durability of shales and similar weak rocks. The sample fragments were placed in a bowl. The bowl with the sample fragments were dried in an oven for 12 to 16 hours or to a constant mass. The sample and bowl were allowed to cool at room temperature for 20 minutes and weighed again.

The natural water content was calculated as:

$w = [(A–B)/(B–C)] \times 100$………….. (1)

where,

w = percentage of water content, A = mass of drum plus sample at natural moisture content (g), B = mass of drum plus oven-dried sample before the first cycle (g), and C = mass of drum (g).

The sample was put in the drum and the drum was mounted in the trough. The sample in the drum was coupled to the motor (Fig. 3). The trough was filled with distilled water at room temperature to 20 mm (0.8 inches) below the drum axis. The drum was rotated at 20 rpm for a period of 10 minutes. The water temperature at the beginning and end of the run was noted. The drum was removed from the trough and the lid was removed from the drum immediately after the rotation period was completed and the sample was dried by retaining them in the oven for 12 to 16 hours at 105 ºC, or to constant mass. After cooling, the sample was weighed to obtain the oven-dried mass for the second cycle.

Table 1: Location and description of mudrock samples

Location	Subgroup	Elevation (m)/Latitude/ Longitude	Sample/Rock type	Weathering grade
L1	Lower Siwalik	384/27.434296/85.023167	L1m massive, greenish grey, non-calc. mudstone; L1z massive siltstone	moderate
L3	Lower Siwalik	388/27.436889/85.027485	L3m massive grey calcareous mudstone; L3z massive yellowish grey slightly altered siltstone	moderate
L5	Lower Siwalik	385/27.442739/85.030943	L5z massive greenish grey calcareous siltstone	moderate
L6	Lower Siwalik	385/27.443538/85.031343	L6m massive, greenish grey calcareous mudstone	moderate
L7	Middle Siwalik	405/27.452311/85.039772	L7c massive, yellowish grey calcareous claystone	moderate
L8	Middle Siwalik	437/27.45171/85.0395	L8c massive, dark grey calcareous claystone	high
L9	Middle Siwalik	402/27.454027/85.040862	L9m massive bluish grey calc. mudstone; L9z massive grey siltstone	moderate
L11	Middle Siwalik	411/27.46147/85.035014	L11z massive dark grey siltstone	high
L12	Middle Siwalik	455/27.471804/85.029725	L12z massive, light grey slightly altered siltstone	high
L14	Middle Siwalik	444/27.474398/85.026377	L14z-sh laminated light grey calc. silt-shale; L14z light grey calc. siltstone	moderate
L17	Middle Siwalik	415/27.453403/85.065217	L17z massive, light grey calcareous siltstone	moderate
L18	Lower Siwalik	400/27.413582/85.017827	L18z massive, greenish grey siltstone	moderate
L19	Lower Siwalik	490/27.386219/85.025528	L19z greenish grey, non-calcareous siltstone	high
L20	Lower Siwalik	332/27.43777/84.947225	L20c-sh laminated bluish grey calc. clay-shale; L20c massive dark grey clay-stone	high
L21	Lower Siwalik	348/27.444022/84.945196	L21z-sh laminated dark grey silt shale; L21z cross-laminated dark grey calc. siltstone; L21m massive bluish grey calc. mudstone	moderate
L22	Lower Siwalik	340/27.445892/84.944012	L22z-sh bluish grey calc. silt-shale; L22z massive yellowish grey non-calcareous altered siltstone	moderate
L23	Lower Siwalik	337/27.449066/84.939656	L23z-sh laminated bluish grey silt-shale; L23z greenish grey calc. siltstone; L23m massive calc. mudstone	moderate
L24	Lower Siwalik	293/27.451292/84.938281	L24m massive bluish grey altered mudstone	high
L25	Lower Siwalik	319/27.45297/84.938011	L25z laminated, bluish grey calcareous siltstone; L25m bluish grey calcareous mudstone	high
L26	Lower Siwalik	645/27.401783/85.126772	L26z-sh laminated light grey silt-shale; L26z light grey calcareous siltstone	moderate
L27	Lower Siwalik	705/27.401286/85.131251	L27z massive grey altered siltstone; L27m massive light grey altered mudstone	high
L29	Lower Siwalik	820/27.410323/85.148745	L29z massive bluish grey calcareous siltstone; L29m massive grey calcareous mudstone	moderate
L31	Middle Siwalik	291/27.297056/84.999306	L31c-sh laminated dark grey clay-shale; L31m massive bluish grey calcareous mudstone	moderate

