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Physical and geomechanical properties of the Siwalik sandstones, Amlekhganj-Suparitar area, central Nepal Himalaya

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ABSTRACT

The Siwalik Group, one of the world's largest fluvial deposits, distributed in the fore deep basin of the rising Himalayas, crops out well in Central Nepal. The group comprises of mudstones, sandstones and conglomerates ranging in age from middle-Miocene to early Pleistocene. Sandstones form the major lithology in the Siwalik Group and distributed pervasively. Forty-four samples of sandstones were tested for physical and geomechanical properties in order to create a database on Siwalik sandstones and to know the variability of these properties with respect to thier stratigraphic levels. Dry density and saturated density of sandstones are 2.10-2.63 g/cm^3 and 2.22-2.66 g/cm^3, respectively. Porosity is found to vary between 1.93 and 15.2%. They bear weak to strong uniaxial compressive strength (1.29-51.6 MPa), very low to high point-load strength (0.05-4.53 MPa, measured across bedding), high deformability (secant modulus = 0.03-0.98 GPa and tangent modulus = 0.06-1.09) and low modulus ratio (17.8-86.6). The Schmidt hammer hardness in sandstones ranges from 12 to 52. Variation of these properties is independent of stratigraphic level. Dry density and porosity correlate well with uniaxial compressive strength, point-load strength and modulus ratio, and bear highly significant relationships. Hence, dry density and porosity can be used for pridicting strength measures for the Siwalik sandstones.

INTRODUCTION

A thick fluvial sedimentary sequence with average thickness of 6000 m, distributed in the foothills (Siwalik Hills) of the Himalaya, constitutes the Siwalik Group (Fig. 1). The sediments of the sequence were supplied from the rising Himalaya, and were deposited between middle-Miocene and early Pleistocene (Chaudhari 1982; Hisatomi 1992; Gautam and Rösler 1999). The Siwalik Group comprises basically of sandstones, mudrocks, and conglomerates. Constituents of sandstones were derived from low- to high-grade metamorphic, sedimentary and crystalline rocks (Chaudhri 1982; Hisatomi 1992; Critelli and Ingersoll 1994; DeCelles et al. 1998). Generally, bed thickness, grain size and mica-content increase, whereas mineralogical maturity index decreases in sandstones from the older to younger formations (Tamrakar 1998 and 1999).

Several studies on geomechanical properties of sandstones were carried out (Dobereiner and De Freitas 1986; Bell and Culshaw 1998; Bell and Lindsay 1999) in the past few decades to record their relations to physical and textural properties. A limited number of such works has been so far made on the Siwalik sandstones. Tamrakar et al. (1999) showed that mechanical properties of sandstones of mid-western Nepal varied irrespective of stratigraphic level, and depended on amount of cement. No attempt has been made yet to record geomechanical data for the Siwalik sandstones of central Nepal. The main objectives of this study in central Nepal were to record physical and geomechanical properties of sandstones, to observe change of properties with lithologic variation in stratigraphic level, and to observe if some of the physical properties can be used as predictors for strength measures.

GEOLOGY AND SAMPLES

The Siwalik Hills, which lie between the Main Frontal Thrust (MFT) in the south and the Main Boundary Thrust (MBT) in the north, form a wide zone in the Amlekhganj-Suparitar area. These hills comprise chiefly of the Siwalik Group between the MFT and the Samari Thrust (ST), and subordinately of the pre-Siwaliks slice (Bundal Formation, Tamrakar 2002) between the ST and the MBT (Fig. 2 and 3).

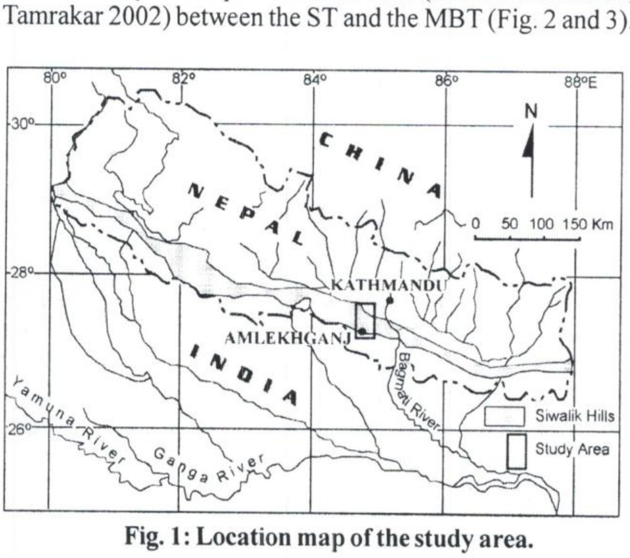

Fig. 1: Location map of the study area.

