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Some mechanical properties of the Siwalik sandstones and their relation to petrographic properties

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Abstract

Some physical and mechanical indices of sandstone samples which were systematically collected from the Siwalik Group, in Mid Western Nepal, have been measured in a laboratory. The measurements show that the dry density of the Siwalik sandstones ranges 2.35 to 2.59 gr/cm^3, and porosity is between 2.88 and 7.68%. The former is higher and the latter is lower in calcareous sandstone. Elastic wave velocity ranges from 1.59 to 4.36 $\times 10^3$m/sec, and the uniaxial compressive strength is of the order of 0.5 to 1.0 $\times$ 10^{2}MPa. Both indices are higher in calcareous sandstone. These indicates that cement materials such as calcium carbonate fill voids among grains in calcareous sandstone.

Uniaxial compressive strength, elastic wave velocity and elastic modulus are closely correlated to each other, and they have negative curvilinear correlation with porosity. These physical and mechanical properties of sandstones closely depend on lithofacies and the contents of calcium carbonate, and are rather independent of stratigraphical horizon or deposition age. These results indicate that such properties reflect the sedimentary environments that were prevelant during the formation of the sandstones.

Introduction

The Siwaliks, the foothills of the Himalayas, have low elevation and low topographic relief compared to the Lesser Himalayas. They are mainly composed of sandstone and mudstone of the Siwalik Group, which are fluvial deposits of the Middle Miocene to the Pleistocene in age. The hills extend more than 1,000 km from Nepal to Pakistan as a wide zone. The East-West Highway connecting the Eastern and far Western Nepal, passes through the Siwaliks, and many people live nearby the highway and transport facilities. Therefore, natural slopes along the highway and such other infrastructure development in the hills have been one of the targets of construction works and will be so in near future also.

Understanding physical and mechanical properties of rocks composing the slopes is therefore important for future construction works. However, there has been no systematic data on the geotechnical properties. The authors have attempted to obtain fundamental data, as index properties (Goodman, 1989), expressing physical and mechanical properties of rocks distributed there.

The sampling locations of sandstones are along the Surai Khola River between Surai Naka and the Rangsing Khola in the Siwalik Hills, Mid Western Nepal (Fig.1). Rock samples were collected from exposures facing the East-West Highway along the

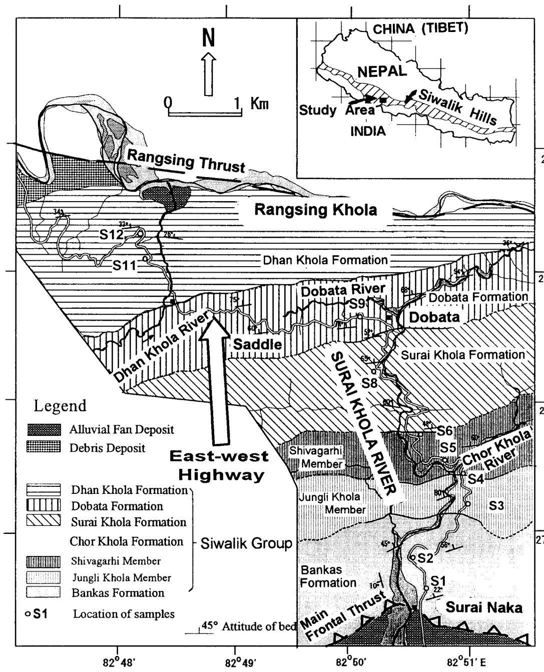

Fig.1 Index map of the Surai Khola area and geological map showing distribution of the Siwalik Group and sampling locations of sandstone (S1 to S12 without S7 and S10) along the East-West Highway. The geological map is based on Dhital *et al.* (1995).

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Surai Khola River. To understand the differences in physical and mechanical properties, petrographic characteristics such as texture and composition of sandstone have also been analyzed in addition to such measurements at certain locations.

Siwalik Group and lithofacies of sandstones

The Siwalik Group along the Surai Khola River outcrops as northward monoclinal sequence more than 5 km thick in east-west trending zone. It ranges between 15 and 2.3 Ma in age (Appel *et al.*, 1991), and constitutes an imbricate thrust sheet (Dhital *et al.*, 1995) between the Main Frontal Thrust and the Rangsing Thrust (Fig.1).

Generally, sandstone is dominant in the Siwalik Group. However, the lithofacies changes with a continuous upward coarsening sequence. Interbedded strata of mudstone and sandstone are dominant in the lower horizon, whereas conglomerate in the upper horizon. The strata have tilted and uplifted after deposition. However, the dip angle is not constant, and the steepest zone is in the middle part of the area. These give hogback topography due to differential weathering and erosion of strata (Tamrakar, 1999).

Five major units of Bankas, Chor Khola, Surai Khola, Dobata and Dhan Khola Formations have been distinguished (Dhital *et al.,* 1995), and they outcrop continuously from the Surai Naka to the Rangsing Khola (Fig.1).

The Bankas, Chor Khola and Surai Khola Formations consist mainly of sandstone and mudstone, whereas Dobata and Dhan Khola Formations comprise sandstone, mudstone and conglomerate. These Formations have been divided into descriptive lithofacies units (Fig.2) based on proportion of sandstone and mudstone, and textural and compositional variation of rocks (Tamrakar, 1999).

Sandstones from the Bankas Formation are thin to thick bedded, very fine- to fine-grained green gray bioturbated, and sometimes they are calcareous. Grain size increases in the upper part of the Formation (B6) (Fig.2).

The Chor Khola Formation comprises two members, Jungli Khola and Shivagarhi Members, respectively. Generally, medium- to thick-bedded, fine- to medium-grained, light green-gray and brownish calcareous sandstones occur in the Jungli Khola Member, whereas medium- to coarse-grained salt-and-pepper sandstones occur in the Shivagarhi Member. In the upper part of the Member (Sh5), sandstones become thicker bedded and coarser grained.

Sandstone in the Surai Khola Formation usually bear pebbly lenses at the base and grain size decreases upwards. Sand ball concretions are contained in the coarse-grained salt-and-pepper sandstones in the upper part of the Formation (Su5).

Sandstones of the Dobata Formation are medium- to coarse-grained, light gray, and salt-and-pepper type with abundant sand ball concretions. In the Dhan Khola Formation, medium- to coarse-grained pebbly sandstones occur. Often, sandstones are localized as lenses in conglomerates although some distinct strata exist with gradational relationship with conglomerates.

Sandstone samples for measuring

Many block samples of sandstones were collected from locations of different stratigraphic horizons of the Siwalik Group, outcropping along the East-West Highway (Fig.1). Samples were numbered from S1 to S12 without S7 and S10. As S7 and S10 were too small to measure, finally, 10 block samples were prepared for measuring. Stratigraphical horizons of individual samples are shown in Fig.2.

Initially, sample size was more than 10cm thickness perpendicular to the bedding plane. Each sample was smoothened at both surfaces parallel to the bedding planes by cutting. The blocks with smoothened surfaces were cored in 20 mm diameter using a diamond drill (core picker), and two cylindrical specimens of approximate length 40 mm were obtained from each block. Consequently, 20 cylindrical specimens were prepared for various measurements.