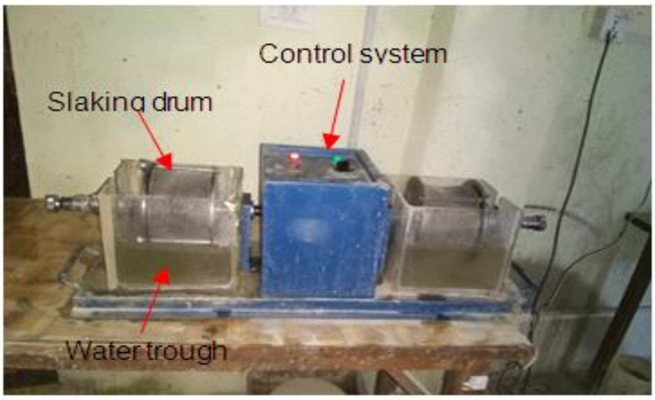

Fig. 3 Apparatus of Slake Durability Test

Table 2: Visual description of rock samples retained after second cycle (after Franklin and Chandra, 1972)

Type	Description
I	Pieces remain virtually unchanged
II	Large and small pieces
III	Exclusively small fragments

Table 3: Slake durability index classification (after Franklin and Chandra, 1972)

ID_2 (%)	Durability classification
0 - 25	Very Low
26 - 50	Low
51 - 75	Medium
76 - 90	High
91 - 95	Very High
96 - 100	Extremely High

Rotating the sample and drying it were repeated for two more cycles, then the sample was weighed again to obtain a final mass. The bowl was cleaned and weighed to obtain its mass. The sample was retained after testing to archive. The type of the sample (Type I, II, or III as described in ASTM Method 4644-87) after the test was recorded to classify and describe its character after the test following [1] (Table 2).

The slake durability index (second cycle) was calculated as follows:

$Id_2 = [(W_F - C)/(B - C)] \times 100$ ………… (2)

Where,

Id_2 = slake durability index (second cycle),

B = mass of drum plus oven-dried sample before the first cycle, g,

W_F = mass of drum plus oven-dried sample retained after the second cycle, g. and

C = mass of drum, g.

The obtained results of slake durability at each of the four cycles were classified following the classification of [1] (Table 3), and were plotted on the graph to describe the behavior of durability of the mudrocks.

IV. RESULTS AND DISCUSSIONS

4.1 Slake Durability Indices of Shales

Among the 38 samples of mudrocks, seven were shale samples. Shale samples exhibit considerable fissility, whereas stone samples were massive. Out of 7 shale samples, five samples (L14, L21, L22, L23, L26) were of silt-shales (e.g., L26, Fig. 4a) and the remaining two samples (L20 (Fig. 4b), L31) were of clay-shales. The silt-shales are laminated. Those of location L21 are bluish grey and other are greenish grey. Silt-shales of location L14 and L22 are calcareous too. The clay-shale samples of the location L20 is bluish grey and L31 is black, both samples are calcareous and laminated. The results of four cycle-test and classification of slake durability index are listed in Table 4.

The silt-shale sample percentage retention after the second cycle or Id_2 ranges between 83.83% and 96.43% (Table 4). The range shows that the samples are of high to extremely high durability according to SDI table of classification (Table 3). The sample L26 retained after second cycle (Fig. 5b), for example, resembles Type II of ASTM Method D 4644-87 as retained sample consists of large and small pieces.

Slake durability indices of clay-shales after second cycle range between 84.95% and 90.82%, which means the samples are of high durability. The sample retained after second cycle resembles the Type II disintegration texture (Fig. 6b). The texture of sample L20 retained even after fourth cycle (Fig. 6a) does not disintegrate much, and shows Type II texture.