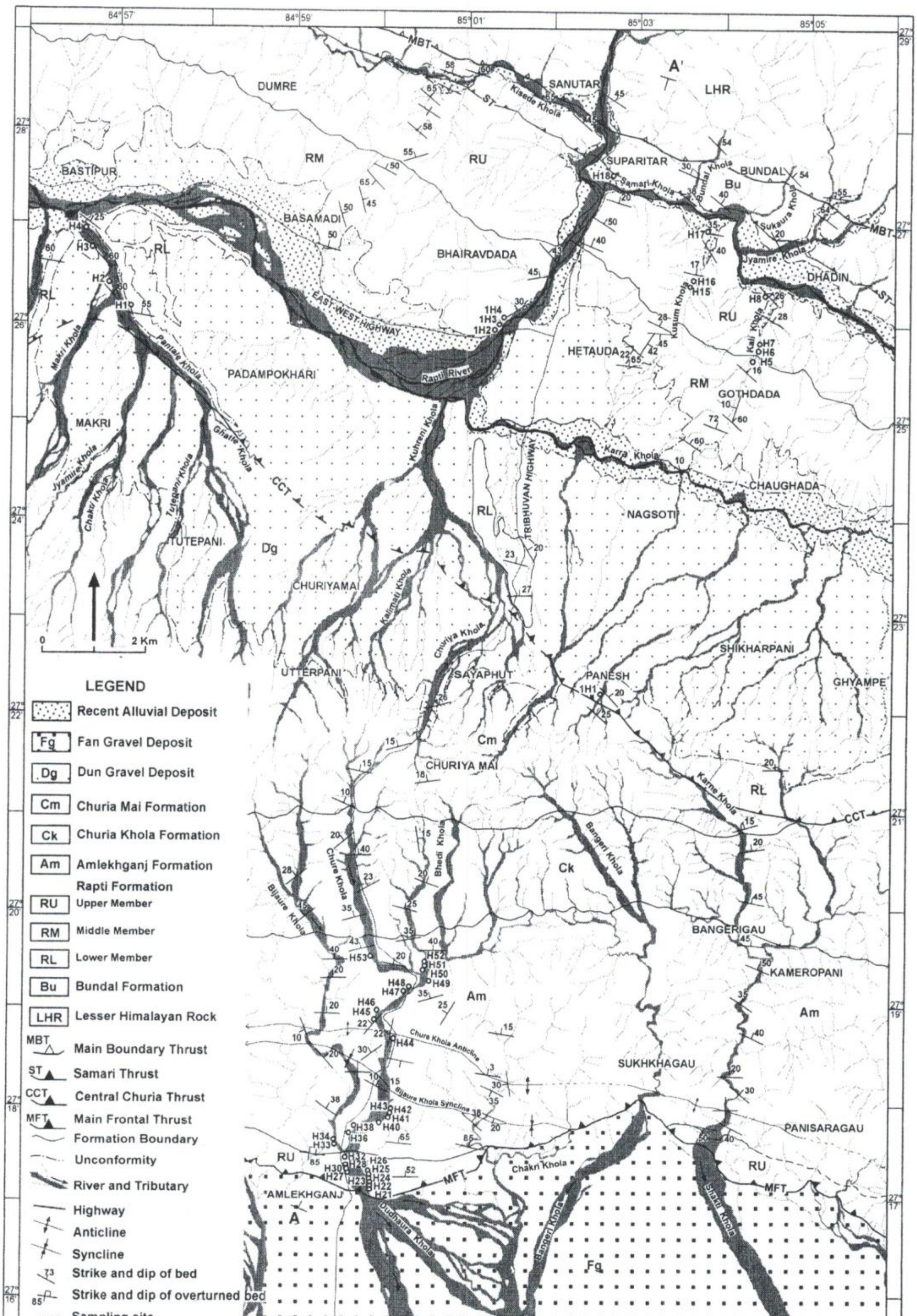

Fig. 2: Geological map showing sampling sites (the map is compiled from Sah et al. 1994; Kimura 1995; Ulak and Nakayama 1998; Tamrakar and Khakurel 2000; and Tamrakar 2002). A-A': line of geological cross section.

The strata of the group generally extend E-W and the Group is divisible into north and south belts separated by the Central Churia Thrust (CCT), along which the northern belt thrusts southward (Fig. 3). Within these belts, several blind thrusts give rise to anticlines and synclines (Fig. 2 and 3).

The Siwalik Group comprising of the Rapti, Amlekhganj, Churia Khola and the Churia Mai formations in the ascending order (Sah et al. 1994; Ulak and Nakayama 1998) has more than 5.5 km thickness. The Rapti Formation consists of fine- to medium-grained sandstone and mudstone. The Amlekhganj Formation consists of multistoried, coarse- to very coarse-grained occasionally pebbly "salt-and-pepper" sandstone, and grey green to reddish brown mudstone. The Churia Khola Formation and the Churia Mai Formation comprise of pebble-cobble conglomerate and boulder cobble conglomerate, respectively.

Sandstone facies

The Rapti Formation, is well distributed in the north belt where its Lower Member crops out in Panesh and the Pantale Khola, whilst its Middle and Upper members are well distributed in Gothdada and the Rapti River sectiion (Fig. 2). In the south belt, the Upper Member is exposed along the Dudhaura and Shakti kholas. The formation has a thickness exceeding 1700 m and age ranging from 14 to 8.5Ma (Gautam and Rösler 1999). Sandstones of the Lower Member are massive, parallel to cross-laminated, fine- to medium-grained, yellowish grey, occasionally micaceous and are interbedded with green grey shales, variegated to purple mottled green-grey mudstones and calcareous siltstones (Fig. 4b). Sandstones of the Middle Member are often massive (3-5 m thick), cross-laminated, fine- to medium-grained, calcareous and indurated. They are interbedded with grey, green and frequently purple mottled yellow mudstones, and siltstones (Fig. 4b). Occasionally, bed thickness exceeds 10 m. The Upper Member in the north belt comprises of massive (usually 5-12 m thick), cross-laminated, medium- to coarse-grained "salt-and-pepper" sandstones, which are intercalated with dark grey to yellow mudstones and shales (Fig. 4c). The Upper Member that exposes out in the Dudhaura Khola constitutes cross- to ripple cross-laminated and occasionally pebbly sandstones, and shales (Fig. 4d).

The Amlekhganj Formation crops out well in the Chure Khola and Bijaure Khola (Fig. 2). The lower part of the formation consists of trough to planar cross-bedded, ripple cross-laminated and coarse-grained sandstones (Fig. 4e). The middle part comprises multistoried, planar to trough cross-bedded "salt and pepper" sandstones (Fig. 4f), whilst the upper part is coarse-grained and pebbly sandstones associated with reddish brown to yellowish green mudstones. Sandstones of the Amlekhganj Formation frequently contains sand ball concretions and mud balls (Tamrakar and Khakurel 2000). Thickness of the formation exceeds 1900 m and the age ranges between 8.5 and 3 Ma.

Sandstone samples

Within a wide zone of the Siwalik Group, sandstones distribute pervasively in the Rapti and the Amlekhganj formations. A stratified-selective sampling of forty-four sandstones (26 from the Rapti Formation and 18 from the Amlekhganj Formation) was made along the rivers and roads in both south and north belts, where Rapti and Amlekhganj formations were well exposed. Sandstones were tested in-situ for Schmidt hammer hardness. Also, 44 sandstone blocks (10^{-3} m^3) were collected from each of the sites (Fig. 2) for further study.

Sandstone samples from the Lower Member of the Rapti Formation were cross-laminated to massive and fine- to medium-grained (Table 1), whereas those from the Middle Member were generally indurated (Table 1). Sandstones of the Upper Member from the Kali and Kusum kholas were fine- and coarse-grained, respectively, whereas those from the Dudhaura Khola were medium- to coarse-grained, micaceous and often "salt-and-pepper" textured. Similarly, the sampled beds of the Amlekhganj Formation often comprised of multistoried "salt-and-pepper" sandstones, which were trough to planar cross-bedded, often ripple cross-laminated in the top of the fining up sequence, and coarse- to very coarse-grained (Table 1).

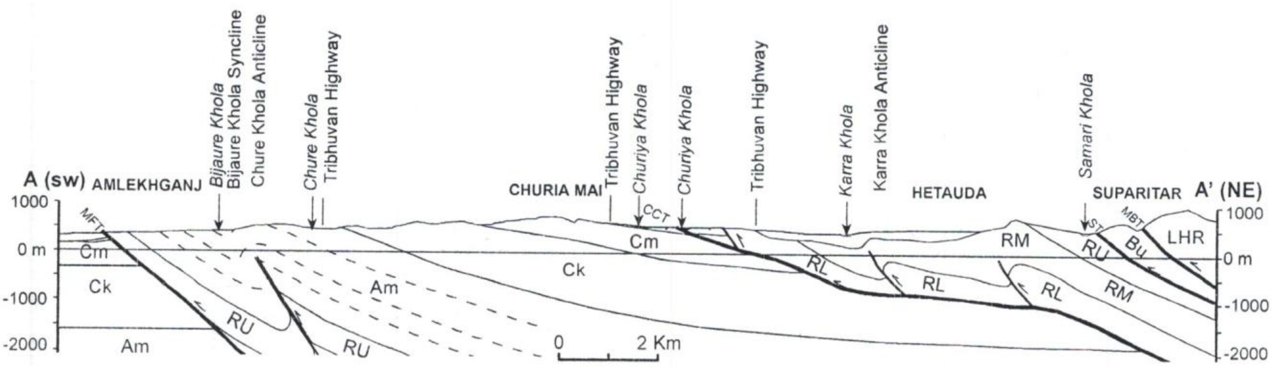

Fig. 3: Cross-section along the line A-A' indicated in Fig. 2 (compiled from Sah et al. 1994; Kimura 1995; Ulak and Nakayama 1998; and Tamrakar 2002).