For measurement of the uniaxial compressive strength, the core surfaces were polished in 1 to 2 mm thick by a diamond polisher. Although 20 specimens were used for measurement of density and elastic wave velocity, only 10 samples were used for measuring of uniaxial compressive strength. Fig.3 shows these specimens before measurement.

Petrographic characteristics of sandstone samples

To analyze petrographical characteristics of samples, 10 thin sections of sandstone were made from 10 block samples. Fig.4 shows textures in photomicrographs of thin sections. Petrographic characteristics are

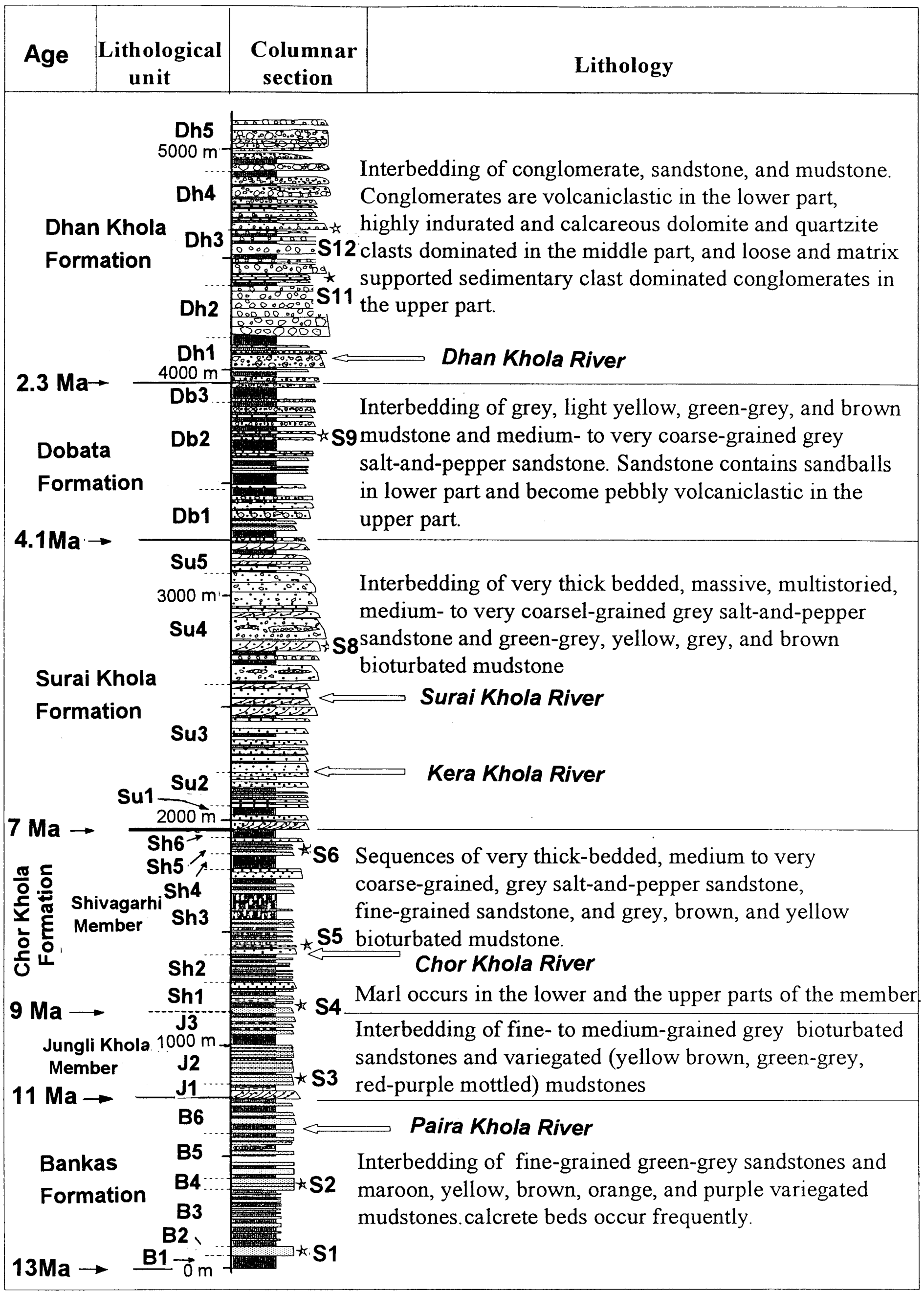


Fig.2 Lithological column of the Siwalik Group along the East-West Highway in the Surai Khola area (after Tamrakar, 1999). Age of the units is based on Appel *et al.,* (1991). S1 to S12 without S7 and S10 in the column are sample numbers.

generally expressed by some indices such as color, rock type, contents, and texture. Contents are expressed by ratio of clast, matrix and cements. Texture includes grain size, roundness, sphericity and packing density.

Percent of clast, cement and matrix was determined in thin sections using a modified comparison chart of Terry and Chilingar (1955). About 200 grains were measured to obtain mean grain size of sandstone. Grain morphologies as roundness and maximum projection sphericity were measured for 100 quartz grains. Roundness was measured using modified Krumbein's chart of two dimensional grain outlines (Lindholm, 1987). Folk's roundness values (Pettijohn *et al.,* 1987 ; Lindholm, 1987) were estimated after measurement. The maximum projection sphericity Ψ_p was measured, using silhouette chart (Lindholm,