4.2 Slake Durability Indices of Mudstones, Claystones and Siltstones

Out of 38 samples 31 samples were of stones, i.e. 11 mudstones, 3 claystones, and 17 siltstones. The mudstone samples L3m, L6m, L9m, L21m, L25m, and L29m are calcareous and other location sample are non-calcareous. The mudstone samples L6m and L1m are greenish grey whereas the remaining samples are bluish grey. Texture of mudstone is massive except L9m mudstone, which is faintly laminated. Claystone L7c is yellowish grey whereas the remaining two samples (L8c and L20c) are bluish grey. All claystones are massive in structure and are calcareous. Regarding the 17 samples of siltstones, the sample L25z is laminated whereas the rest of the siltstone are massive. The samples L5z, L9z, L14z, L17z, L21z, L23z, L25z, L26z, and L29z are calcareous cemented. The samples L3z, L12z, L19z, L22z, and L27z are slightly altered with lesser induration compared to other samples.

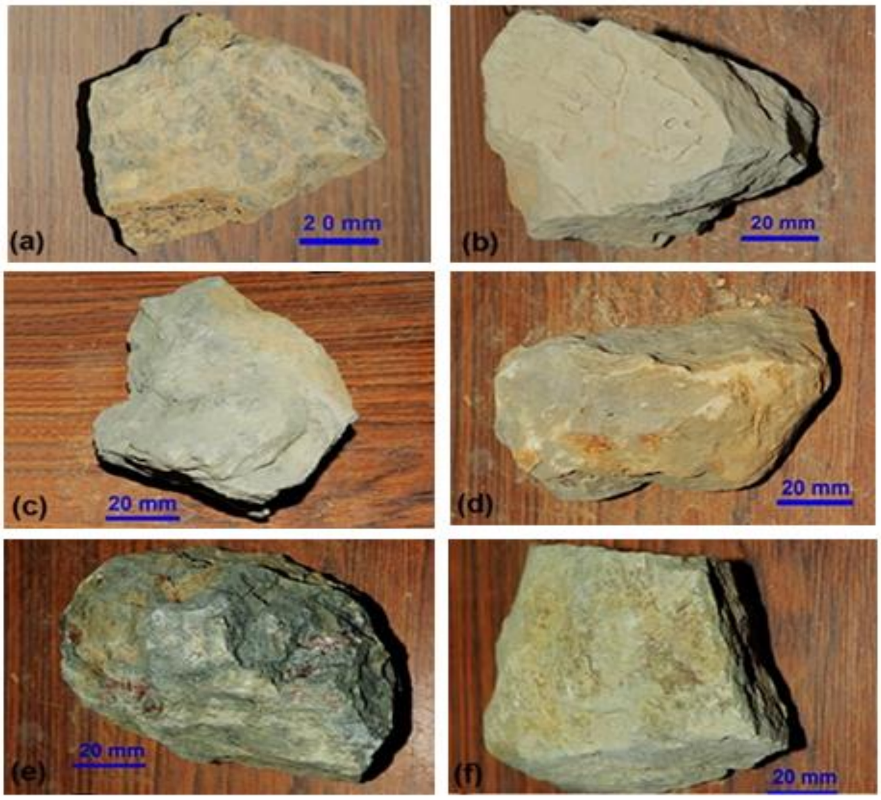

Fig. 4 Handspecimens of mudrock samples. (a) Silt-shale, L26z-sh, (b) Clay-shale, L20c-sh, (c) Mudstone, L29m, (d) Claystone, L8c, (e) Siltstone, L18z, and (f) Siltstone, L22z.

Table 4: Slake durability indices at four cycles of shales, durability indices, and classification

Rock type/(Sample number)	Location	Average SDI (%) in each of cycles				ID_2 (%)	Durability	Type
		1	2	3	4			
Silt-shale (L14z-sh)	L14	97.62	96.43	83.99	81.87	96.43	Extremely high	II
Silt-shale (L21z-sh)	L21	94.34	89.63	85.48	83.01	89.63	High	II
Silt-shale (L22z-sh)	L22	94.17	91.05	88.44	84.84	91.05	Very high	II
Silt-shale (L23z-sh)	L23	94.78	83.83	80.89	72.17	83.83	High	II
Silt-shale (L26z-sh)	L26	94.57	87.82	82.47	77.04	87.82	High	II
Clay-shale (L20c-sh)	L20	95.21	90.82	87.78	84.07	90.82	High	II
Clay-shale (L31c-sh)	L31	88.82	84.95	76.66	71.39	84.95	High	II

a b c

Fig. 5 (a) Silt-shale sample (L26z-sh) before first cycle, (b) Silt-shale wet sample retained after second cycle (Type II), and (c) Silt-shale dried sample retained after fourth cycle (Type II).