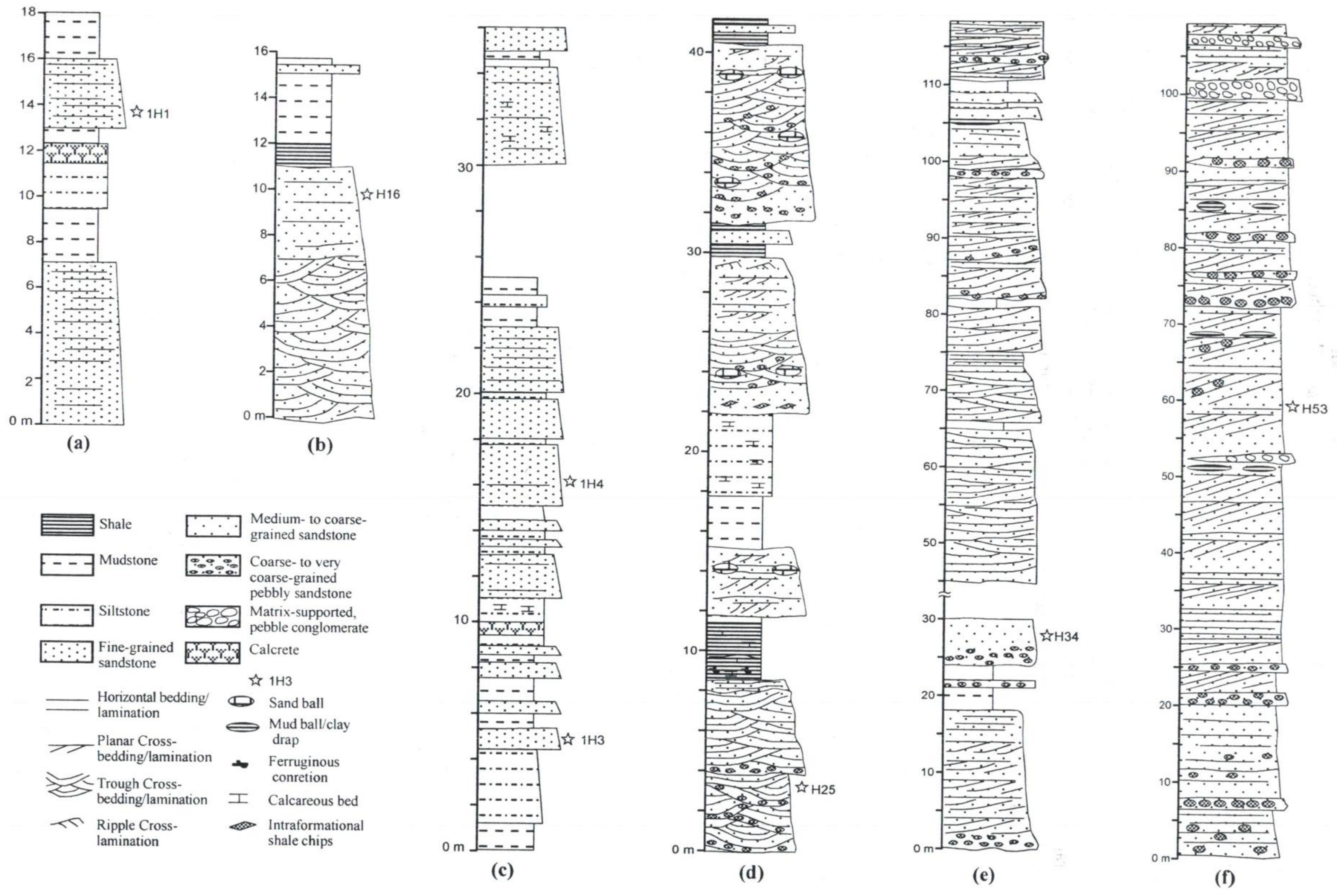

Fig. 4: Columnar section of (a) Rapti Lower Member, (b) Rapti Middle Member, (c) RaptiUpper Member, (d) Rapti Upper Member (south belt), (e) Amlekhganj Formation (lower part) and (f) Amlekhganj Formation (middle part).

Table 1: Sample description and physical and geomechanical properties.