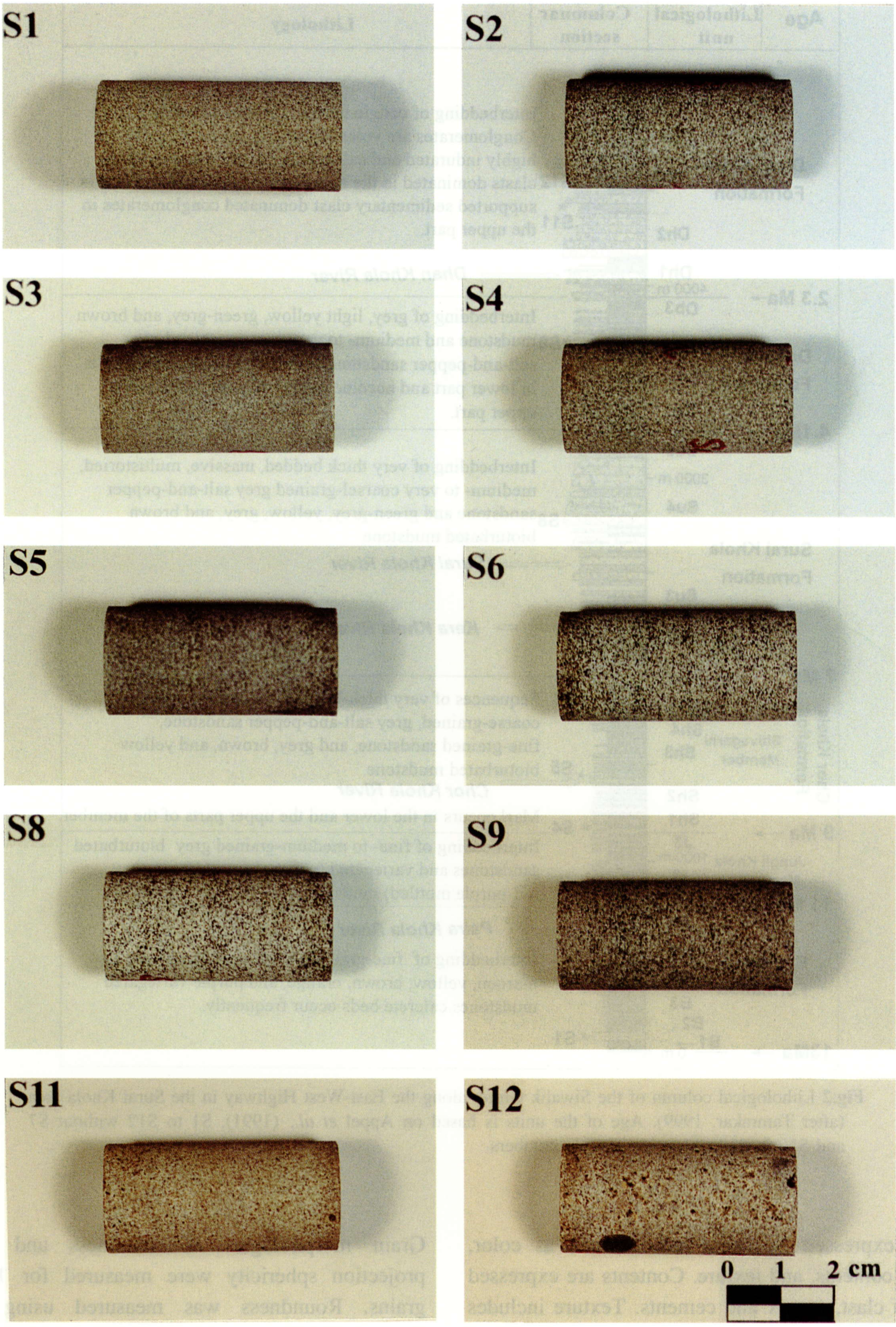


Fig.3 Cylindrical specimens before measurement. S1 to S12 without S7 and S10 are sample numbers. Diameter and length are 2.0cm and 4.0cm respectively.

1987). Packing density (Kahn, 1956), defined as the ratio of length of grain intercept to traverse length, was estimated measuring 200 traverses in each thin section. Results of these petrographic characteristics including color, rock type, contents and textures are listed in Table 1. Those on each sample are described briefly as follows :

Sample S1 (Unit B2 of Bankas Formation) is massive, highly fractured, and slightly weathered fine-grained, light yellow-gray sandstone with considerable matrix (15%) produced due to alteration. Contents of cement and matrix are almost same. Packing density is 96% with grains having tangential to concave-convex contacts.

Sample S2 (Unit B4 of Bankas Formation) is medium-grained yellow-gray sublithic sandstone, in which cement to matrix ratio is 7, and packing density is 66% with grains having tangential to concavo-convex contacts.

Sample S3 (Unit J2 of Jungli Khola Member, Chor Khola Formation) is fine-grained yellow-gray sandstone with calcareous cement to matrix ratio 8, and comparatively lower packing density (50%) than in other samples. Grains usually show tangential to float contacts.

Sample S4 (Unit Sh1 of Shivagarhi Member, Chor Khola Formation) is fine-grained yellow-gray sublithic sandstone, that has lower cement to matrix ratio 3 and lower order of packing density (53%) where grains have mostly tangential to float contacts.

Sample S5 (Unit Sh3 of Shivagarhi Member, Chor Khola Formation) is medium-grained gray calcareous sandstone in which cement to matrix ratio is 3.5, and packing density is 52% with grains having tangential to float contacts.

Sample S6 (Unit Sh5 of Shivagarhi Member, Chor Khola Formation) is laminated coarse-grained, light gray, micaceous salt-and-pepper sandstone. Laminae are distinct in the specimen (Fig.4 (f)) due to high mica- and lithic-contents. It is also highly calcareous with higher cement to matrix ratio 8 and lower packing density (59%) due to high cement-content and due to float texture of grains.

Sample S8 (Unit Su4 of Surai Khola Formation) is salt-and-pepper type of laminated, coarse-grained, light gray, highly micaceous, and lithic sandstone (Fig.4(g)). The strata in this formation are multistoried (Corvinus, 1992) with sandstone having higher lithic- and mica-contents. Cement to matrix ratio 7 is relatively higher . The sample has lower packing density (52%) with grains commonly exhibiting float to tangential contacts forming distinct lamina of lithic grains and micas.

Sample S9 (Unit Db2 of Dobata Formation) appears coarse-grained, light gray micaceous and lithic, and has lower cement to matrix ratio 3 and moderate packing density (59%). Grains show tangential to float contacts, however, mica and lithic grains form distinct laminae.

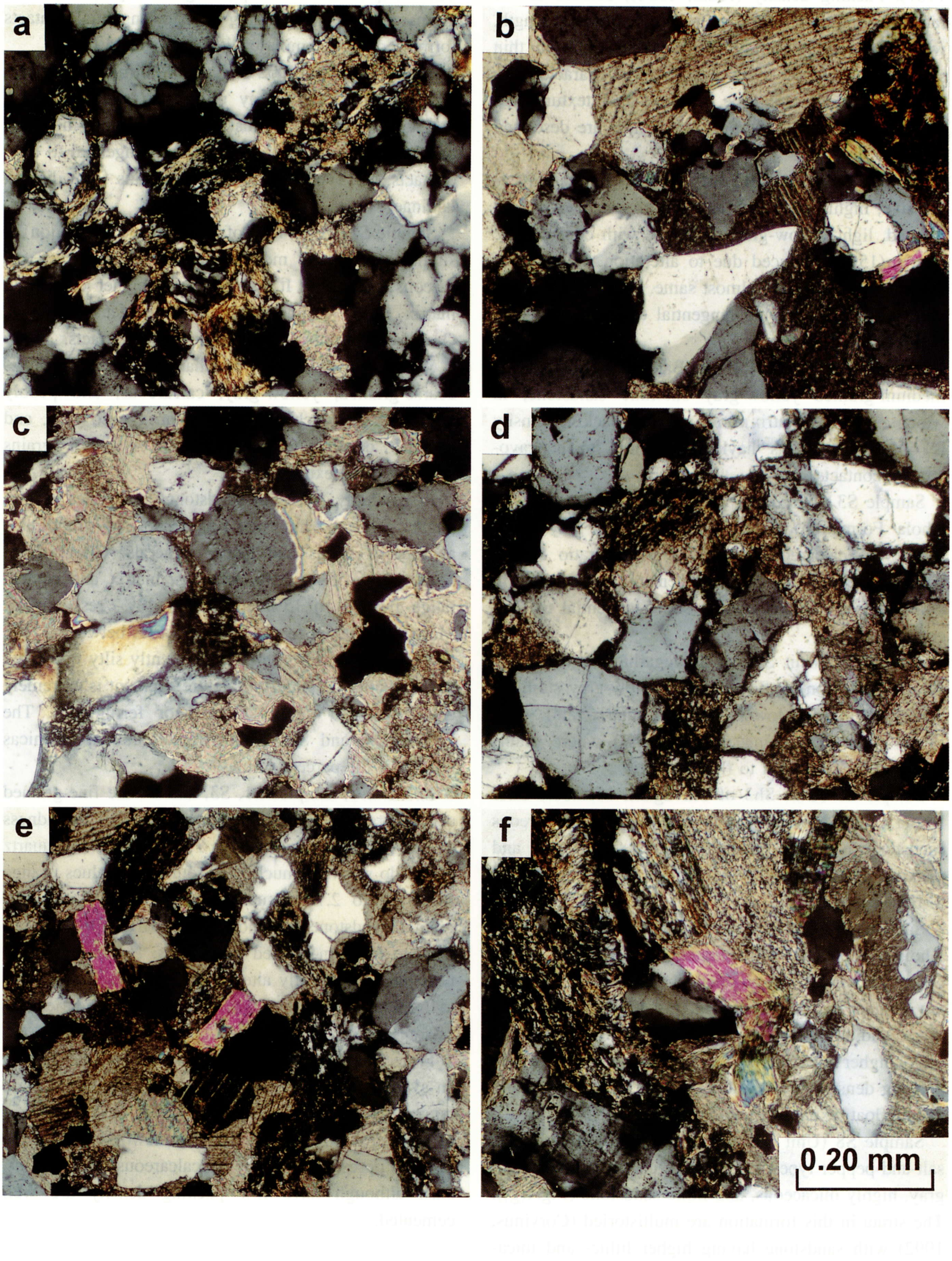
Sample S11 (Unit Dh3 of Dhan Khola Formation) is slightly weathered medium-grained yellow-gray calcareous sandstone. It has relatively higher cement to matrix ratio 7 and higher packing density (73%). Grains exhibit mostly flat to tangential contacts.

