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| RESEARCH ARTICLE

Correlation Between Strength and Durability of Sandstones from the Dumri Formation, Tinau Khola Area, West-Central Nepal

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| ABSTRACT
Strength and Durability indices are two significant geotechnical criteria that can describe rock fragments' strength and weathering resistance. The Dumri Formation is the youngest and thickest of the Tansen Group, Lesser Himalaya. A thick succession of medium-grained, bluish-grey quartzose sandstone and red-purple shale represents it. To assess the quality of the sandstones, different laboratory tests and analyses were made to characterize the physical and mechanical properties of the sandstones. Physical properties were greatly influenced by composition and texture. The intact rock strength was figured out by the point load strength index (PLSI) and Aggregate impact value (AIV). Rock durability against slaking was determined using the slake durability index (SDI) test. The strength and durability indices were correlated through regression analysis. Sandstones assessed were classified as lithic and feldspathic wacke. Sandstones exhibited high resistance to slaking and are extremely durable (SDI = 99.53-99.86%) under a two-cycle test. Sandstones are strong to very strong (PLSI = 5.28-8.92 MPa) and possess high impact resistance (AIV = 6-9%). The correlation between PLSI and SDI was found to be high (r=0.86). Similarly, a correlation between AIV and SDI was (r=0.98), and between AIV and PLSI was (r=0.86).

| KEYWORDS

Point Load Strength Index, Slake Durability Index, Aggregate Impact Value, Dumri Formation, Correlation.

| ARTICLE INFORMATION

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1. Introduction

Evaluating the quality of rocks involves various physio-mechanical tests that categorize them based on the results obtained. However, relying on a single test is insufficient for a comprehensive assessment of rock quality. Geoscientists are therefore encouraged to conduct multiple tests, combining their results to better understand the rock's suitability for different applications. In this context, the strength and durability of the rock are crucial factors that significantly influence the performance of geological materials.

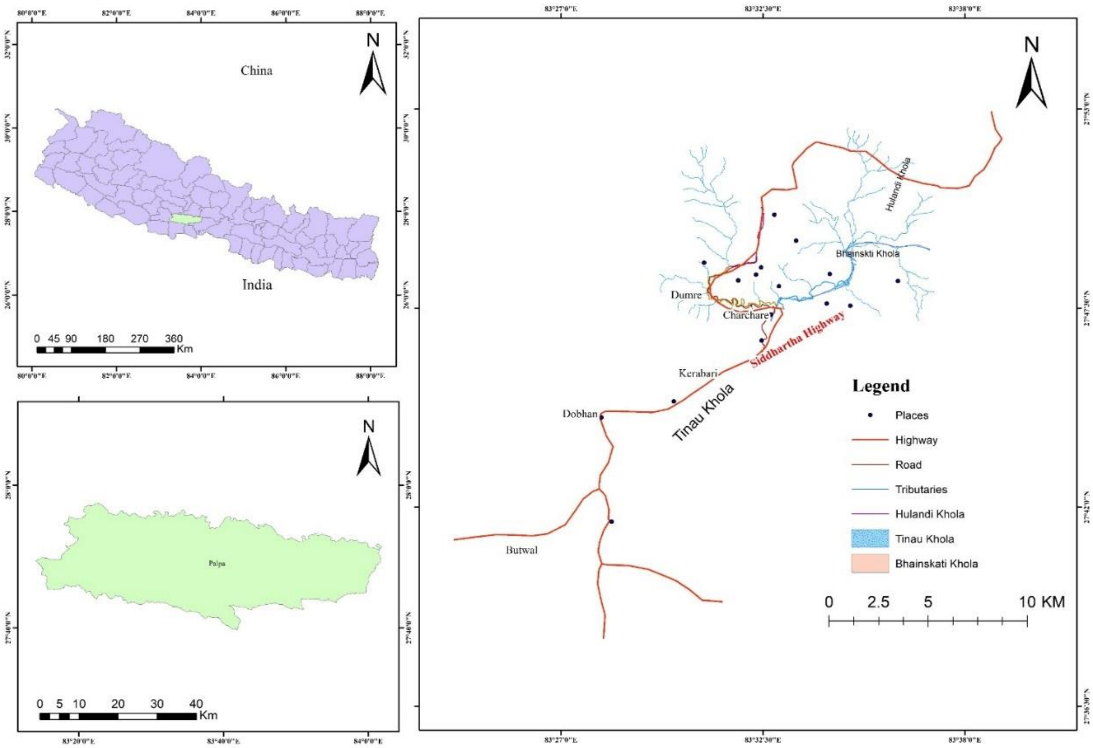
Aggregate Impact Value (AIV) is a measure of the resistance of rock aggregates to sudden shock or impact, which is particularly important in construction applications (Smith and Collis, 2001). This parameter, along with point load strength and slake durability indices, plays a crucial role in assessing the quality and durability of rock materials. Point load strength and slake durability indices are two significant geotechnical parameters used to describe the strength and weathering resistance of rock fragments (Ayakwah et al., 2009). SDI index is determined through a standardized test that evaluates the degradability of rocks when subjected to two cycles of wetting and drying (Çiçek et al., 2016). Another important test is the point load test, which is used to assess the mechanical strength of rocks (Price, 2009). This test can be performed on specimens of various shapes and is often considered a substitute for the unconfined compressive strength test (Broch and Franklin, 1972).