Formation/	Member	Sample No.	Stratigraphic level m	BT	St	GS	O	ρ_d g/cm^3	ρ_{sat} g/cm^3	n %	σ_c MPa	$I_{s(50)}$ MPa	$^*I_{s(50)}$ MPa	SHH	E_s GPa	E_t GPa	MR
Rapti Fm (North belt)	Lower Member	1H1	51	Ms	H	M-F	yellowish grey	2.14	2.25	11.3	7.90	0.18	0.18	12.0	0.28	0.34	43.0
		H1	327	Ms	Cp	C-M	mica & grey	2.33	2.58	7.94	11.2	0.22	0.49	18.4	0.90	0.97	86.6
		H2	337	Ms	H	F	green grey	2.52	2.62	5.43	12.6	1.42	0.58	32.6	0.44	0.67	53.2
		H3	510	Ms	Cp	F	green grey	2.57	2.42	4.13	51.6	1.96	0.89	33.6	0.86	0.92	17.8
		H4	585	Ms	Cp	M	yellowish grey	2.35	2.35	7.37	28.8	1.02	0.53	53.0	0.73	0.90	31.2
	Middle Member	1H2	802	Ms	Cp	F	calc. & green gre	2.59	2.63	3.43	49.8	3.46	3.04	40.0	0.80	0.94	18.9
		1H3	843	TB	H	F	green grey	2.57	2.60	3.65	47.5	4.00	3.12	43.3	0.88	1.02	21.5
		1H4	852	Ms	Cp	M-F	light grey	2.34	2.40	5.60	29.4	1.25	0.71	39.5	0.64	0.79	26.9
		H5	1173	Ms	H	F	yellowish grey	2.23	2.35	11.9	28.7	1.03	0.67	22.4	0.57	0.72	25.1
	Upper Member	H6	1243	TB	Cr	F-M	calc. & grey	2.24	2.37	13.1	18.5	0.40	0.04	20.0	0.34	0.47	25.5
		H7	1278	Ms	H	F	yellowish grey	2.25	2.37	11.7	12.6	0.36	0.13	43.8	0.98	1.09	86.2
		H15	1352	Ms	H	F	green grey	2.46	2.55	8.60	34.8	1.56	1.16	37.1	0.66	0.78	22.4
		H16	1386	Ms	Ct-H	C-F	mica & light grey	2.31	2.42	10.6	29.3	0.62	0.71	34.9	0.76	1.00	34.1
		H8	1561	Ms	H	F	yellowish brown	2.17	2.32	14.6	15.2	0.67	0.40	36.6	0.52	0.71	46.7
		H17	1648	TB	Cp	C	yellowish grey	2.10	2.22	12.0	1.29	0.05	0.05	32.6	0.03	0.06	46.5
		H18	1785	Ms	Cp	C-M	yellowish grey	2.11	2.22	11.0	9.57	0.27	0.05	42.0	0.44	0.60	62.7
Rapti Fm (South belt)	Upper Member	H21	122	MB	Cp	C-M	mica & light grey	2.49	2.55	6.52	19.0	0.62	0.18	25.8	0.49	0.54	28.4
		H22	168	Ms	Cp	C-F	mica & light grey	2.54	2.59	5.07	32.2	2.54	0.98	40.0	0.81	0.87	27.0
		H23	185	Ms	Cp	M-F	mica & light grey	2.30	2.43	12.4	9.00	0.13	0.05	18.0	0.31	0.41	45.6
		H24	203	Ms	Ct	C-M	mica & light grey	2.51	2.57	5.59	19.2	1.02	1.21	22.5	0.55	0.63	32.8
		H25	252	Ms	H-Ct	VC-(	light grey	2.51	2.55	4.65	21.8	1.02	0.54	34.0	0.55	0.80	36.7
		H26	296	MB	L	F	light grey	2.55	2.60	4.65	31.9	1.43	1.25	30.5	0.69	0.82	25.7
		H27	338	Ms	Cp-L	C	calc. & light grey	2.56	2.60	3.78	42.7	2.45	1.51	20.0	0.93	0.99	23.2
		H28	365	Ms	Ct	C	yellowish grey	2.36	2.46	11.3	9.08	0.27	0.09	18.5	0.35	0.43	47.4
		H30	474	VTB	Cp-L	VC-(	mica &light grey	2.52	2.58	6.09	21.4	1.07	0.71	29.5	0.59	0.78	36.4
		H32	504	Ms	Cp	VC	mica & grey	2.45	2.54	8.48	24.0	0.67	0.45	38.5	0.55	0.69	28.8
Amlekhganj Formation (South belt)		H33	639	Ms	Cp-Ct	C	mica & grey	2.35	2.55	19.2	11.7	0.27	0.18	26.5	0.30	0.40	34.2
		H34	692	Ms	H	VC	mica & light grey	2.61	2.63	2.42	48.4	2.18	1.29	34.3	0.90	0.99	20.5
		H36	835	Ms	Ct-Cp	VC	mica & light grey	2.53	2.58	5.71	15.4	0.76	0.89	27.8	0.40	0.57	37.0
		H38	970	Ms	Cp	VC	light grey	2.56	2.61	4.27	33.4	1.29	0.71	36.4	0.62	0.81	24.3
		H40	1100	Ms	Cp	C	light grey	2.55	2.59	3.50	36.4	1.16	1.25	52.3	0.91	0.92	25.3
		H41	1208	Ms	Cp	C	mica & light grey	2.51	2.57	6.01	24.0	0.80	0.40	33.5	0.55	0.7	29.2
		H42	1299	Ms	Cp-L	VC	mica & light grey	2.39	2.60	15.2	8.02	0.31	0.18	14.0	0.24	0.34	42.4
		H43	1350	Ms	Cp-L	C	light grey	2.62	2.64	2.38	48.4	3.11	3.12	46.4	0.97	1.07	22.1
		H44	1450	Ms	Cp-L	C	mica & light grey	2.55	2.60	5.34	25.0	1.07	0.58	30.3	0.74	0.79	31.7
		H45	1505	Ms	Cp-L	C	mica & light grey	2.56	2.61	5.29	27.8	1.16	0.71	17.0	0.73	0.75	27.0
		H46	1519	Ms	L	VC	calc. & light grey	2.55	2.59	4.45	27.9	1.51	0.49	36.1	0.61	0.73	26.2
		H47	1543	Ms	Cp-L	VC	indurated & grey	2.59	2.63	3.53	41.4	1.87	1.34	23.4	0.83	1.05	25.4
		H48	1573	Ms	Cp-L	M	indurated & grey	2.63	2.66	2.62	40.4	2.18	1.88	45.3	0.84	0.98	24.3
		H49	1609	Ms	Cp-L	C	mica & light grey	2.57	2.61	3.86	31.6	1.91	1.97	32.3	0.75	0.86	27.2
		H50	1650	Ms	Cp	C	mica & light grey	2.61	2.65	4.04	38.5	1.74	1.34	29.0	0.36	0.89	23.1
		H51	1668	Ms	Cp	C	calc. & light grey	2.63	2.65	1.93	48.4	3.11	2.58	40.0	0.86	1.06	21.9
		H52	1684	Ms	Cp	C	calc. & light grey	2.55	2.61	6.47	43.2	1.69	1.70	33.9	0.94	0.98	22.7
		H53	1890	Ms	Cp-L	C	yellowigh grey	2.31	2.45	13.8	7.90	0.18	0.18	12.0	0.27	0.31	39.2

Structure and texture of sandstone: BT = bed thickness (Ms = massive bed, VTB = very thick-bedded and TB = thick-bedded). St = structure (H = massive, L = laminate/ horizontal bedded, Cp = planar cross-bedded/laminated, Ct = trough cross-bedded and Cr = ripple cross-laminated), GS = grain size (VC = very coarse, C = coarse, M = medium, F = fine and VF = very fine), and O = other properties. $^*I_{s(50)}$ = point-load strength measured parallel to bedding

Each of the sandstone blocks was cored in to cylinders (diameter=2.5 cm) with length/diameter ratio ranging from 1.45 to 1.72 after being polished the ends by the carborundum powder. These cylindrical samples possessed bedding planes perpendicular to their lengths. Other set of cylindrical samples, which was prepared for diametral point-load test, consisted of a set of bedding plane parallel to the core-length and another set with bedding plane perpendicular to the core-length.

PHYSICAL PROPERTIES

Density and porosity are index properties (Johnson and DeGraff 1988; Goodman 1989), which are often determined for characterisation of rocks in geotechnical uses. Generally, density of a rock depends on density of the mineral constituents and the volume of void it possesses. Porosity that is obtained by saturation method is given by a ratio of volume of void to total rock volume and is expressed in percentage. The porosity so measured is the effective porosity, which is influenced by volume of connected pores.

Dry density, saturated density and effective porosity (hereafter referred as porosity) were determined for cylindrical samples by caliper and saturation method of ISRM (1979), and were calculated using the following relations:

Dry density, $\rho_d = M_s/V$ (1)

Saturated density, $\rho_{sat} = M_{sat}/V$ (2)

Effective Porosity, $n = \{\{(M_{sat} - M_s)/\rho_w\}/V\}\ 100$ (3)

where, M_{sat} is a surface dry saturated mass of the sample, M_s is a solid mass, ρ_w is density of water and V is a bulk volume.

Dry density and saturated density of the Siwalik sandstones ranged from 2.10 to 2.63 g/cm^3 and 2.22 to 2.66 g/cm^3, respectively (Table 1). Samples possessed a moderate to high density according to the classification of Anon (1979). Porosity ranged from 1.93% to 15.2%. Except in few samples, porosity varied within narrow range for sandstones from the Amlekhganj Formation. All the samples showed low to high porosity following Anon (1979).

GEOMECHANICAL PROPERTIES

Geomechanical properties of the sandstones such as uniaxial compressive strength (σ_c), point-load strength ($I_{s(50)}$) and Schmidt hammer hardness (SHH) were measured. Point-load and Uniaxial compression tests were made for air-dried cylindrical samples. Uniaxial compressive strength and elastic modulus were determined following the suggested methods by ISRM (1979), except for the case where length/diameter ratio deviated. An electrically operated uniaxial compression machine, gradually loaded the pressure along the axis of specimen cut perpendicular to bedding. The rate of displacement was 0.03 mm/sec. The force and displacement were read from the graphical plot as output. Secant modulus (E_s), tangent modulus (E_t), and modulus ratio (MR = E_t / σ_c, after Deer and Miller, 1966) were computed from the uniaxial compressive strength test-results.

Point-load strength was measured using diametral testing of samples cut parallel to and perpendicular to bedding (Broch and Franklin 1972; Bieniawski 1975; Hassani et al. 1980). The failure load in KN was read when specimen broke between the platens. The point-load strength obtained initially for each sample was normalized to $I_{s(50)}$ and * $I_{s(50)}$, respectively for the results obtained from the tests normal to and parallel to bedding, after Hassani et al. (1980).

The SHH was tested in-situ for sandstones using the L-type Schmidt hammer and following the suggested method of ISRM (1978). The propelled direction was perpendicular to bedding surface. Out of twenty observations, the higher ten were averaged for reporting of a hardness value.