Sample S12 (Unit Dh4 of Dhan Khola Formation) is coarse-grained, yellow-gray, calcareous, and pebbly sandstone in which cement to matrix ratio is 6, and packing density is moderate (61%) with grains showing float texture.

In generally, clasts in sandstones comprises mainly quartz, feldspar, and rock fragments, and subordinate amount of micas and heavy minerals. Clast-content ranges from 55 to 65%, whereas, matrix and cement range from 5 to 15% and 15 to 40%, respectively. Moreover, cement to matrix ratio varies between 1 (S1) and 8 (S3 and S6). Matrix is frequently silty to clayey, but is mainly secondary in nature. Cement is extremely calcareous and rarely siliceous or ferruginous. The samples S6 and S8 contain higher amount of micas (<15% of the percent of clast).

In Table 1, samples S1, S3, and S4 are fine-grained and others are medium- to coarse-grained. Roundness ρ and projection sphericity Ψ_p measured for quartz grains do not vary much. The roundness values ρrange from 1.4 to 2.77. Usually, quartz grains of coarse-grained sandstones are more angular than the grains of fine- to medium-grained sandstones. However, roundness has been greatly altered in all of the samples due to replacement of grains or grain boundaries by calcareous cement.

Projection sphericity Ψ_p varies from 0.77 to 0.85. In an average, quartz grains are compact. Packing density ranges between 50 and 73% (Table 1). It is a measure of closeness of clasts in the framework. In all the samples pores are filled up by calcareous cement, thus, clast although have low packing density are well cemented.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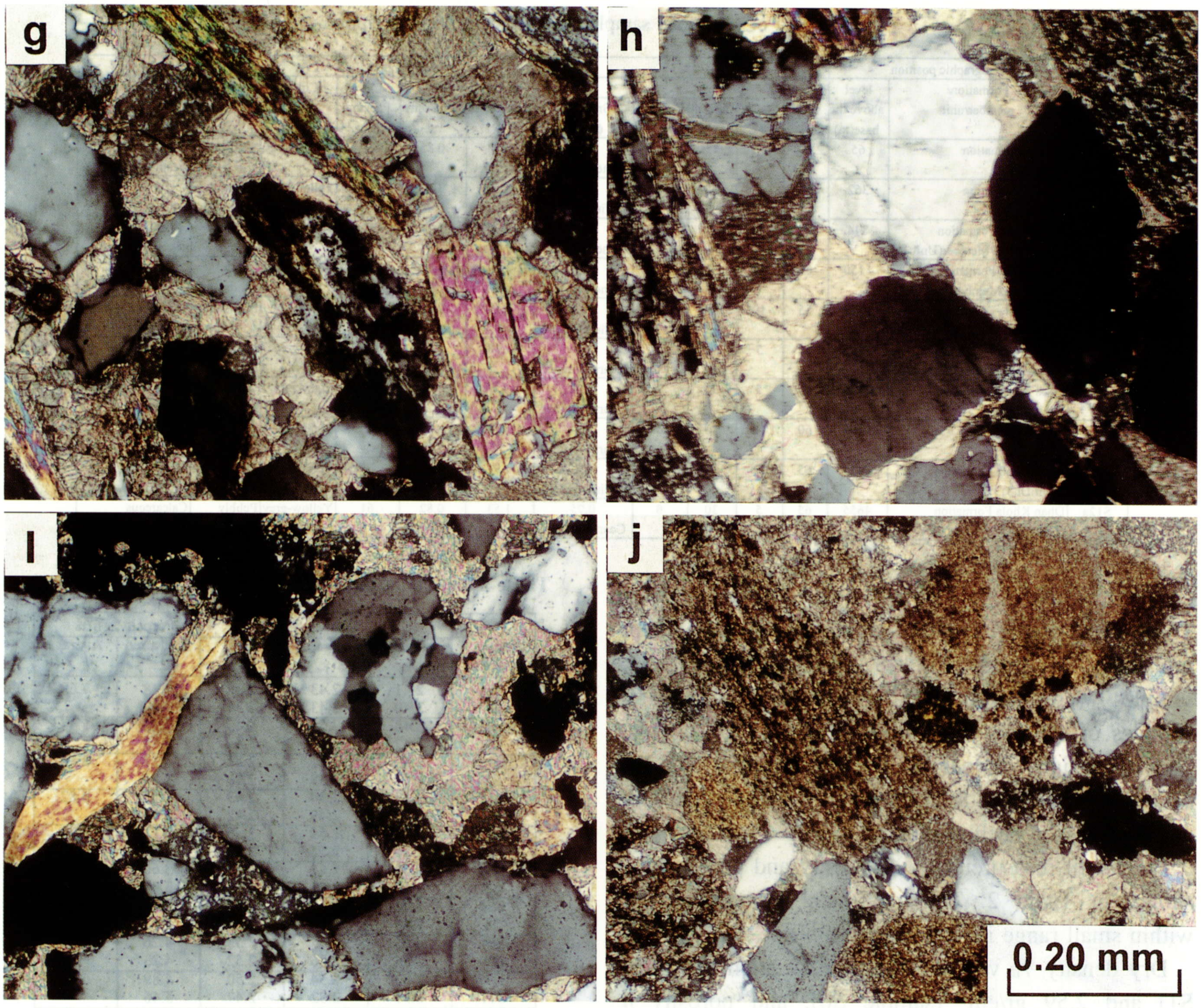

Fig.4 Photomicrographs of textures in thin sections of sandstones under the microscope. (a) to (j) are thin sections obtained from samples S1 to S12 without S7 and S10, respectively. (a) S1, (b) S2, (c) S3, (d) S4, (e) S5, (f) S6, (g) S8, (h) S9, (I) S11, (j) S12.