Research has shown that there is often a correlation between AIV, point load strength, and slake durability index. For instance, rocks with higher point load strength and slake durability indices typically exhibit lower AIV values, indicating greater resistance to impact (Kahraman and Gunaydin, 2009). However, the exact relationships between these parameters can vary depending on rock type and geological conditions, emphasizing the importance of comprehensive testing in geotechnical assessments (Diamantis et al., 2009).

Rock strength and durability, critical in geotechnical engineering, are often evaluated using the Point Load Strength Index (PLSI), Aggregate Impact Value (AIV), and Slake Durability Index (SDI). Ahmad et al. (2017) found PLSI values ranging from 1.9 MPa to 12.3 MPa, AIV values ranging from 9.5% to 39.5%, and SDI values ranging from 92.19 to 99.63% for sedimentary, metamorphic and igneous rocks altogether forty-five samples. PLSI, AIV, and SDI reported for quartzites from the Fagfog Quartzite are 2.04-11.55 MPa, 14.85- 22.77%, and 96.94-100%, respectively (Sharma and Tamrakar 2023). PLSI and SDI reported for sandstones from the Siwalik Group, Hetauda, are respectively 0.024-2.16 MPa and 43.69-99.14% (Budhathoki and Tamrakar 2022). These results generally align with global findings, where sandstone's PLSI values have been observed to vary from 0.5 to 8.4 MPa, and SDI values from 86% to 100% (Shakoor and Bonelli, 1991; Dhakal et al., 2002; Tsiambaos and Sabatakakis, 2004; Sabatakakis et al., 2008; Çelik and Kaçmaz, 2016). Maharjan and Tamrakar (2007) determined AIV values of fluvial gravel from the Rapti Rivers between 14.2% and 16.1%, whereas global AIV values for sandstones typically range from 15% to 40%, with lower values indicating higher strength (Sabatakakis et al., 2008).

Linear regression analysis, a fundamental statistical method for modeling relationships between variables (Montgomery et al., 2012), was employed in this study to explore correlations among key geotechnical parameters: Point Load Strength Index (PLSI), Slake Durability Index (SDI), and Aggregate Impact Value (AIV). This technique, which fits a linear equation to observed data for predictions and insights (Weisberg, 2005), is particularly useful in geotechnical engineering for understanding rock properties. By examining these correlations, researchers aim to gain valuable insights into how these indices interact and potentially predict one another, contributing to more informed decision-making in construction and mining projects (Kahraman, 2001; Diamantis et al., 2009). The present study employs this analytical approach to investigate the relationships among key geotechnical parameters: Point Load Strength Index (PLSI), Slake Durability Index (SDI), and Aggregate Impact Value (AIV).

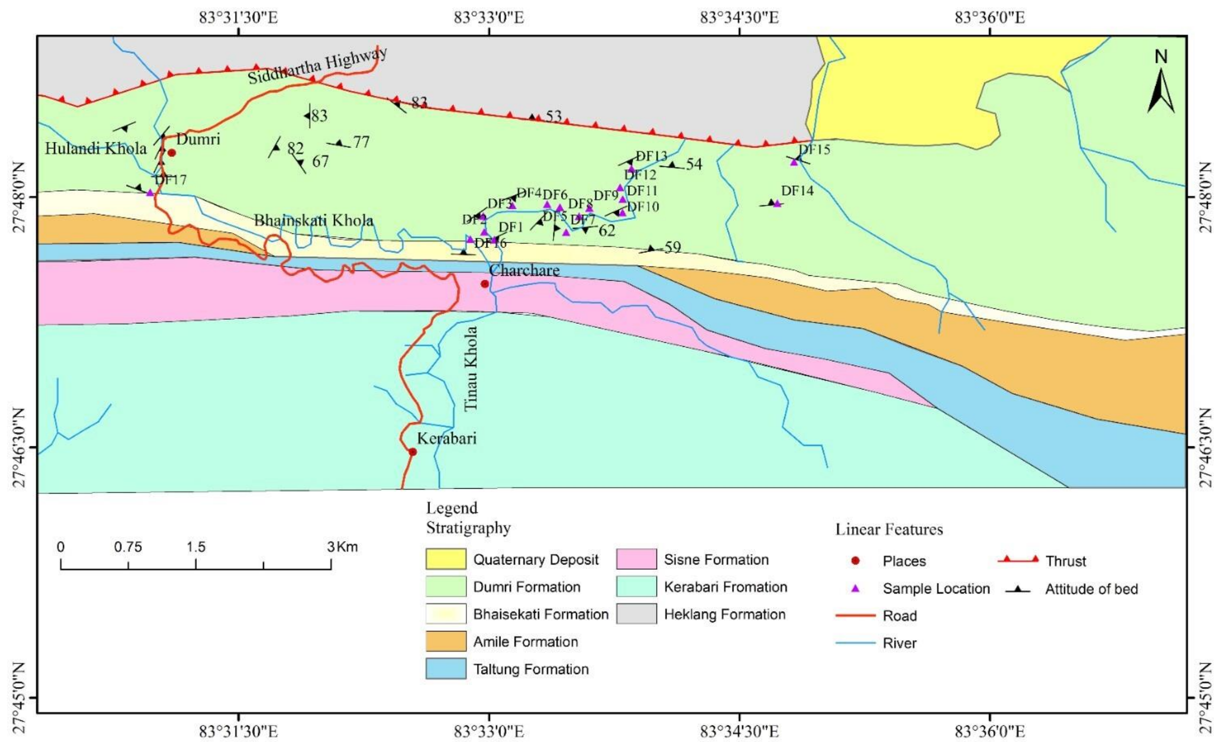
Figure 1: Location map of the study area