Uniaxial compressive strength, point-load strength and Schmidt hammer hardness

The results of all the geomechanical properties are given in Table 1. The uniaxial compressive strength ranged from 1.29 to 51.6 MPa. Sandstones from the Amlekhganj Formation gave somewhat narrower range between 7.90 and 48.4 MPa compared to those of the Rapti Formation (1.29-51.6 MPa). The sandstones exhibited weak to strong uniaxial compressive strength according to the classification of Anon (1979).

The point-load strength ($I_{s(50)}$) extended from 0.05 to 4.53 MPa. The sandstones from the Rapti Formation possessed the same range, whereas those from the Amlekhganj Formation ranged from 0.31 to 3.11 MPa. The samples possessed very low to high point-load strength according to the classification of Bieniawski (1975).

The point-load strength obtained parallel to bedding (*$I_{s(50)}$) varied for overall sandstones between 0.04 and 3.12 MPa (Table 1). Considering the results, sandstones showed anisotropy where most of the samples possessed higher point-load strength, measured perpendicular to bedding, and few possessed lower values measured in the same direction.

SHH of the overall Siwalik sandstones ranged between 12 and 53. This shows wide range of hardness of the sandstones. Calcareous sandstones generally but not always gave high hardness values.

Elastic modulus and modulus ratio

The stronger rocks have a high elastic modulus. Secant modulus shows deformation at the initial stage of loading that is up to 50% ultimate strength of the sample (ISRM 1979). Tangent modulus is deformability at fixed percent of the ultimate strength. To understand behaviour of sample deformation under loading, both secant modulus and tangent modulus were computed, and were 0.03-0.98 GPa and 0.06-1.09 GPa, respectively. These ranges lie within high deformability according to Anon (1979). Often, tangent modulus exceeded secant modulus. The initial deformation was generally high in most of the samples (Fig. 5). With progressive deformation at initial phase, the internal adjustment in grains could have occurred. With continued applied force, the sample infused the force and deformation was somewhat slow. However, almost all of the samples bore large strain and deformation. Most of the samples broke developing parallel fractures along the direction of loading and then giving rise to conical fracture and wedge-shaped end pieces, which commonly results during compression tests (Vutukuri et al. 1974), after failure (Fig. 6); and this could be owing to the internal packing of grain fabric during initial phase of loading.

The modulus ratio (MR) varied from 17.8 to 86.6. This range fell within a low modulus ratio according to the classification of Deer and Miller (1996). The MR of sandstones from the Amlekhganj Formation varied within lower range (21.9-42.4) than that of sandstones from the Rapti Formation (17.8-86.6).

Different types of deformation curve (roughly five) from those of steep and straight, to ones of gentle but concave-up and convex-down, were obtained (Fig. 5). The steep-straight curves often belonged to the brittle samples possessing high uniaxial compressive strength and density, but low porosity and MR. Few gentle curves showing large deformation belonged to the samples, which possessed low uniaxial compressive strength and density, but high porosity and MR.

SPATIAL VARIATION OF PHYSICAL AND GEOMECHANICAL PROPERTIES

Fig. 7 shows plots of physical and geomechanical properties against stratigraphic thickness. No distinct regional trend can be observed through the stratigraphic thickness, although local trends exist in the north belt. Porosity and MR decrease from the Lower to the Middle Member of the Rapti Formation and then gradually increase towards the Upper Member. The rest of the other properties show opposite trends. With exception of some samples (H33, H42 and H53), the variation trends in sandstones of the south belt are somewhat narrower than the range of the rocks in the north belt (Fig. 7 and Table 1). Also sandstones from the Upper Member of the Rapti Formation (south belt) possess somewhat greater range of values than those from the Upper Member of the north belt.

LITHOFACIES VERSUS PHYSICAL AND GEOMECHANICAL PROPERTIES

Sandstones from the Siwalik Group have various structures and textures (Table 1 and Fig. 4). Those of the Rapti Formation are even more varied than of the Amlekhganj Formation. Sandstones show a wide range of values of physical and geomechanical properties. Nevertheless, the results from the "salt-and-pepper" sandstones of the Amlekhganj and Rapti formations were limited in range excluding some samples exhibiting very high and low values. The results of physical and geomechanical properties (Table 1) along with the field information exhibited that the

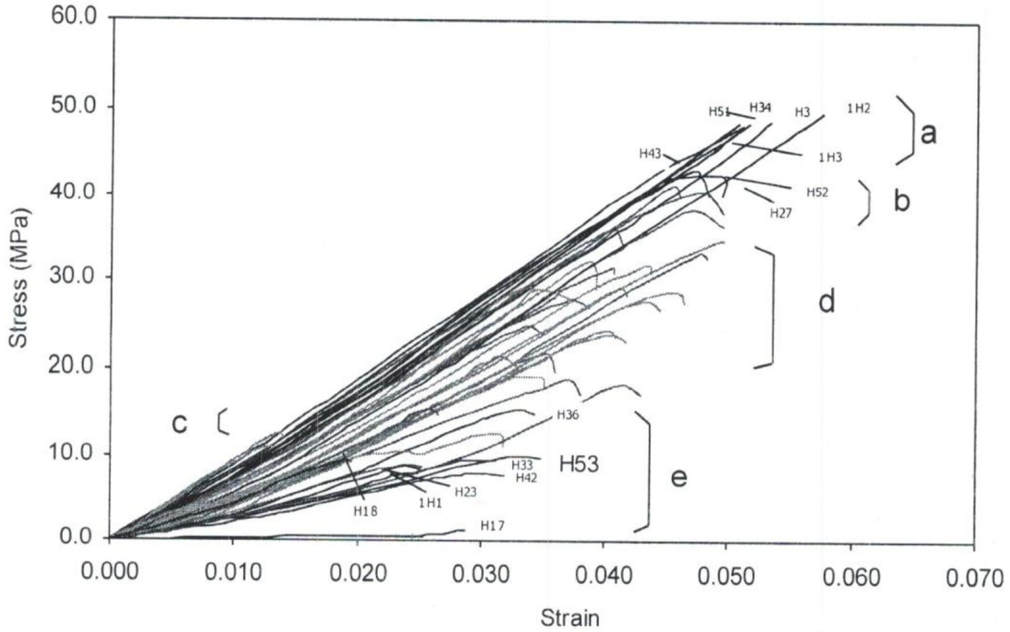

Fig. 5: Typical stress-strain curves of the Siwalik sandstones: (a) steep-straight curves showing brittle deformation and low MR, (b) straight curves showing ductile deformation between yield and ultimate strengths, (c) straight curves showing brittle deformation but with low σ_c (d) curves with intermediate MR and σ_c, and (e) gentle and concave up-convex down curves possessing greater MR and showing ductile deformation.