Measurements of physical and mechanical properties

Density and porosity

Both density and porosity are two major physical indices commonly measured for various purposes. In general, density of rock samples is defined as their ratio of weight to volume at different condition. For example, natural, wet and dry densities are defined as ;

$$\gamma_n = \frac{W_n}{V},\ \gamma_w = \frac{W_w}{V} \text{ and } \gamma_d = \frac{W_d}{V} \qquad (1)$$

where, γ_n, γ_w and γ_d are natural, wet and dry densities respectively, and W_n, W_w and W_d are weights of samples at natural, wet and dry conditions respectively. V is the total volume of the sample.

Porosity n in solid is defined as a ratio of void volume to total volume of the sample, and is expressed in percentage. The void volume is also given by the difference of weights of the sample under wet and dry conditions as follows ;

$$n = \frac{\text{(void volume)}}{\text{(solid volume)}} \times 100$$

$$= \frac{W_w - W_d}{V} \times 100\ (\%) \qquad (2)$$

Here, the volume V for each sample was obtained by measuring length l and diameter d of it in cylindrical sample. Each sample was weighed and dried in an oven at 70℃ for 48 hours. Dried samples were then weighed as soon as they were taken out of the oven.

Table 1 List of sandstone samples and petrographic description.

Sample number	Stratigraphic position		Description of samples											
	Formation/ member/unit	level above the base(m)	Content				Texture				Colour	rock type	Remarks
			Clast %	Matrix %	Cement %	Cement/ matrix	Grain size ϕ scale	Roundness ρ	Sphericity ψ	Packing density, %			
S1a S1	Bankas Formation (Unit:B2)	65	60	15	15	1	3 Fine-grained	2.08	0.85	69	Yellow-grey	Sandstone	Slightly weathered
S2a S2	Bankas Formation (Unit:B4)	362	65	5	35	7	2 Medium-grained	2.2	0.8	66	Yellow-grey	Sublithic Sandstone	
S3a S3	Chor Khola Formation Jungli Khola Member(Unit:J2)	844	55	5	40	8	2.75 Fine-grained	2.07	0.77	50	Yellow-grey	Sandstone	Highly calcareous
S4a S4	Chor Khola Formation Shivagarhi Member(Unit:Sh1)	1150	60	10	30	3	2.3 Fine-grained	2.77	0.84	53	Yellow-grey	Lithic Sandstone	
S5a S5	Chor Khola Formation Shivagarhi Member(Unit:Sh3)	1409	55	10	35	3.5	2 Medium-grained	2.19	0.82	52	Grey	Sandstone	Calcareous and Micaceous
S6a S6	Chor Khola Formation Shivagarhi Member(Unit:Sh5)	1885	55	5	40	8	1 Coarse-grained	1.68	0.84	56	Light-grey	Lithic Sandstone	Micaceous and Laminated
S8a S8	Surai Khola Formation (Unit:Su4)	2790	60	5	35	7	1.1 Coarse-grained	1.6	0.84	52	Light-grey	Lithic Sandstone	Micaceous and Laminated
S9a S9	Dobata Formation (Unit:Db2)	3495	60	10	30	3	1 Coarse-grained	1.4	0.82	59	Light-grey	Lithic Sandstone	Micaceous
S11a S11	Dhan Khola Formation (Unit:Dh3)	4425	65	5	30	6	1.1 Medium-grained	1.91	0.81	73	Yellow-grey	Sandstone	Slightly weathered
S12a S12	Dhan Khola Formation (Unit:Dh4)	4655	65	5	30	6	0.75 Coarse-grained	1.53	0.82	61	Yellow-grey	Pebbly Sandstone	Calcareous Slightly weathered

Then they were allowed to cool and were kept immersed in water for 48 hours. Consequently, samples were weighed in wet condition allowing surfaces of samples to be soaked. All those observations of weights in natural W_n, dry W_d and wet W_w conditions have been referred for calculation of density and porosity for each sample.

Results of measurements of density and porosity are shown in Table 2. These physical properties vary within small range in sandstone samples.

Dry density γ_d varies between 2.35 gr/cm^3 (sample S1) and 2.59 gr/cm^3 (sample S6), and porosity n between 2.88% (S3) and 7.68% (S1) (Table 2). The sample S1 with the lowest density and highest porosity is fine-grained muddy sandstone. As seen in Table 1, this is probably due to high matrix-content with low cement-content. On the contrary, the higher density values are obtained in laminated lithic salt-and-pepper sandstone (S6) and calcareous sandstones (S3 and S5) in which porosity is also the lowest.

Table 2 Results of measurements of density and porosity.

Sample number	Density, gr/cm^3			Porosity, n %	
	Natural γ_n	Wet γ_w	Dry γ_d	Measured	Average
S1a S1	2.41 2.40	2.43 2.43	2.36 2.35	7.48 7.88	7.68
S2a S2	2.48 2.47	2.50 2.49	2.45 2.44	5.22 5.68	5.45
S3a S3	2.59 2.57	2.61 2.58	2.57 2.56	3.27 2.49	2.88
S4a S4	2.47 2.47	2.50 2.49	2.43 2.42	6.79 6.85	6.82
S5a S5	2.58 2.56	2.59 2.58	2.56 2.55	3.22 3.57	3.40
S6a S6	2.59 2.60	2.61 2.62	2.57 2.59	3.60 3.06	3.33
S8a S8	2.56 2.55	2.57 2.57	2.52 2.52	5.08 4.92	5.00
S9a S9	2.54 2.54	2.57 2.56	2.53 2.52	4.26 4.23	4.25
S11a S11	2.53 2.51	2.54 2.52	2.50 2.47	4.89 5.46	5.18
S12a S12	2.45 2.46	2.47 2.47	2.40 2.42	6.46 5.68	6.07

Elastic wave velocity

The elastic wave velocity of rocks V_p is obtained using the ultra sonic velocity measurement apparatus. Assuming that the length of sample is l and time taken for wave to pass through the sample is Δt, V_p is determined as ;

$$V_p = \frac{\text{length of the sample } (l)}{\text{time } (\Delta t)} \tag{3}$$

The equipment (Ultra soniscope, Marui Co., Japan) comprises an oscillator, receiver, and recorder. The oscillator and receiver are small cylinders with smooth surfaces, and they are used to place a sample in contact between them. The principle of measurement is that the oscillator transmits a wave of 50 KHz, while the wave is received after passing through the sample. The recording unit of the equipment in microsecond records the time required to transmit a wave through the sample.

The core of sample with flat surfaces was kept between the oscillator and the receiver tightly by applying silicon grease. Both oscillator and receiver are held firmly attached to the sample and travel time for the wave was noted from the recorder.