Table 5: Slake durability indices at four cycles of mudstones, durability indices, and classification

Rock type/(Sample number)	Location	Average SDI (%) in each of cycles				ID_2 (%)	Durability	Type
		1	2	3	4			
Mudstone (L1m)	L1	92.84	91.04	89.67	89.66	91.04	Very high	II
Mudstone (L3m)	L3	97.57	96.25	95.14	93.92	96.25	Extremely high	II
Mudstone (L6m)	L6	98.84	98.10	97.78	97.72	98.10	Extremely high	II
Mudstone (L9m)	L9	97.12	94.66	92.19	90.01	94.66	Very high	II
Mudstone (L21m)	L21	98.02	96.83	95.75	94.76	96.83	Extremely high	II
Mudstone (L23m)	L23	96.40	94.01	92.00	86.42	94.01	Very high	II
Mudstone (L24m)	L24	91.56	85.31	80.49	75.08	85.31	High	II
Mudstone (L25m)	L25	96.81	94.63	92.54	90.45	94.63	Very high	II
Mudstone (L27m)	L27	97.08	94.48	91.89	89.43	94.48	Very high	II
Mudstone (L29m)	L29	98.59	97.29	96.10	94.80	97.29	Extremely high	II
Mudstone (L31m)	L31	96.12	94.80	92.03	90.50	94.80	Very high	II
Claystone (L7c)	L7	96.44	94.45	92.88	91.21	94.45	Very high	II
Claystone (L8c)	L8	96.56	94.66	91.77	89.27	94.66	Very high	II
Claystone (L20c)	L20	95.00	91.30	86.70	82.50	91.30	Very high	II
Siltstone (L1z)	L1	96.29	93.49	91.31	90.17	93.49	Very high	II
Siltstone (L3z)	L3	92.10	83.98	78.90	75.96	83.98	High	II
Siltstone (L5z)	L5	99.22	98.34	97.86	97.64	98.34	Extremely high	II
Siltstone (L9z)	L9	95.53	90.13	85.46	84.42	90.13	High	II
Siltstone (L11z)	L11	94.48	91.56	87.05	82.71	91.56	Very high	II
Siltstone (L12z)	L12	92.94	85.89	79.03	74.84	85.89	High	II
Siltstone (L14z)	L14	97.64	95.05	93.47	91.72	95.05	Very high	II
Siltstone (L17z)	L17	98.03	96.07	95.14	93.69	96.07	Extremely high	II
Siltstone (L18z)	L18	95.56	91.23	87.11	82.98	91.23	Very high	II
Siltstone (L19z)	L19	82.38	68.56	55.95	48.84	68.56	Medium	II
Siltstone (L21z)	L21	97.84	96.51	95.69	94.05	96.51	Extremely high	II
Siltstone (L22z)	L22	79.36	69.41	62.04	56.86	69.41	Medium	II
Siltstone (L23z)	L23	97.27	95.28	94.44	92.86	95.28	Very high	II
Siltstone (L25z)	L25	98.32	97.43	96.55	95.86	97.43	Extremely high	II
Siltstone (L26z)	L26	98.53	97.16	95.2	93.93	97.16	Extremely high	II
Siltstone (L27z)	L27	88.76	84.52	76.00	72.88	84.52	High	II
Siltstone (L29z)	L29	98.21	96.63	94.56	93.56	96.63	Very high	II

The sample percentage retention of mudstones after the second cycle or Id_2 ranges between 85.31% and 98.1% (Table 5). This signifies that samples are of high to extremely high durability. Mudstones often have high sensitivity to slaking. [15] reported that Id_2 of mudstones ranged from 12 to 68% respectively for highly weathered to moderately weathered samples. However, the samples they tested were not calcareous. [24] reported Id_2 variation (33% to 86%) of mudstones with sampled depth from the surface of landslide area. Relatively weathered rocks from the shallow depth indicated high potential of slaking. The retained fragments of sample resemble Type II as retained pieces consist of large and small pieces (Fig. 7). The resulting fragments after fourth cycle do not differ much from those retained in the second cycle (Fig. 7b and 7c). Except for L24, the rest of the samples lie in very high to extremely high durability. This can be attributed to calcareous nature of the samples and absence of fissility in the stones.