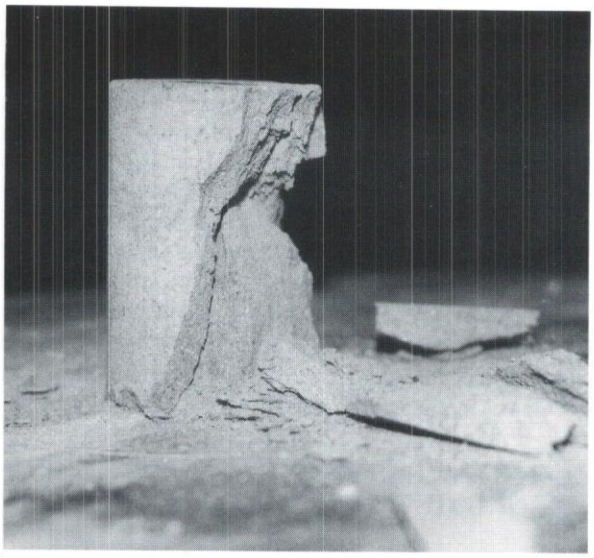

Fig. 6: Samples after the test showing a fracture pattern.

higher and lower values were perhaps influenced by degree of cementation, compactness and induration. Similar influence was suggested by Dobereiner and DeFreitas (1986), Yates (1992) and Tamrakar et al. (1999). The analysis of the results indicated features that would distinguish sandstones as below:

(1) Thick-bedded to massive, homogenous to cross-bedded, fine- to coarse-grained and yellowish grey to yellowish brown sandstones (H1, H7, 1H1, H8, H17, H18 and H23 of the Rapti Formation) gave lower densities and strength measures (where SHH was not well correlated for H17 and H18), but higher porosity and MR. Fig. 8a shows one of such sandstones.

(2) Thick-bedded to massive, homogenous to cross-bedded, very fine- to medium-grained, calcareous, indurated and green grey sandstones of the Rapti Formation (1H2, 1H3, H3, H27 and H22) yielded higher densities (ρ_d and ρ_{sat}) and strength measures ($I_{s(50)}$, σ_c, E_s, E_t and SHH) but lower porosity and MR. Fig. 8b shows one of the examples of such sandstones.

(3) Massive, cross-bedded, coarse- to very coarse-grained, micaceous, less indurated and friable "salt-and-pepper" sandstones (H33, H36, Fig. 8c, H42 and H53 of the Amlekhganj Formation) gave lower densities and strength measures but higher porosity and MR.

(4) Massive, homogenous to cross-bedded, coarse- to very coarse-grained, calcareous, indurated and light grey "salt-and-pepper" sandstones (H34, H43 (Fig. 8d), H51 and H52 of the Amlekhganj Formation) bear higher densities and strength measures but lower porosity and MR.

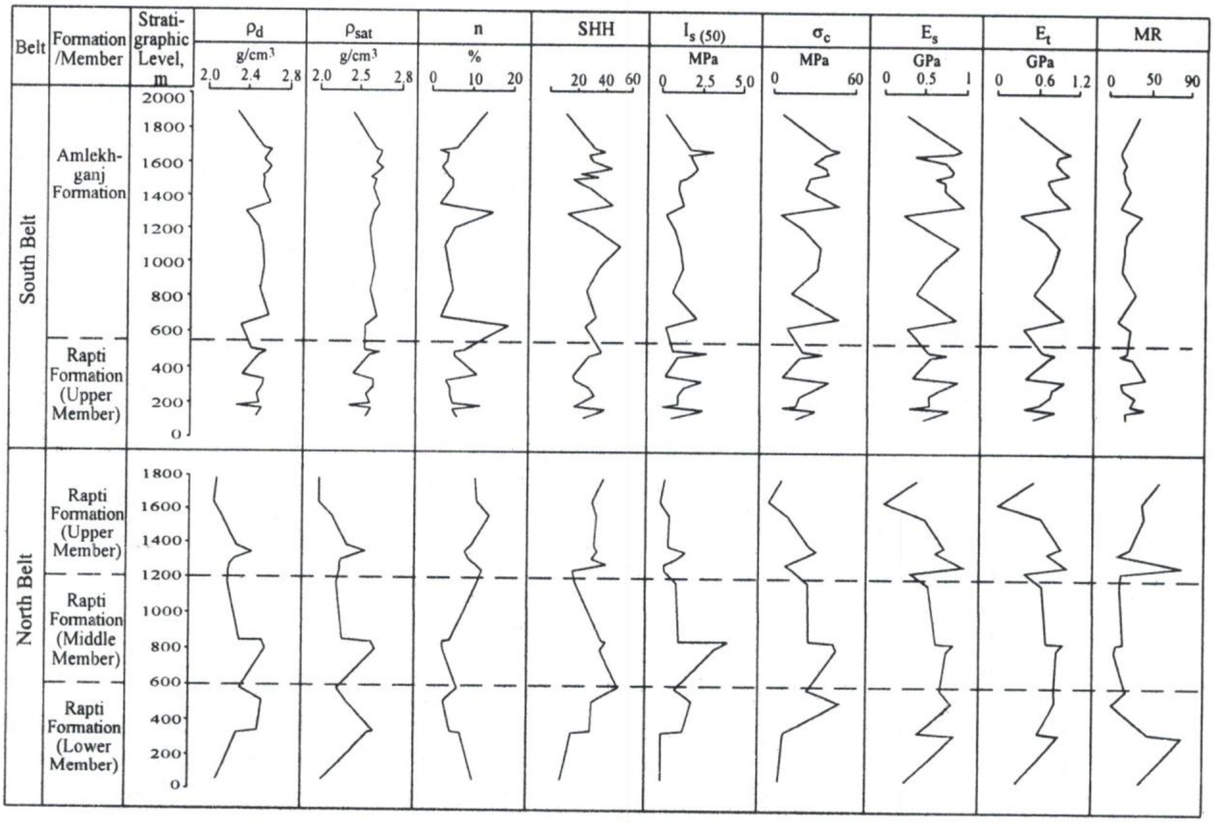

Fig. 7: Variation of physical and mechanical properties against stratigraphic level.

RELATIONSHIPS BETWEEN PHYSICAL AND GEOMECHANICAL PROPERTIES

Considering the variation trends in Fig. 7, the trends between dry and saturated densities, and those among uniaxial compressive strength, secant modulus, tangent modulus, point-load strength and SHH much resemble to each other showing that they are related positively to one another. However, the trends of porosity and MR exhibit negative relationships with other physical and geomechanical properties.

The dry and saturated densities show positive and highly significant correlation with uniaxial compressive strength and point-load strength (Table 2) with the relationships: $\sigma_c = 67.114\,\rho_d - 137.56$, $\sigma_c = 61.460\,\rho_{sat} - 128.18$, $I_{s(50)} = 4.6166\,\rho_d - 10.013$ and $I_{s(50)} = 4.6439\,\rho_{sat} - 10.419$. It showed that uniaxial compressive strength and point-load strength of the Siwalik sandstones tended to increase as dry density and saturated density increased. Strong and highly significant correlation between dry density and uniaxial compressive strength was also obtained for various sandstones by Bell (1978), Dobereiner and De Freitas (1986), Bell and Lindsay (1999) and Tamrakar et al. (1999). Comparing the correlation of dry density and saturated density with mechanical properties other than SHH, relationships of dry density are stronger and more significant than those of saturated density. Therefore, dry density may be used as one of predictors for mechanical properties.