Table 3 shows results of measurements of elastic wave velocity V_p with uniaxial compressive strength S and elastic modulus E as stated later. The average values of elastic wave velocity V_P obtained range from 1.59 to 4.36 × 10^3 m/sec. The V_P is highest in fine-grained highly calcareous sandstone (S3) from the Jungli Khola Member. Contrarily, it is lowest in the salt-and-pepper sandstone (S8) from the Surai Khola Formation. In weathered fine-grained muddy sandstone (S1) also V_P is lower. It means that V_P is higher in highly calcareous sandstone and is independent of grain size of sandstones.

Uniaxial compressive strength

Uniaxial compressive strength is obtained by measuring the load at failure of sample. The principle of measurement is that the test instrument uses a sample kept between the pistons, the lower one of which runs by hydraulics. A gauge fixed at the lower piston measures a displacement of length of sample during deformation by loading. The piston loads and deforms the sample while the monitor records and displays the displacement (mm) against the load (KN) at the interval of two seconds. The sample is finally allowed to fail. At deformation, the equipment displays the maximum load applied. In these measurements, displacement rate was set in 0.02 to 0.04mm/min.

As shown in Table 3, the uniaxial compressive strength obtained ranges from 33.1 to 117 MPa, and this means that Siwalik sandstones almost belong to lower grade of hard rocks (hard rocks defined by Franklin and Dusseault, 1989). Considering that uniaxial strength of mudstone estimated based on penetrative hardness is the order of 0.1 to 1MPa (Tamrakar, 1999), mechanical contrast between sandstone and mudstone is very large in the Siwalik Group, and this is one of physical and mechanical characteristics of the Group. Some slope movements in this area described by the authors (Tamrakar *et al.,* 1999) may also depend on this contrast in addition to other mechanical properties.

Higher values of uniaxial compressive strength were obtained in calcareous samples such as S3 (117 MPa) and S5 (76.6 MPa) respectively. Lower values were measured in salt and pepper sandstone such as S8 (33.1 MPa) and fine-grained muddy sandstone of S1 (37.0 MPa). The higher values obtained in calcareous samples is attributed to stiffness of materials due to well cemented nature, and the lower values to micaceous laminae and soft nature of sandstone with high matrix-content.

Behavior under uniaxial compression and stress-strain curves

Fig.5 shows stress-strain curves of each sample obtained during loading. Curves are approximately straight lines in most of the samples, and this exhibit elastic deformation as behavior of material. However, they show rather convex curves at high strain stages just before failure, and this means slightly plastic behavior.

Out of ten samples, samples S3 and S5 are more brittle than others as indicated by the sharp stress-strain curves. This may be attributable to greater stiffness and resistance of calcareous cemented framework against external forces. The curves of S1, S6 and S8 are more or less S-type showing initial plastic and then respectively elastic and plastic behaviors. Higher rates of deformation in the S1, S6 and S8 probably occurred when grains readjusted against loads giving ductile behavior (Goodman, 1989). The former with the highest porosity might have undergone compaction and great lose its voids. The samples S6 and S8 with greater amount of flacky micas and pelitic rock fragments tend to deform at faster rate by squashing of those constituents. Other samples being stiffer resist load with lower rate of axial shortening of the sample.

Elastic modulus (Young's modulus)

Young's modulus *E,* one of elastic moduli showing deformability of rocks, was obtained from the relationship between load and shortening of sample during loading. It is given by ;

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{4}$$

where, $\Delta\sigma$ and $\Delta\varepsilon$ are increments of stress and strain

Table 3 Results of measurement of elastic wave velocity, elastic modulus, and uniaxial compressive strength.

Sample No	Elastic Wave Velocity Vp (×10^3 m/sec)	Elastic Modulus E (×10^3 MPa)	Uniaxial Compressive Strength S (MPa)
S1	2.07	4.67	37
S2	3.06	9.33	61.3
S3	4.36	22.70	117
S4	2.73	7.33	44.3
S5	3.43	13.00	76.6
S6	2.32	9.60	66.8
S8	1.59	3.33	33.1
S9	3.45	15.30	66.1
S11	3.05	12.70	50.4
S12	3.41	18.00	52.1

respectively. Practically, it has been calculated from the gradient of the stress-strain curve during loading in uniaxial compressive strength measure (for example Allison, 1987).

Young's modulus E obtained ranges from 3.33 to 22.7×10^3MPa (Table 3). While higher values are obtained in fine- to coarse-grained calcareous sandstone samples (S3 and S12), lower are obtained in fine -grained muddy sandstone (S1) and in micaceous lithic sandstones, salt-and-pepper sandstones (S6 and S8).

Variation of indices in stratigraphical and lithological changes

Considering that the Siwalik Group ranges from the Middle Miocene to Early Pleistocene in age, physical and mechanical properties of sandstone may also change depending on stratigraphical horizons from lower to upper. Fig.6 shows such stratigraphical changes of indices of porosity, elastic wave velocity, uniaxial compressive strength and elastic modulus (Young's modulus). Variation is large in each value of index, especially large in lower horizon such as Bankas and Chor Khola Formations. However, this does not mean the depending on stratigraphical depth or deposition age, and rather closely depend on lithofacies and sedimentary environments as stated in followings.

Comparing the changes in values with petrographical characteristics listed in Table 1, these values may strongly depend on cement materials or texture of sandstone rather than stratigraphical depth or age. For example, porosity varies within lower range in samples as the latter are well cemented filled voids among constituent clasts. However, porosity is lower in majority of the samples from the Chor Khola and the Dobata Formations. Moreover, some of calcareous sandstone (S3) show high strength, fine-grained sandstone (S1) is relatively low strength. Similarly, fine- to medium-grained calcareous sandstones from the Chor Khola Formation are sound. The change of V_p, E and S indicate similar trend of variation as shown in Fig.6. However, the local abrupt variation of porosity and strength in upper horizon of the Chor Khola Formation (Jungli Khola Member) is attributable to highly calcareous fine-grained nature in sample S3.

Relations among indices of physical and mechanical properties and petrographic characteristics