Slake durability indices of claystones range from 91.3% to 94.66% (Table 5). This signifies that samples are of high durability according to the table of classification (Table 3). The claystone samples show high durability because these samples are calcareous in nature with massive structure without fissility. The sample obtained resembles Type II pattern, and the fragments of samples retained after second and fourth cycles are similar (Fig. 8).

Slake durability indices of siltstones vary in a wide range, from 68.56% to 98.34% (Table 5). The durability is classified as medium to extremely high. Non-calcareous and weathered samples of siltstones (L19z, L22z, L27z, etc.) give relatively low durability indices. The retained fragments of siltstone samples resemble to Type II pattern (Fig. 9). Although both L18 and L22z samples are non-calcareous, sample L22z is less durable than the sample L18z, perhaps due to presence of fractures and alteration, therefore yielding more fragmented pieces (Fig. 9). Degree of

Fig. 6 (a) Clay-shale sample (L20c-sh) before first cycle, (b) Clay-shale wet sample retained after second cycle (Type II), and (c) Clay-shale dried sample retained after fourth cycle (Type II).

Fig. 7 (a) Mudstone dried sample retained after fourth cycle (Type II), (b) Mudstone wet sample retained after second cycle (Type II), and (c) Mudstone sample before first cycle.

a b c

Fig. 8 (a) Claystone sample (L8c) before first cycle, (b) Claystone wet sample retained after second cycle (Type II), and (c) Claystone dried sample retained after fourth cycle (Type II).

Table 6: Categorization and description of durability curves and rock types showing corresponding curve types

Curve type	Description	Shale	Mudstone	Claystone	Siltstone
A	Little progressive diminish or no significant change in durability from the beginning to the end of the 4th cycles		L3m, L6m, L9m, L21m, L25m, L27m, L29m, L31m		L1z, L5z, L14z, L17z, L21z, L25z, L26z, L29z
B	no initial sign of disintegration, but deteriorate significantly after 3rd cycle down to medium durability (mild convex curve)		L23m		
C	Slight deterioration in the 2nd cycle, constant in the 3rd cycle and further deterioration in the 4th cycle (mild s-shaped curve)				L23z
D	no initial sign of disintegration, but deteriorate significantly after 2nd cycle down to medium durability				L11z
E	Same rate of deterioration from the initial to the 4th cycle but with initial extreme to very high durability and later down to high durability	L20c-sh, L21z-sh, L22z-sh, L26z-sh	L24m	L7c, L8c, L20	L18z
F	Progressive deterioration up to 3rd cycle and then negligible up to 4th cycle down to high durability (concave curve)		L1m		L3z, L9z, L12z
G	Little initial deterioration followed by notable one at 3 cycle, followed by little late deterioration (z-shaped curve)	L31c-sh, L14z-sh,			L27z
H	Notable initial deterioration at 2nd cycle followed by little at 3rd cycle and again notable deterioration at 4th cycle (s-shaped curve)	L23z-sh			
I	Progressive deterioration up to 3rd cycle and then reduced deterioration up to 4th cycle down to medium durability (high gradient concave curve)				L19z, L22z

weathering has significant effect in durability of siltstones. Despite of this, both fresh and moderately weathered siltstones studied by [25] were of extreme durability to medium durability, showing that durability and its change with subsequent cycles vary independent of weathering grade.

calcareous shales. Presence of more prominent fissility in L31c-sh could have caused greater deterioration in this sample compared to L20c-sh. Microcracks when present and degree of cementation also play important role in differing durability indices [26].

Fig. 9 (a) Siltstone samples (L18z and L22z) before first cycle, (b) Siltstone wet sample retained after second cycle (Type II) and (c) Siltstone dried sample retained after fourth cycle (Type II).

4.3 Durability Behavior

Four cycle test of slake durability was conducted to establish durability behavior of each of the samples. From the patterns of curves that were obtained from graphical plots (Figs. 10 and 11), various types of patterns of curves from types A to I have been identified and are listed in Table 6.