2. Geological Setting

The study area, Dumri Formation lies in Tinau VDC in the Palpa District, Lumbini Province. (Figure 1). The study area lies about 40 km North of Butwal along the Siddhartha Highway. The rock outcrops of the Kaligandaki Super Group and the Tansen Group (Sakai, 1983) are well exposed on the Siddhartha Highway and on the banks of the Tinau River. The rocks of these groups are separated by disconformity. The Tansen Group constitutes the Tansen Synclinorium, which attains a maximum thickness of 2400 m and is divided into five geological formations: (i) the Sisne Formation consisting mainly of glacio-fluvial, glacial-lacustrine and marine sediments of late carboniferous to Permian, lower Gondwana age, (ii) the Taltung Formation, fluvial sediments of late Jurassic to cretaceous, upper Gondwana age, (iii) the Amile formation, fluvial-deltaic sediments of late Jurassic to cretaceous, (iv) the Bhainskati formation, shallow marine to brackish water deposited in middle to late Eocene age, and (v) the Dumri formation (fluvial deposits). The Tansen Group of rocks was deposited in a sedimentary basin that extended back to the Paleogene and Cretaceous periods. It is situated on the eroded surface of the Precambrian bedrock of the Lesser Himalaya, as reported by (Sakai 1983; DeCelles et al. 1998). Coalfield fragments and a rhythmic succession of sandstone, shale, and scour channels indicate that the Dumri Formation was rapidly formed from a river floodplain deposit.

Figure 2: Geological map of the study area (Modified after Sakai, 1983)



3. Methodology

3.1 Sampling

Samples were collected from seventeen different locations in the Tinau Khola section of the Dumri Formation, considering a selection of fresh samples stratigraphically representative of succession and rock types (Figure 2). From each sampling location, about 34.5 kg of sample was collected for laboratory tests, whereas outcrops of sampled bedrock were described in the field.

3.2 Microscopic examination of sandstone

All the samples were thin-sectioned and were observed under a polarizing microscope to determine rock composition and texture. Three hundred points per thin section of rock were counted as quartz, feldspar, rock fragments, mica, opaque, matrix, and cement. The dominant size, largest size, sorting, and roundness were measured and estimated to characterize rocks under the microscope.

3.3 Testing for AIV following IS: 2386 part IV: 1993 standard

3.3.1 Testing for strength parameters

Two tests involved point load strength index (PLSI) and aggregate crushing value (ACV), respectively, following ASTM D5731–02 (2003) and IS 2386 part IV (1993). For the former test, a rock block with lumps measuring 30 to 85 mm in size and form was used. Lumps were measured for their dimensions and were loaded under compressive force until the sample failed. The PLSI was obtained as:

$$I_s = P/De^2 \text{ .... } (1)$$

Where,

$$De^2 = \frac{4A}{\pi} \text{ .... } (2)$$

Where A is the minimum cross-sectional area (mm^2) of the plane via the platen contacts point for expressing equivalent diameter De, and P= load in KN. Once I_s was obtained, the corrected point load strength index ($I_{s\,(50)}$) was obtained as:

$$I_{s\,(50)} = F \times Is \text{ .... (3)}$$

Where F is the size correction factor obtained using the following relation:

$$F = (De/\ 50)^{\,0.45} \text{ .... (4)}$$

To classify rocks, uniaxial compressive strength (UCS) was computed by multiplying the corrected PLSI by some factor, as suggested by Bieniawski (1975).

$$UCS = 23.9 * I_{s\,(50)} \text{ .... (5)}$$

The aggregate impact value (AIV) test measured the resistance of an aggregate passing from 12.5 mm and retained on a 9.5 mm sieve to sudden impact. The test sample mass was around 500 grams. Firstly, a sample was filled into the cylindrical cup with a taping rod on the base of the machine. A hammer attached of about 14 kg was raised to an optimum height of about 380 mm above the cup containing aggregates and then released making it fall on the surface up to 15 blows. After that, crushed aggregates were removed and sieved with a 2.36 mm IS sieve. The AIV was calculated according to equation 2.1, which is given below.

$$AIV = W_2/W_1 * 100\% \text{ .... (6)}$$

Where W_1= total weight of the sample and W_2 = total weight passing from 2.36 mm sieve.

3.4 Testing for Slake Durability Index (SDI)

The ASTM procedure 4644-19 87 standard test procedure was used to conduct the test. The test procedure uses 10 pieces of equal-sized rock samples, each weighing between 40 and 60 gm. The corners of the particles were worn out by rubbing and removing dust from the surface of the particles. The test sample was initially oven-dried for the first 15 to 20 minutes at 110°, cooled at room temperature for the same amount of time, and weighed to determine its natural moisture content. Then, the test sample was placed in the wired drum and was revolved for ten minutes, taken out and oven-dried at 110°C for 16 hours, cooled for 15 minutes, and weighed. Such a cycle was repeated one time to finally obtain the slake durability of samples from the first to the second cycle. The SDI was calculated as:

$$I_{d\,(2)} = (W_{final}/\ W_{initial}) \times 100 \text{ .... (7)}$$

Where $I_{d\,(2)}$ = second-cycle slake durability index (%), W_{final} is oven-dried mass of the test sample before the first cycle (g), and $W_{initial}$ = mass of oven-dried test sample after the second cycle (g).