In general, there are some empirical relations among

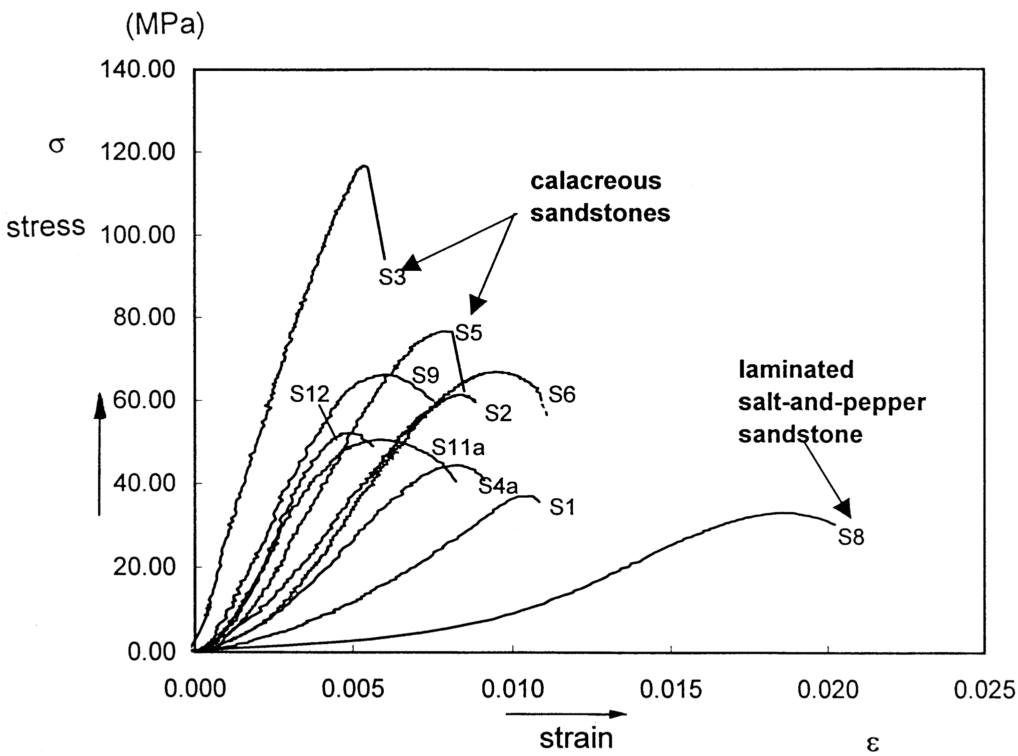

Fig.5 Stress-strain relations in uniaxial compressive test of sandstones. Displacement rate of compression was set in 0.02 to 0.04mm/min.

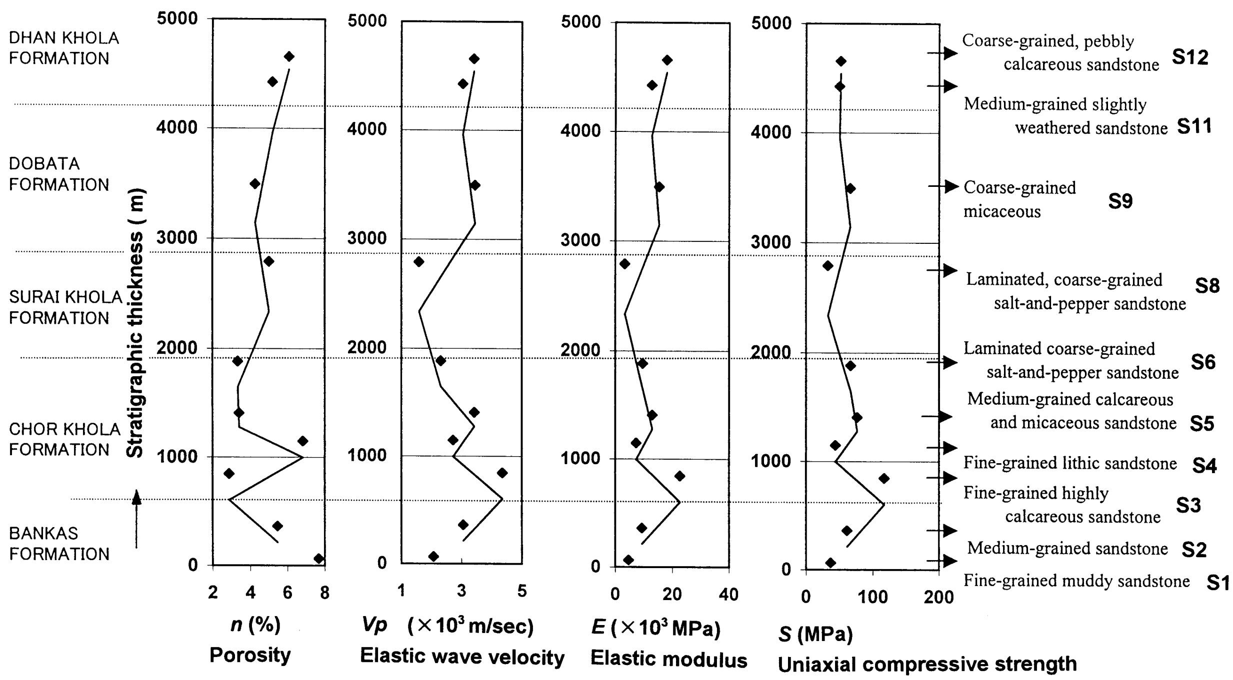

Fig.6 Stratigraphical changes of physical and mechanical properties of sandstones.

indices expressing physical and mechanical properties. For example, positive correlation is well known between uniaxial compressive strength and elastic wave velocity or elastic modulus (for example, Bell and Culshaw, 1988 ; Ulusay *et al.,* 1994).

Sandstone data mentioned above also show a good positive correlation between them as shown in Fig.7 (a). Correlation coefficient r attains to 0.82 (t = 4.04), except for S3 and S6 which are laminated salt-and-pepper sandstone and fine-grained calcareous sandstone respectively. Based on this relation, the uniaxial strength can be estimated from elastic wave velocity which are easily obtained. According to Fig.7 (a), the relation is approximately expressed by ;

$$S = 0.023\ V_P - 6 \qquad (5)$$

where, S (MPa) and V_P (m/sec) are uniaxial compressive strength and elastic wave velocity respectively.

The uniaxial compressive strength S tends to decrease with increase of porosity (Fig.7 (b)). This negative curvilinear correlation have been pointed out by many authors (for example, Kelsall *et al.,* 1986). Correlation would not be satisfactory due to dispersion in plots of the samples S3 and S8, if they were considered in the trend. The majority of the samples vary between 40 and 80 MPa with small variation of porosity n between 2.88 and 7.68%.

Likewise, Fig.7 (c) shows the similar relationship between elastic wave velocity and porosity, and these also resembles to Fig.7 (b), because of high correlation between uniaxial compressive strength and elastic wave velocity. Elastic wave velocity V_P decreases curvilinearly with porosity n without considering samples S6 and S8, both of which are salt-and-pepper sandstones. (Fig.7 (c)). S6 and S8 have rather lower porosity influenced by preferred arrangement of grains, sorting of micas. The lower values of V_P in S6 and S8 may be attributed to the presence of micaceous laminae perpendicular to direction of wave propagation. Restricted range of porosity gives wide variation in elastic wave velocity as shown in Fig.7 (c).

Mechanical properties depend generally on change in properties as amount of labile constituents (Pettijohn, 1984) such as micas and pelitic rock fragment, and matrix-content, texture or mass properties (porosity and packing), and sedimentary structures of sandstones. Fig.8 (a) shows the relationship between uniaxial compressive strength and amount of cement materials in Siwalik sandstone data. Almost positive correlation is recognized in the graph. Fig.8 (b) shows the relationship between uniaxial compressive strength and projection sphericity. Almost negative correlation is recognized in the graph. Sphericity gives more or less good, positive and highly significant correlation with strength.