4.3.1 Durability Behavior of Shales

The slake durability index (SDI) curves of shales in Fig. 10 show that the curves are of three different nature. However, all are in decreasing pattern which means slaking behavior of shales of the Siwalik is progressive in nature. Samples L14z-sh (G-type), L31c-sh (G-type) and L23z-sh (H-type) show irregular curves with overall diminishing of ID_2 showing that slaking is non-uniform (Fig. 10), whereas the rest of the curves show progressive diminishing of Id_2 with E-type pattern (Fig. 10), and in them high to very high Id_2 values in the second cycle diminish to high Id_2 between 75 and 90% in the fourth cycle.

Two similar clay-shales (L20c-sh and L31c-sh) differ with one another slightly in Id_2 and the way of deterioration (Fig. 10). Both are

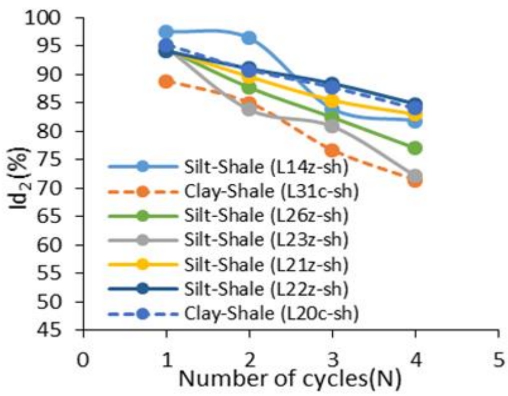

Fig. 10 Average Slake Durability Index (%) versus number of cycle (N)

In case of silt-shales, three different types of curves, i.e., E-type, G-type and H-type are obtained (Fig. 10). Among the samples showing the E-type curves, in which Id_2 varies in the narrow range, L26z-sh deteriorates more rapidly compared to the other samples. The sample L14z-shows G-type deterioration behavior in which initially sample show extreme durability in the second cycle, but it deteriorates giving Id_2 of 82%. The L23z-sh represents H-type deterioration behavior showing initial high Id_2 (84%) in the second cycle remaining medium durability (72%) in the 4th cycle. Rapid deterioration between first and second cycles could be due to erosion of the weathering rim from the fragments of rock.

4.3.2 Durability Behavior of Mudstones, Claystones and Siltstones

Mudstones show regular and constantly decreasing A-type curves, which signify that the slaking is slow and uniform in nature (Fig. 11a; Table 6) without significant deterioration of the samples up to the fourth cycle. The remaining three samples differ in durability behavior showing B-type (L23m), E-type (L24m) and F-type (L1m) deterioration pattern (Table 6). Deterioration after first cycle is remarkable in L24m because this sample is non-calcareous, while other samples are calcareous giving higher durability. Degree of induration largely defines the rate of softening of argillaceous materials in contact with water [27]. It means better indurated rocks with its natural water content, remain intact with immersed in water because of better induration compared to soft rocks. Calcareous and indurated nature of most of the mudstones perhaps played role in durability up to forth cycle.

Regular and constantly decreasing C-type deterioration curves of claystones are obtained (Fig. 11b; Table 6). Two samples L7c and L8c are more or less similar in pattern, whereas L20c deteriorates at greater rate (Fig. 11b). All the samples show low deterioration up to fourth cycle most probably owing to well bonding of mineral grains by calcareous cement. In overall, it is observed that almost all claystone samples are clay-bearing in significant amount. [4] found that the clay-bearing rocks such as mudstones have considerable decrease in slake durability index as the number of cycle increases. The rocks have a different slaking speed in water for 0-48 hours [28]. Since, the claystone samples from the Siwaliks are of calcareous nature, the rate of deterioration under slaking is found to be not so significant.