3.5 Linear Regression Analysis

Statistical analysis often employs linear regression to examine the relationships between continuous variables. This technique involves fitting a straight-line equation to a set of observed data points, enabling researchers to make predictions and gain insights into the nature of these relationships. In our research, we apply linear regression methodology to investigate the potential correlation between two specific variables: strength and durability. By using this approach, we aim to uncover any significant linear associations between these factors and quantify their relationship.

4. Results

4.1 Petrography of sandstones

The exposure consists of thin to medium-bedded, fine- to medium-grained, slightly to moderately weathered greenish-grey sandstones interbedded with thin to medium-bedded red and purple shales.

The composition and texture of each sample were determined through meticulous petrographic examination (Table 1). The sandstone model composition is $Q_{29\text{-}48\%}$ $F_{6\text{-}13\%}$ $RF_{3\text{-}21\%}$. The matrix varies from 13% to 20%, whereas cement ranges between 5% and 21%. Cementing materials are dominated by ferruginous material, followed by carbonate and siliceous minerals.

Table 1 Result of petrographic analysis of sandstone from the Dumri Formation

S.N.	Composition											Texture			Recalculated			Rock name
	Quartz (%)	Feldspar (%)		Mica (%)		RF (%)	Matrix (%)	Cementing material (%)			Others (%)	Grain size (µm)	Shape	Sorting	Q%	F%	RF%	
		K	P	Mu	Bi			Cf	Cs	Cc								
DF1	45	8	1	1	1	10	20	8	1	3	2	180	Sub Angular	Moderate Sorted	70	14	16	Lithic Wacke
DF2	43	6	2	1	2	16	13	11	3	2	1	185	Sub Angular	Poorly Sorted	64	12	24	Lithic Wacke
DF3	39	9	3	3	2	19	16	5	1	1	2	180	Sub Angular	Moderate Sorted	56	17	27	Lithic Wacke
DF4	43	5	2	2	2	12	18	11	1	2	2	195	Sub Angular	Moderate Sorted	70	11	19	Lithic Wacke
DF5	38	8	2	3	1	17	19	10	1	-	1	200	Sub Rounded	Poorly Sorted	59	15	26	Lithic Wacke
DF6	41	6	2	2	1	16	18	11	1	1	1	205	Sub Angular	Moderate Sorted	63	12	25	Lithic Wacke
DF7	42	7	5	2	2	10	20	8	2	-	2	190	Sub Rounded	Moderate Sorted	66	19	15	Feldspathic wacke
DF8	44	8	5	2	4	6	20	5		5	1	70	Sub Rounded	Moderate Sorted	70	21	9	Feldspathic wacke
DF9	38	10	2	3	4	16	18	3	2	-	4	210	Sub Rounded	Poorly Sorted	58	18	24	Lithic Wacke
DF10	33	8	3	1	3	16	15	13	5	-	3	205	Angular	Well Sorted	55	18	27	Lithic Wacke
DF11	29	7	6	1	5	21	16	8	3	4	1	200	Sub Rounded	Moderate Sorted	46	21	33	Lithic Wacke
DF12	43	2	4	1	2	17	20	4	6	-	1	190	Sub Rounded	Poorly Sorted	65	9	26	Lithic Wacke
DF13	44	2	5	1	2	20	20	2	3	-	1	185	Sub Rounded	Poorly Sorted	62	10	28	Lithic Wacke
DF14	39	3	8	1	2	9	15	5	4	12	2	105	Sub Angular	Well Sorted	66	19	15	Feldspathic wacke
DF15	48	5	5	-	2	3	16	7	2	10	1	110	Sub Rounded	Moderate Sorted	79	16	5	Feldspathic wacke
DF16	47	8	4	1	1	10	20	5	2	1	1	195	Sub Angular	Poorly Sorted	68	17	15	Feldspathic wacke
DF17	39	9	3	1	1	18	16	2	10	-	1	180	Sub Angular	Poorly Sorted	57	17	26	Lithic Wacke

Where, Q = Quartz, F = Feldspar, K= Alkali feldspar, P = plagioclase feldspar, Mu= muscovite, Bi = Biotite, RF= Rock Fragments, Cf= Ferruginous, Cs= Silicious, Cc= Calcareous

Based on recalculated quartz, feldspar and rock fragments, and matrix percent, the sandstones are classified as feldspathic wacke (Fig. 3) and lithic wacke (modified Dott's classification (Pettijohn et al. 1973). Matrix are proto to pseudo-matrix. The latter was generated by the compaction and squeezing of politic rock fragments. Regarding texture, all the sandstones are fine-grained with subrounded angular particles, which are well interlocked. Sandstones also exhibit poorly sorting of constituent mineral grains (Table 1). Major constituent minerals and texture do not vary much among the sandstones. Lithic wacke exceeds over feldspathic wacke.