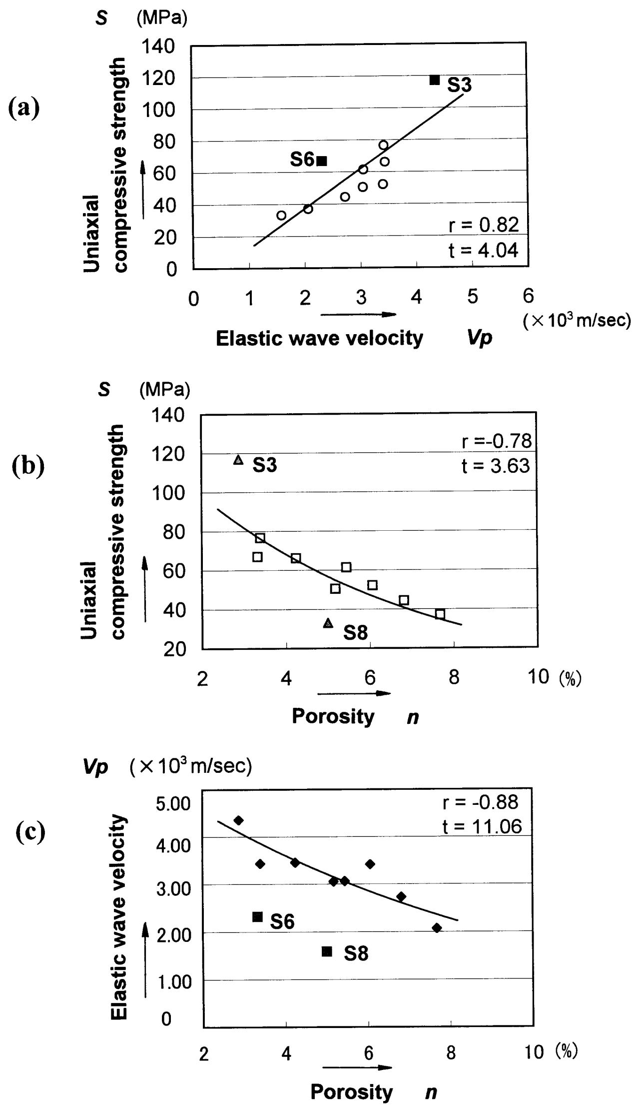

Fig.7 Plots showing relationships among index properties.
(a) Relationship between uniaxial compressive strength and elastic wave velocity
(b) Relationship between uniaxial compressive strength and porosity
(c) Relationship between elastic wave velocity and porosity.
S6 and S8 are laminated salt-and-pepper sandstones, and S3 is fine-grained calcareous sandstone.

Bell and Culshaw (1988) pointed that interlocking of grains and the cement is important as regards strength than content of quartz grains in quartz arenite. Even though the coarse-grained lithic sandstones of the younger formations are calcareous cemented, they become friable either due to labile grains and solution of cement or due to sorting of platy grains, and differential cementation. Therefore, physical and mechanical indices in the Siwalik sandstone depend on calcareous cemented framework, laminated textural feature, and fine-grained muddy nature of sandstones.

Regarding another relations among strength and indices expressing petrographical characteristics, some relations are obtained. Roundness of quartz grains alters due to diagenetic replacement of grains by calcareous cement that almost all the samples give limited range of roundness. Thus, roundness has poor correlation with strength. Packing density has negative but poor correlation with strength. Although packing density seems to be measure of closeness of grains related to reduction in space between grains and increase in compaction, it has less meaning when pore spaces are occupied by cement binding the grains. In the latter case, stiffness of sandstone is due mainly to bonding by cement. Replacement of grains and grain boundaries by calcareous cement has also extremely reduced packing density in sandstone.

These relations mean that the physical and mechanical properties of the Siwalik sandstones closely depend on their sedimentary environments rather than stratigraphical depth or deposition age.

Conclusions

Some physical and mechanical indices of sandstone samples which were systematically collected from the Siwalik Group have been measured, and the variations with their stratigraphical horizons and petrographical characteristics are discussed. Concluding remarks are as follows :

(1) Dry density of the Siwalik sandstones ranges 2.35 to 2.59 gr/cm^3, and porosity is between 2.88 and 7.68%. The former is higher and the latter is lower in calcareous sandstone.

(2) Elastic wave velocity ranges from 1.59 to 4.36x10^3 m/sec, and the uniaxial compressive strength is of the order of 0.5 to 1.0 x 10^2 MPa.

(3) Both elastic wave velocity and uniaxial compressive strength are higher in calcareous sandstone.

(4) Uniaxial compressive strength, elastic wave velocity and elastic modulus are closely correlated to each other, and they have negative curvilinear correlation with porosity.

(5) These physical and mechanical properties of sandstone closely depend on lithofacies and contents of calcium carbonate, and rather independent of stratigraphical depth or depositional age.

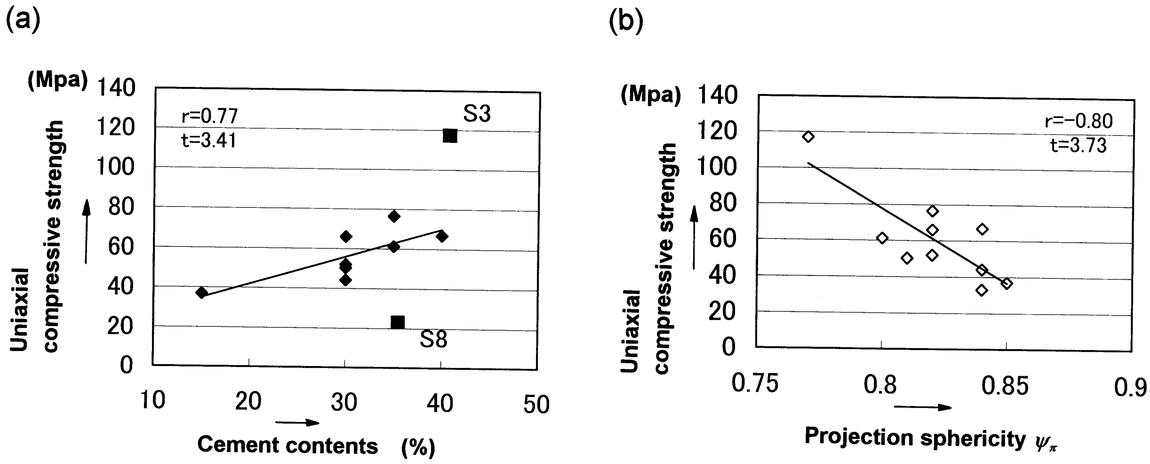

Fig.8 Relationship of uniaxial compressive strength with cement-content (a) and projection sphericity (b).

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（要　旨）

Naresh Kazi Tamrakar・横田修一郎・中村　学，1999，ネパールのSiwalik層群を構成する砂岩の力学的性質およびそれらの岩石学的性質との関係，島根大学地球資源環境学研究報告，18， 41-54

西ネパール，Surai Khola地域から採取したSiwalik層群の砂岩の物理的性質（密度，間隙率）と力学的性質（弾性波速度，一軸圧縮強度，弾性係数）を実験室内にて測定した．さらに砂岩試料から薄片を作成し，顕微鏡下にて岩石組織や構成物を観察し，上記の諸性質との関係を調べた．その結果，石灰質の砂岩で密度は大きく，間隙率は小さい．また一軸圧縮強度や弾性係数も石灰質砂岩では高い．一軸圧縮強度，弾性波速度，弾性係数の間には互いに強い正の相関があり，それらは間隙率と負の相関がある．結果として，これらSiwalik層群の砂岩の物理的・力学的性質は層序的位置や形成時期よりも岩相に大きく依存しており，堆積環境の違いがそれらに反映されていることが明かとなった．