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Statistical Correlation between Petrographical and Physico-Mechanical Properties of Kaimur Sandstone

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***Abstract:*Present work is carried out on the sandstone rocks of Kaimur Group, Mirzapur district, India. The rock samples of Dhandraul sandstone and Scarp sandstone were collected from different locations, prepared for thin section study and laboratory tests. The quantification of mineral composition was done through Modal composition analysis using traditional point counting method and the image analysis of thin sections was carried out to determine the petrographical parameters (Grain Area Ratio, packing density, form factor). The properties of 32 rock samples were determined and an attempt has been made to establish correlation between petrographical parameters and physical & mechanical properties including porosity, density, specific gravity, uniaxial compressive strength, slake durability index & Young's modulus. Simple linear regression model is used to establish the correlation between the parameters. The mean absolute error (MAE) of the predicted equations ranges from 0.01 to 5.5. The p-value of predicted equations is less than 0.05, deciphering statistically significant correlation. These correlation equations can serve as vital tool in quick forecasting of mechanical properties of sandstones and for estimating design and stability costs of tunnels and bridges.**

***Index Terms:*Kaimur sandstone, Correlation, Simple Linear regression**

I. INTRODUCTION

Mechanical properties of rocks always have an impact on controlling the stability of slopes, underground structures as well as on other infrastructures (Singh et al., 2012). These properties are uniaxial compressive strength, tensile strength, Shear strength, Young's modulus, Poisson ratio and Bulk modulus. Though, it is not always possible, to directly determine these properties as their tests are expensive, depends upon instrumentation availability and sometimes time consuming. In such tricky situations, the estimation of these properties can be forecasted using the statistically predicted correlation equations with some quickly determinable parameters.

Rocks are aggregates of minerals and rock strength is directly related to mineral type present, their proportion, packing density and grain area ratio (Jeng et al. 2004). Therefore, many researchers haveestablished the correlation of petrographical parameters with mechanical strength factors on Tertiary sandstone and other sedimentary rocks (Sabine et al., 1954; Hartley, 1974; Howarth and Rowlands, 1987; Räisänen, 2004; Nespereira, 2010; Cantisani et al. 2013; Seif, 2016; Vazquez et al. 2018).

The recent work is based on the Proterozoic sandstones of Kaimur group. Vindhyan sandstones have been used in several monuments for being unique combination of strength and marvellous beauty. The study of its compositional and strength attributes can throw some light on its applicability as building stones. Furthermore, quick estimation of their strength attributes with easily determinable parameters can give valuable input during the cost estimation and stability assessment of underground structures. In the current work, correlation between petrographical parameters (Grain Area Ratio (GAR), packing density (PD), form factor) and physical & mechanical properties including porosity, density, specific gravity, uniaxial compressive strength (UCS), slake durability index (Sd) and Young's modulus (E) has been established.