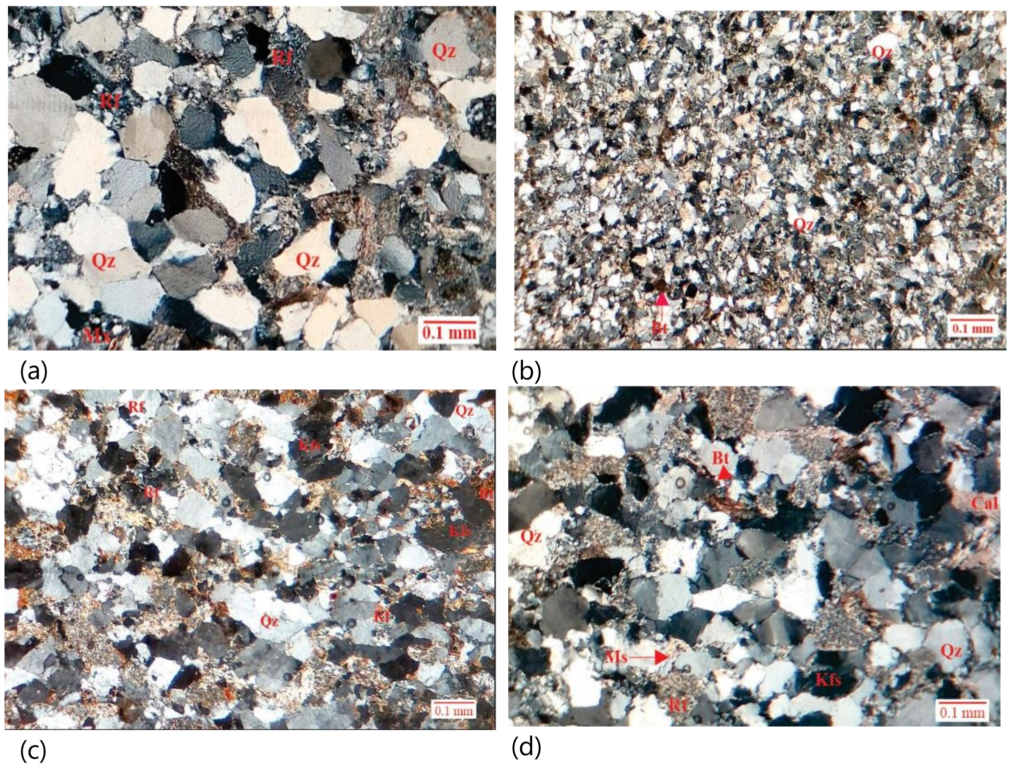


Fig. 3 Photomicrograph of sandstones from the Dumri Formation (a) DF1 exhibits a moderately sorted lithic wacke with the (45% quartz, 9% feldspar, 10% rock fragments, 20% matrix); (b) DF8 a moderately sorted feldspathic wacke with (44% quartz, 13% feldspar, 6% rock fragments, 20% matrix); (c) DF12 poorly sorted lithic wacke with (43% quartz, 6% feldspar, 17% rock fragments, 20% matrix); and (d) DF17, a poorly sorted lithic wacke (39% quartz, 12% feldspar, 18% rock fragments, 16% matrix).

4.2 Point Load Strength Index

The PLSI values of the sandstone, which range from 5.28 MPa to 8.92 MPa, indicate a continuum of strength characteristics throughout the sandstone samples. A comprehensive assessment of the various strength variations within the test samples under study is made possible by this extensive data. From the center of the block, the majority of the test samples split into two pieces. According to the calculated value of UCS (Bieniawski, 1975), the test samples are classified as very strong rock (Table 2).

Table 2 Result of point load index of sandstone from the Dumri Formation

S.N.	Thickness avg(mm)	Width avg (mm)	Load (KN)	De (mm)	De^2 (mm^2)	I_S (MPa)	F (mm)	$I_{s (50)}$ (MPa)	UCS (MPa)	Class
DF1	28.5	53.5	18.33	44.06	1941.37	9.44	0.94	8.92	213.18	Very strong
DF2	27.4	51.6	10.23	42.43	1800.16	5.68	0.93	5.28	126.15	Very strong
DF3	28.2	51.4	10.88	42.96	1845.54	5.90	0.93	5.51	131.60	Very strong
DF4	29.6	52.8	13.38	44.61	1989.92	6.72	0.95	6.39	152.66	Very strong
DF5	28.8	49.4	13.47	42.56	1811.46	7.44	0.93	6.92	165.29	Very strong
DF6	30.4	54.8	14.94	46.06	2121.12	7.04	0.96	6.79	162.23	Very strong
DF7	29.2	51.6	17.33	43.80	1918.42	9.03	0.94	8.51	203.41	Very strong
DF8	29.6	53.2	18.16	44.78	2005.00	9.06	0.95	8.62	205.99	Very strong
DL9	28.8	52.8	15.31	44.00	1936.14	7.91	0.94	7.47	178.43	Very strong
DF10	26.4	48.6	12.81	40.42	1633.62	7.84	0.91	7.13	170.30	Very strong
DF11	29.7	47.4	15.13	42.34	1792.44	8.44	0.93	7.83	187.19	Very strong
DF12	26.8	47.2	14.71	40.13	1610.60	9.13	0.91	8.27	197.72	Very strong
DF13	27.6	47.6	11.14	40.90	1672.73	6.66	0.91	6.08	145.41	Very strong
DF14	26.8	48.4	10.13	40.64	1651.54	6.13	0.91	5.59	133.54	Very strong
DF15	28.4	48.2	15.46	41.75	1742.91	8.87	0.92	8.18	195.47	Very strong
DF16	27.6	48.6	10.68	41.33	1707.87	6.25	0.92	5.74	137.18	Very strong
DF17	26.4	46.8	12.51	39.66	1573.11	7.95	0.90	7.17	171.25	Very strong