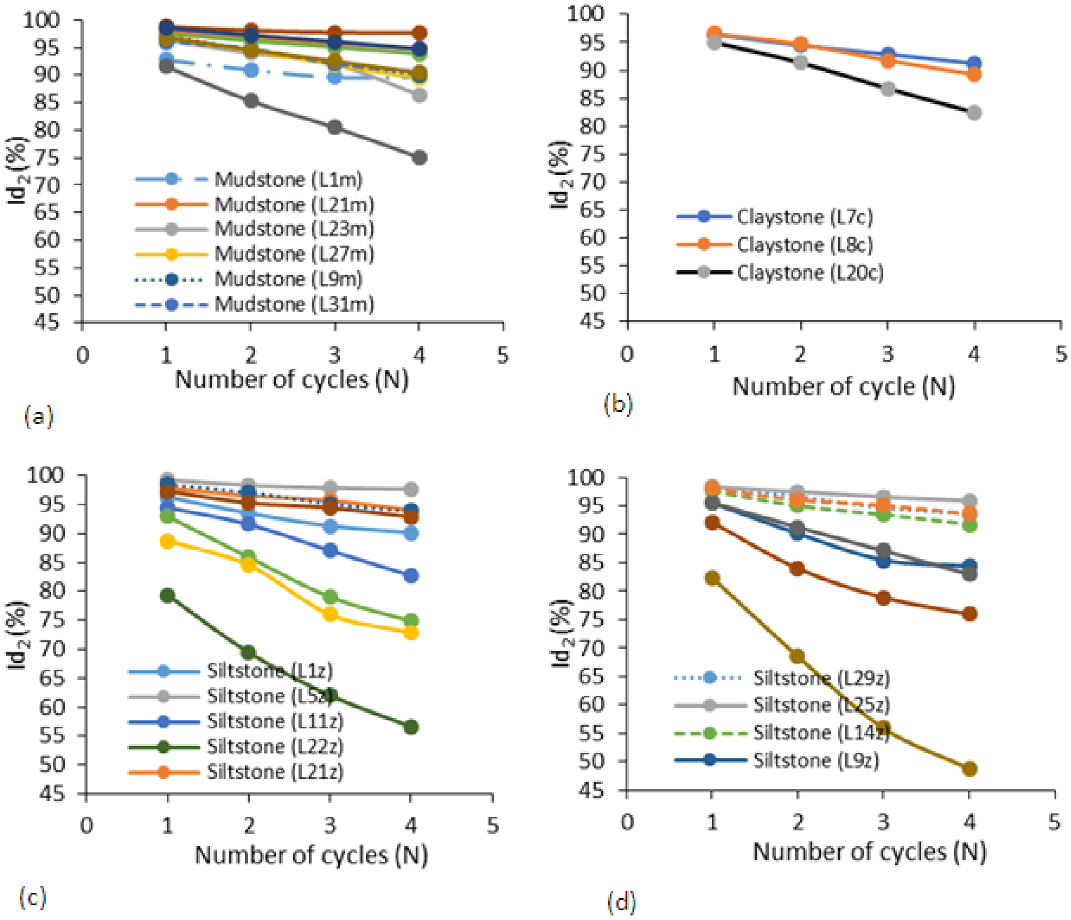

Fig. 11 Average Slake Durability Index, SDI versus number of cycle (N): (a) curves of mudstones, (b) curves of claystones, and (c) and (d) curves of siltstones

SDI curves of siltstones are of widely varying nature giving A-, C-, D-, E-, F-, G-, and I-type patterns among the mudrocks (Figs. 12c and 12d; Table 6). Here, the E-type (L18z), F-type (L3z and L12z), G-type (L27z) and I-type (L19z and L22z) deterioration patterns are detrimental showing greater potential of slaking. Firstly, they have lower durability indices among the samples, and secondly, they deteriorate significantly during subsequent cycles. Some siltstone samples of the locations L3z, L12z, L19z, L22z, L27z have significant decrement in SDI values because they are somewhat altered and moderately to highly weathered in the outcrops. Thus, such siltstones, perhaps owing to non-calcareous nature and weak bonding among the mineral grains, and with alteration show poor deterioration behavior among the siltstone samples.

After getting visualized the SDI curves from Figs. 10 and 11, the schematic SDI curves from A- to I-types are represented in Fig. 12. Among these types, A-, B-, C- and D-types are representatives of somewhat durable rock types, whereas the rest of the other SDI curve types such as E-, F-, G-, H- and I-types represent rock types with relatively lower durability and significant deterioration behavior. Among the relatively lower durability patterns, the rock types with very poor durability behavior are those exhibiting I-type deterioration patterns.