The relationships of MR with dry and saturated densities were not so strong, but were highly significant to significant, respectively. Generally, MR tended to decrease with increase of densities. Densities did not correlate well with SHH (Fig. 9a and b; Table 2) and the correlation was weaker and not so significant as compared to other relations,

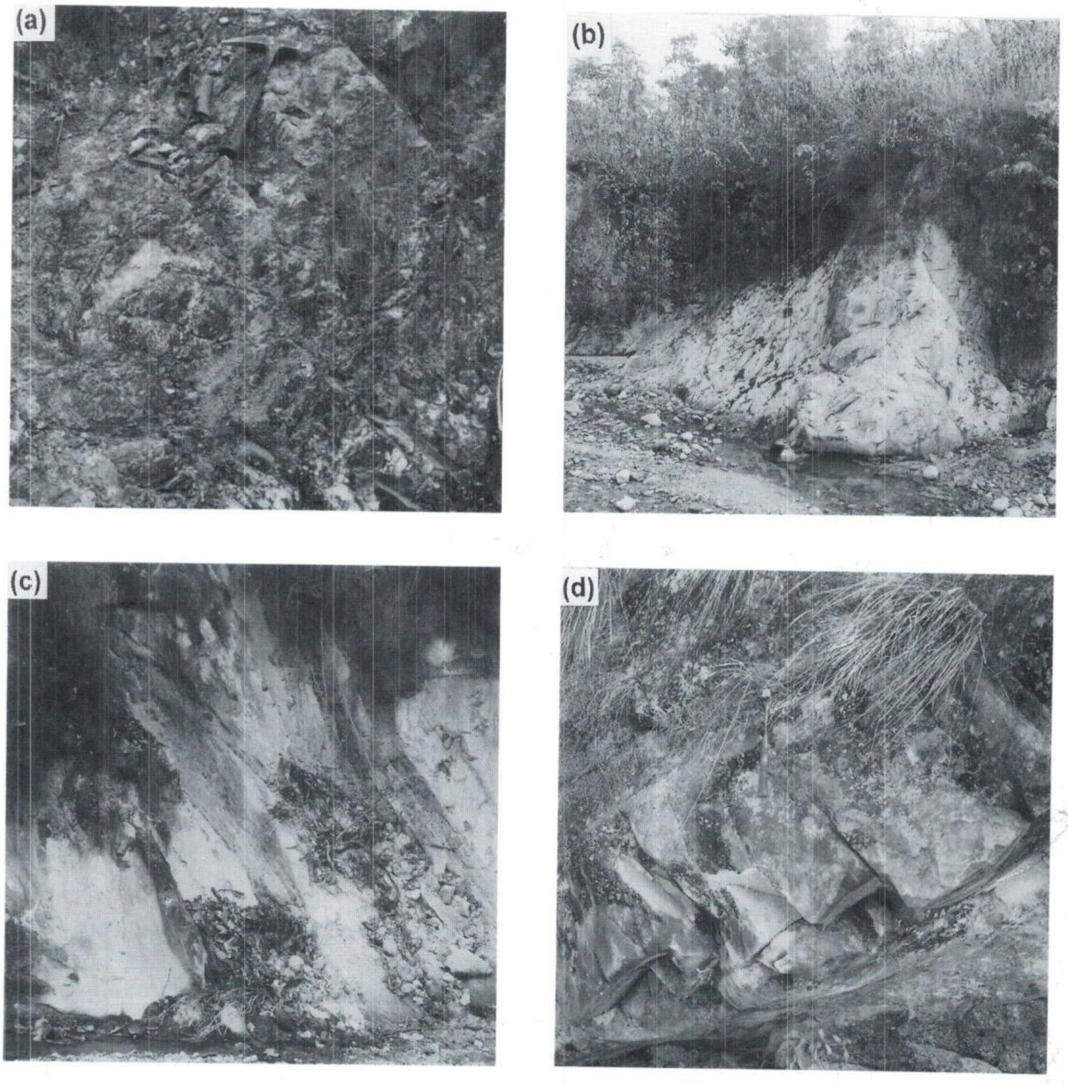

Fig. 8: Outcrops of sandstones: (a) 1H1 in Panesh, (b) H22 at the left bank of the Dudhaura Khola, near Amlekhganj, (c) H36 at the right bank of the Chure Khola, (d) H43 at the left bank of the Chure Khola (see Fig. 1 for location).

Table 2: Correlation among physical and geomechanical properties

		σ_c	$I_{s(50)}$	SHH	E_t	E_s	MR
ρ_d	r	0.737	0.720	0.247	0.595	0.558	-0.598
	t	7.063 (HS)	6.729 (HS)	1.649 (NS)	4.794 (HS)	4.355 (HS)	4.838 (HS)
	S_e	9.547	0.674	10.099	0.198	0.200	12.393
	S_b	9.474	0.669	10.022	0.196	0.198	12.299
ρ_{sat}	r	0.540	0.577	0.076	0.485	0.448	-0.415
	t	4.285 (HS)	4.779(HS)	0.579 (NS)	3.596 (HS)	3.248 (S)	2.957 (S)
	S_e	11.888	0.794	11.888	0.215	0.215	14.071
	S_b	14.638	0.977	14.638	0.265	0.265	17.326
n	r	-0.750	-0.738	-0.418	-0.685	-0.646	0.480
	t	7.341 (HS)	7.087 (HS)	2.984 (S)	6.091 (HS)	5.487 (HS)	3.542 (HS)
	S_e	9.347	0.656	9.346	0.179	0.183	13.572
	S_b	0.343	0.024	0.343	0.007	0.007	0.498

r = Coefficient of correlation, t = Student's value, Se = Standard error of estimates, S_b = Standard error of regression coefficient, HS = Highly significant (99.9% confidence limit), S = Significant (99% confidence limit) and NS = Not significant

probably because of difference in tests applied to intact samples in one hand and rock mass in the other. SHH should have been influenced by structure (laminae and joints) of sandstones.

Uniaxial compressive strength, point-load strength and SHH had negative correlation with porosity. Contrarily, MR had positive relationships with porosity (Fig. 10a and b; Table 2). The relationships of SHH and MR with porosity were not so strong although they were significant. For the Siwalik sandstones, uniaxial compressive strength and point-load strength tended to increase with decrease of porosity, showing somewhat stronger and highly significant relationships; $\sigma_c = 45.374 - 2.5316n$ and $I_{s(50)} = 2.5618 - 0.173n$. Similar negative relationships were obtained in earlier studies (Dobereiner and De Freitas 1986; Shakoor and Benelli 1991; Ulusay et al. 1994; Bell and Culshaw 1998; Bell and Lindsay 1999; Tamrakar et al. 1999). Increase in pore volume probably leads to weaken fabric of sandstones, and hence reduce their strength. Considering the strong and highly significant relationships of uniaxial compressive strength and point-load strength with porosity, the latter may be used as a indicator of those strength measures for the Siwalik sandstones.

CONCLUSIONS

The Siwalik rocks are very diverse in physical and geomechanical properties as suggested by wide ranges of these properties. Dry density, saturated density and porosity of the Siwalik sandstones were 2.10-2.63 g/cm^3, 2.22-2.66 g/cm^3 and 1.93-15.2%, respectively. Samples possessed low to high density and porosity.

Uniaxial compressive strength, $I_{s(50)}$, SHH, secant modulus, tangent modulus and MR were 1.29-51.6 MPa, 0.05-4.53 MPa, 12-52, 0.03-0.98 GPa, 0.06-1.09 GPa, and 17.8-86.6, respectively. The sandstones possessed weak to strong uniaxial compressive strength, very low to high point-load strength, high deformability and low modulus ratio.

Sandstones also exhibit anisotropy to some extent, therefore requiring consideration of test results along required direction related to bedding, and of rock mass properties depending on engineering structures. The results obtained (in this study) by the tests made across bedding may need adjustment in rating before utilizing for geomechanics classification, if the engineering construction is going to be influenced by this phenomenon.