UCS=23.9* PLSI (Bieniawski, 1975)

Extremely Strong= >250 MPa; Very Strong= 100-250 MPa; Strong= 50-100 MPa; Medium Strong= 25-50 MPa; Weak= 5-25 MPa; Very Weak= 1-5 MPa; Extremely Weak= 0.25-1 MPa

4.3 Aggregate Impact Value

The aggregate impact value in the Dumri Formation ranges from 6% to 9% (Table 3). The highest AIV is in sample DF2, DF3, DF4, DF5 and DF16 and lower value in sample DF1, DF8, DF12 and DF15. The AIVs of the sandstones reflect that these sandstones are quite resistant to impact force. The lower AIVs of the studied sandstones reflect their superior quality due to greater interlocking and cementing than common sandstones.

Table 3 Result of aggregate impact value of sandstone from the Dumri Formation

Sample number	Wt. of oven dry passing 12 mm and retained at 10 mm (w_1), g	Wt. retained on 2.36 mm after the test (w_2), g	Wt. fraction passing 2.36 mm sieve (w_3)	AIV, %
DF1	512.89	481.28	30.77	6
DF2	486.38	442.10	43.77	9
DF3	508.75	462.44	45.79	9
DF4	506.46	460.62	45.58	9
DF5	506.29	459.97	45.57	9
DF6	507.47	471.23	35.52	7
DF7	494.94	459.62	34.65	7
DF8	492.49	462.77	29.55	6
DL9	499.2	463.81	34.94	7
DF10	508.82	472.40	35.62	7
DF11	504.23	468.70	35.30	7
DF12	500.05	469.62	30.00	6
DF13	506.73	465.43	40.54	8
DF14	500.03	459.30	40.00	8
DF15	505.12	474.28	30.31	6
DF16	492.84	447.92	44.36	9
DF17	502.63	467.18	35.18	7

4.4 Slake Durability Index

The two-cycle slake durability index was used to determine the SDI (I_{d2}) and visualize the kind of disintegration. SDI values range from 99.53% to 99.86%. All the test samples lie on the type I disintegration pattern (ASTM D 464487, 1992). According to the classification proposed by Franklin and Chandra (1972), these values correspond to an extremely high durability rating (Table 4).

Table 4 Result of slake durability index of sandstone from the Dumri Formation

Sample No.	Initial weight (gm.)	IODW before 1st cycle (gm)	Moisture Content (%)	ODW after 1st cycle (gm)	ODW after 2nd cycle (gm)	I_{d1}%	I_{d2}%	Durability Classification	Disintegration Type
DF1	523.81	523.43	0.07	522.96	522.70	99.91	99.86	EH	I
DF2	524.28	523.84	0.08	523.00	521.38	99.84	99.53	EH	I
DF3	488.62	488.5	0.02	487.67	486.35	99.83	99.56	EH	I
DF4	496.35	495.62	0.15	494.13	493.54	99.7	99.58	EH	I
DF5	475.35	474.36	0.21	473.17	472.42	99.75	99.59	EH	I
DF6	514.35	513.21	0.22	512.85	512.03	99.93	99.77	EH	I
DF7	520.72	519.74	0.19	519.17	518.65	99.89	99.79	EH	I
DF8	547.59	546.93	0.12	546.44	545.89	99.91	99.81	EH	I
DL9	509.35	508.32	0.20	507.91	507.25	99.92	99.79	EH	I
DF10	502.96	501.8	0.23	500.95	500.65	99.83	99.77	EH	I
DF11	519.57	518.94	0.12	518.16	517.69	99.85	99.76	EH	I
DF12	549.29	548.67	0.11	548.18	547.85	99.91	99.85	EH	I
DF13	532.04	531.42	0.12	530.30	529.72	99.79	99.68	EH	I
DF14	536.35	535.35	0.19	534.71	533.69	99.88	99.69	EH	I
DF15	531.89	530.76	0.21	530.23	529.91	99.9	99.84	EH	I
DF16	547.89	546.76	0.21	545.72	544.41	99.81	99.57	EH	I
DF17	520.22	519.59	0.12	518.76	518.29	99.84	99.75	EH	I

IODW=Initial oven-dried weight, ODW=Oven dried weight; I_{d1}=First cycle SDI, I_{d2}=Second cycle SDI.

4.5 Linear Regression

Regression analysis was employed to investigate the connections between various mechanical properties and the durability of sandstones. The equation for the line of best fit was found, along with its associated 95% confidence interval and coefficient of determination (R^2), to interpret the experimental results. These findings are visually represented in Fig. 3. The analysis revealed that linear models provided the best fit for the data in all cases. Three distinct correlations were examined among the SDI, PLSI, and AIV tests (Fig. 3). Table 5 presents a comprehensive summary of these correlational findings. This approach allowed us to quantify and characterize the relationships between the strength and durability properties.