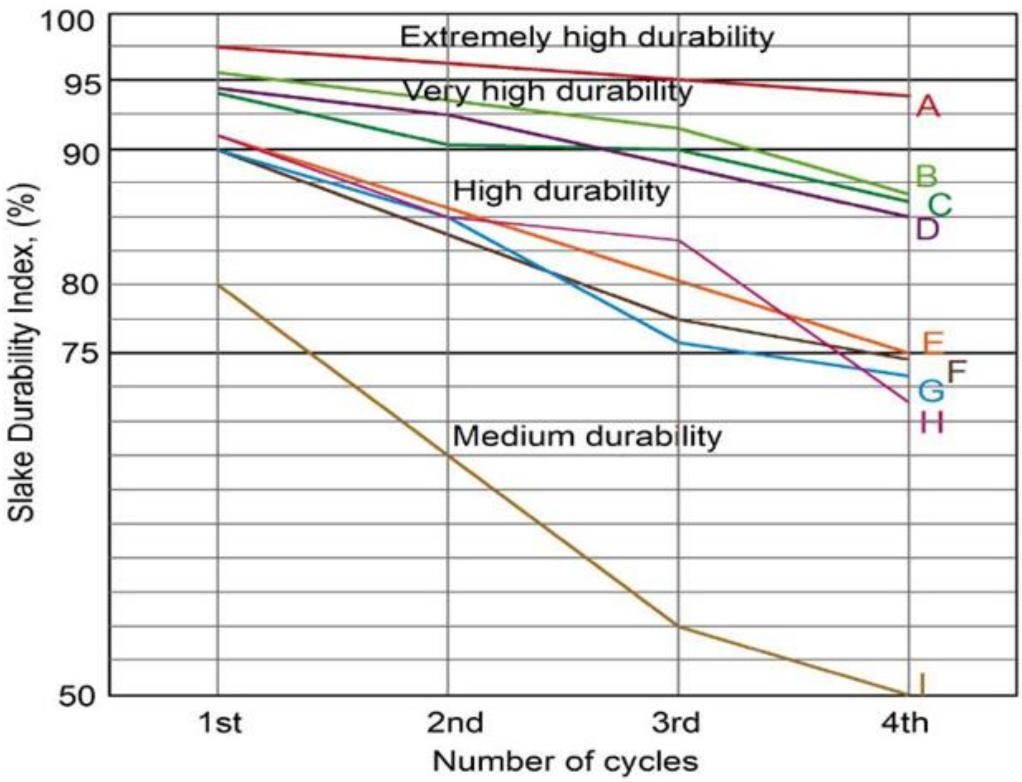

Fig. 12 Schematic deterioration curves of mudrocks under slake durability tests

V. CONCLUSIONS

Cyclic drying and wetting is one of the causes of disintegration of the mudrocks. Slake durability of rocks is varying with the time in water or the cycle of drying and wetting. The slaking process of mudrock samples is seen gradually increasing during wetting and drying cycle. Clay-bearing rocks disintegrate relatively easily, but with calcareous binding of mineral grains, slake durability tends to enhance.

The average SDI value of mudstone and claystone samples are 94.30% and 93.47% which are greater than the average SDI value of siltstone samples 90.07%, and the average SDI value of silt-shale samples 89.73% and clay-shale 87.88%.

Therefore, mudstone and claystone are found to be very high durable than siltstone and shale as mudstone and claystone samples are calcareous and massive in structure without fissility.

The silt-shale samples have greater SDI values than the clay-shale. However, there occur 5 to 15% reduction of durability from the second to the fourth cycle, and the durability behavior of shales are variable due to presence of fissility. The mudstones due to presence of massive structure and calcareous binders, have very high to extreme durability. They show consistent durability behavior except one sample which is non-calcareous. Claystones also show very high durability, with consistent durability behavior. Siltstones show wide range of durability from medium to extremely high. Their durability behavior via deterioration patterns is also wide compared to other mudrock samples. Despite of varying durability and durability behavior, the mudrocks have showed the same category (Type II) of fragmented samples retained after second cycle of the slake durability test.

Based on how does slaking proceed during four cycles, the deterioration curves yielded by mudrocks have been categorized into A-, B-, C-, D-, E-, F-, G-, H-, and I-type curves. Mudrocks yielding E-, F-, G-, H-, and I-type curves seem to have greater potential to slaking compared to the remain types of deterioration curves. Where these types of mudrocks occur in association with stiffer sandstones, contribute in slope movement due to erosion of mudrocks leaving sandstones to hang and fail under various kinematics.

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