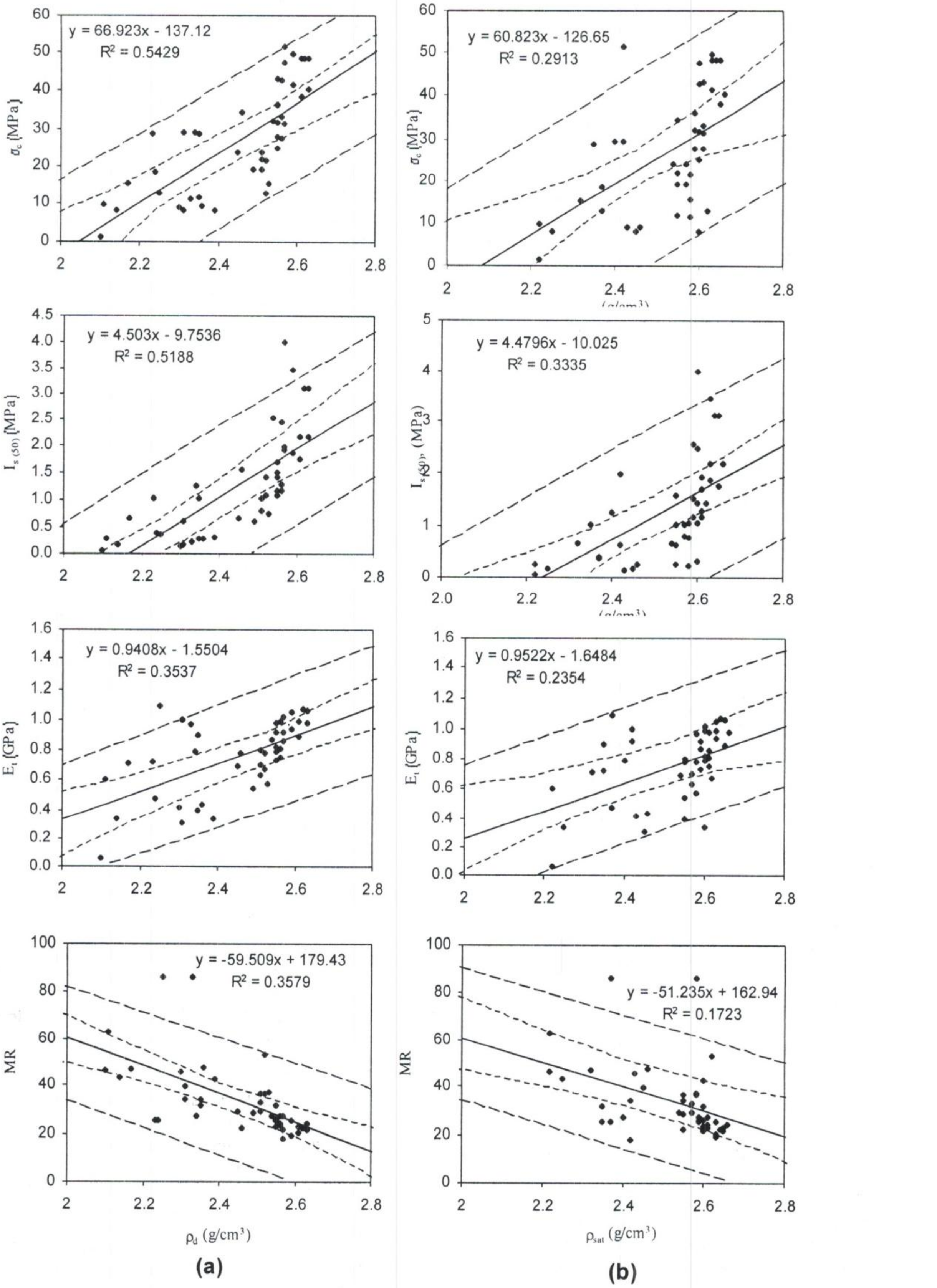

Fig. 9: Relationships of uniaxial compressive strength, point-load strength, tangent modulus and MR with (a) dry density and (b) saturated density. The outer dashed lines represent prediction interval band at 95.5% confidence level and the inner dashed curves represent confidence interval boundary at 95% confidence level.

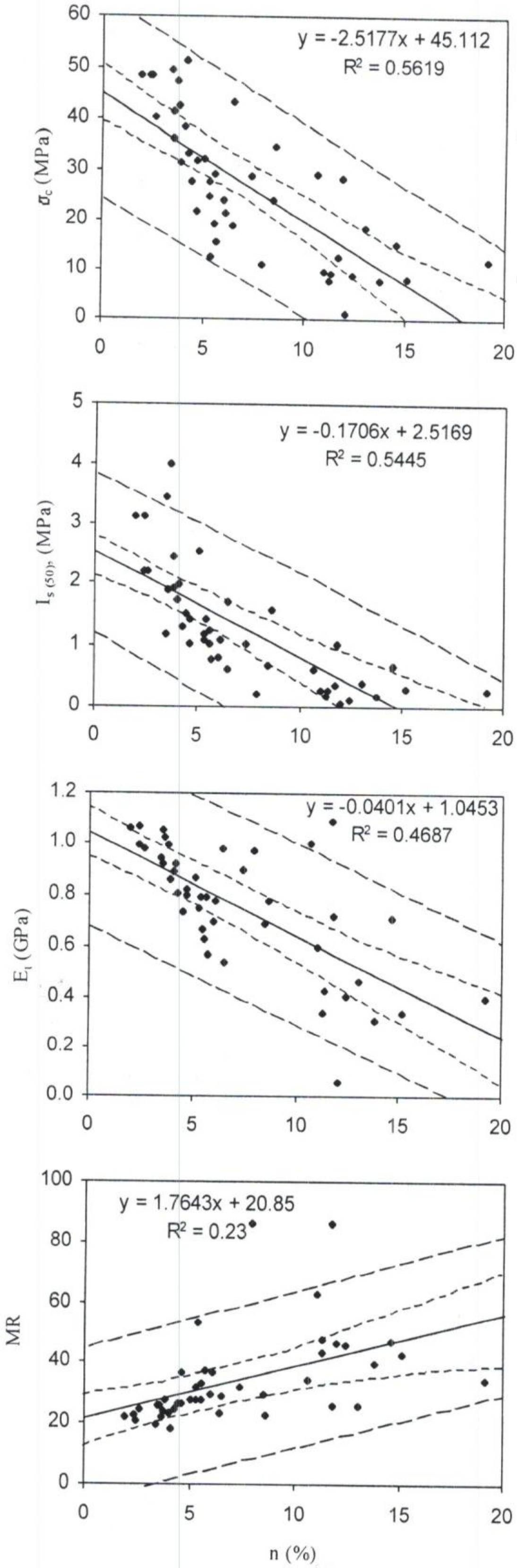

Fig. 10: Relationships of SHH, point-load strength, uniaxial compressive strength and MR with porosity (see Fig. 9 for explanation of dashed curves).

Variation of physical and geomechanical properties of the sandstones from the Amlekhganj Formation was limited to a lower range than that for the sandstones from the Rapti Formation. However, the regional variation trends were not distinct against stratigraphic level.

Highly calcareous and indurated sandstones of both Rapti and Amlekhganj formations generally gave higher strength measures than less calcareous and indurated ones. Similarly, very fine to medium-grained, calcareous, indurated and green grey sandstones of the Rapti Formation gave higher strength measures and densities. On the other hand, fine to coarse-grained yellowish grey to yellowish brown sandstones or micaceous less indurated sandstones resulted in lower strength measures and densities.

The relationships of dry density and porosity against uniaxial compressive strength, point-load strength and MR were good and highly significant compared to the relationships with SHH. Therefore, dry density and porosity can be used as good indicators for strength measures.

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