Good correlations are found between SDI vs. AIV (R^2 = 0.96), PLSI vs AIV (R^2 = 0.74), and SDI vs PLSI (R^2 = 0.74). The correlations between SDI and AIV and AIV and PLSI are inverse. It means that the slake durability index tends to diminish with increased aggregate impact value. Similarly, aggregate impact value tends to diminish when the point load strength index increases. The relationship between the point load strength index and the slake durability index is positive, indicating that when the PLSI of sandstones increases, SDI also tends to increase. All these correlations are statistically significant, reinforcing the connection between these indices and the measured properties (Table 5).

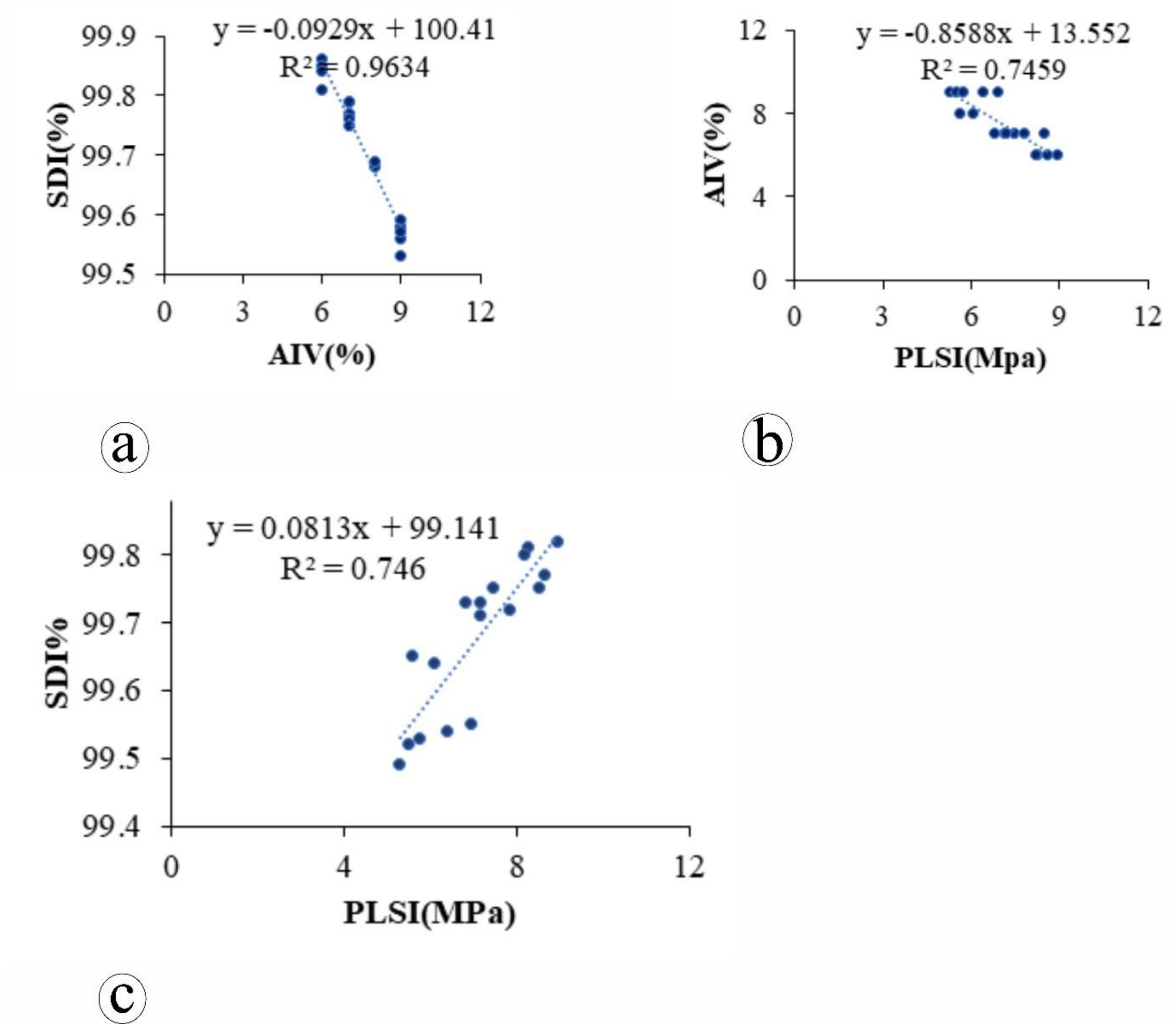


Fig. 3 Correlation of best-fitted curve under linear regression (a) SDI vs. AIV, (b) AIV vs PLSI, and (c) SDI vs AIV.

Table 3 Correlation between distinct tests under single linear regression

Correlation	Equation	R^2	r	*Critical r
SDI vs AIV	SDI = -0.0929AIV + 100.41	0.9634	0.98	0.482
AIV vs PLSI	AIV = -0.8588PLSI + 13.552	0.7459	0.86	0.482
SDI vs PLSI	SDI = 0.0813PLSI + 99.141	0.746	0.86	0.482

*Critical r at 95% confidence level and degree of freedom df=n-2=17-2=15, where n is number of samples.

5. Discussion

Sandstone samples from the Dumri Formation revealed a narrow range of PLSI (5.28-8.92 MPa) (Table 2). This is higher than reported for the Sudanese Nubian sandstone formation (0.025-1.5Mpa) by (Zein and Sandal 2018), sandstone from the Siwalik Sub-group (0.024-2.16 MPa) by (Budhathoki and Tamrakar 2022), Sandstone from the Siwalik Group (0.05-4.53 Mpa) by Tamrakar et al. (2002) and sandstone from the QwaQwa sandstone deposit of south Africa (1.30-1.92Mpa) by (Kolapo and Munemo 2021). The corresponding UCS values, ranging from 126.15 MPa to 213.18 MPa, indicate that the sandstones are "very strong" according to the International Society for Rock Mechanics (ISRM) standards (ISRM, 1979, 1981). Strong grain interlocking with good cementing perhaps increased the strength of sandstones (Gökceoğlu et al., 2000; Tamrakar et al., 2007). Aligholi et al. (2017) found that the rock containing lower moisture content exhibits the highest strength. This relation can also be seen in the sandstone of the Dumri Formation. The sample DF1 with maximum strength is found to have the lowest moisture content among other samples. Whereas the sample DF14 and DF16 having the highest moisture content, lags with the low PLSI value. Furthermore, the sandstone's significant quartz content may enhance its entire hardness. The higher the quartz content, the higher will be the mechanical strength (Yusof and Zabidi, 2016). It is possible that the samples' grain size facilitated varying strength (Yusof and Zabidi, 2016).

The aggregate impact value (AIV) quantifies a material's resistance to abrupt forces, which may differ from its response to gradually applied compressive loads. Essentially, AIV serves as an indicator of aggregate toughness. Samples DF1, DF8, DF12, and DF15 demonstrated the highest toughness with an AIV of 6%, while samples DF2, DF3, DF4, DF5, and DF16 exhibited slightly lower toughness with an AIV of 9% (Table 4). According to the British Standard (BS 812-112, 1990), all samples fall within the exceptionally high resistance category. The range of AIV obtained indicates a lower range than most of the other sandstones. For instance, the AIV value of metamorphic and sedimentary rocks from the Lesser Himalaya of the Malekhu-Thopal Khola area is 8.54 – 34.28% (Bista and Tamrakar, 2015), and of 11.02-23.84% from the Lesser Himalayan rocks in the Kavre area. (Paudel and Tamrakar, 2013).

The sandstones from the Dumri Formation are classified as extremely highly durable, indicating higher resistance to wetting and drying cycles. The two-cycle slake durability index (I_{d2}) varies between 99.53% and 99.86% (Table 3). This range is comparable to higher than Siwalik Group sandstones (30.37-93.23%) from Hetauda (Budhathoki and Tamrakar, 2022). Sample DF2, DF3, DF4, DF5, and DF16 are of high durability and the rest are of very high durability against slaking. The higher durability of the rocks can be attributed to the mineralogical composition. Sample DF1, DF8, and DF15 with high quartz content have very high durability. Other factors contributing to the durability of the sandstone can be the fine-grain size and well-cementation of the grains. The higher SDI of the overall samples can be linked to their lower moisture content (Franklin and Chandra, 1972). Type I disintegration pattern is shown by all samples after the second cycle, indicating that the samples did not fragment into pieces.

Sandstone from the Dumri Formation revealed significant correlations among mechanical and durability properties. The slake durability index (SDI) and point load strength index (PLSI) showed a strong relationship (R^2 = 0.746), surpassing the critical r-value of 0.482. This aligns with findings by Khajevand and Fereidooni (2018) for travertine samples and Ahmad et al. (2017) for sedimentary, metamorphic, and igneous rocks of altogether 45 samples (R^2 = 0.812), though it contrasts with Liang et al. (2015) who noted a weaker correlation between SDI and uniaxial compressive strength (UCS) in stronger rocks. Sharma and Tamrakar (2023) found a weak correlation between SDI and PLSI (R^2 = 0.039) and SDI vs AIV (R^2 = 0.166). Also, there is found robust correlations between SDI and AIV (R^2 = 0.96) and between AIV and PLSI (R^2 = 0.74) (Table 5). The strong interconnections among strength, durability, and impact resistance in sandstone from the Dumri Formation suggest a potential for developing accurate predictive models for geotechnical applications, enabling efficient estimation of one property based on another.

6. Conclusions

Petrographic analysis classified the sandstone from the Dumri Formation as lithic wacke and feldspathic wacke. Sandstone from the Dumri Formation exhibited very strong to extremely strong compressive strength (PLSI: 5.28–8.92 MPa) and high resistance to impact (AIV: 6–9%). The slake durability indices of sandstones are of extremely high durability (SDI 99.53–99.86%). The strength and durability indices of sandstones suggest that the sandstones are of good quality and can withstand load and weathering. The relationship between SDI and AIV is negative; SDI = -0.0929AIV + 100.41 (r=0.98), between AIV and PLSI is negative: (0.86), and between SDI and PLSI is SDI = 0.0813PLSI + 99.141 (r=0.86).

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