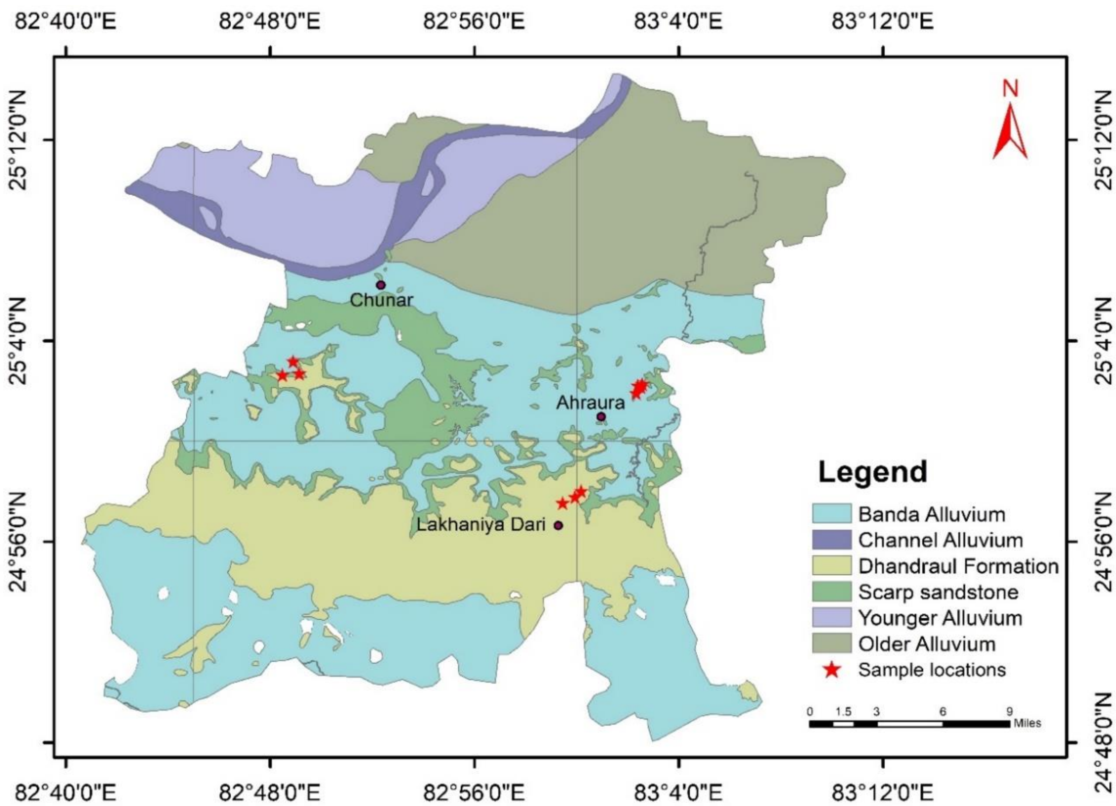

Fig.1. Geological map of Chunar region (http://bhukosh.gsi.gov.in/Bhukosh/Public)

II. Geological setting

Vindhyan is one of the largest intra-cratonic basins in the world, having alternate sequence of argillaceous, arenaceous and carbonate rocks of sedimentary origin (Auden, 1933; Bhattacharya, 1996; Ray et al., 2003). It is exposed primarily in three sectors of India viz. Rajasthan sector, Bundelkhand sector and Son valley sector (Chakraborty, 2006). Vindhyan Supergroup starts the lowermost Semri Group, followed by Kaimur, Rewa and Bhandar groups respectively from older to younger (Crawford and Compston,1969; Bose et al. 2001). A basin-wide unconformity has divided the Vindhyan into two subdivisions known as Lower Vindhyan and Upper Vindhyan (Bose et al. 2001, Singh et al. 2013). Lower Vindhyan includes Semri Group which is dominated with carbonate rocks and Upper Vindhyan succession consists of Kaimur, Rewa and Bhander Groups which are rich in siliciclastic rocks (Sen et al. 2014).

Kaimur is the oldest Group in tectonically undisturbed Upper Vindhyan succession. It consists of sub-horizontal to gently dipping rocks of arenaceous sandstones and argillaceous shales (Mishra and Sen, 2010). Kaimur Group has two subdivisions: Lower Kaimur and Upper Kaimur. Sasaram sandstone is found at the base of Lower Kaimur Group, followed by deposition of Ghurma shales and Markundi sandstone. Bijagarh shale, Scarp sandstone and Dhandraul sandstone are three distinct units of Upper Kaimur Group in ascending order from older to younger (Shukla and Shukla, 2013, Sen et al, 2014, Quasim et al. 2017).

The present work is carried out in Kaimur Group rocks of Son valley sector and rock samples of Dhandraul and Scarp sandstone of Kaimur Group were collected from Mirzapur district, U.P., India (Fig. 1).

III. Methodology

Microscopic properties of rocks were studied under Leica microscope, followed by modal composition analysis and microscopic image analysis. Afterwards, the sandstone samples were prepared as per ISRM standards for different testing methods. Finally, statistical analysis was performed to know the scientific correlations among the parameters.

A. Petrography

The rocks were cut into the slices of suitable size for mounting on glass slides. After cutting, these slices were glued on glass plates and then one side of the slice was smoothened on rotating cast iron lap with 400 grit carborundum powder after that it was smoothened and polished with 600 grit carborundum to obtain the standard thickness of 0.03 mm (Reed and Mergner, 1953). After preparing the thin sections, the slides were studied under petrological microscope and modal composition analysis was also performed.

1) *Modal Composition Analysis*

The thin section study showed that different sandstones compositions are dominated by quartz with subsequent amount of felspar and rock fragments (Fig. 2). The properties under the

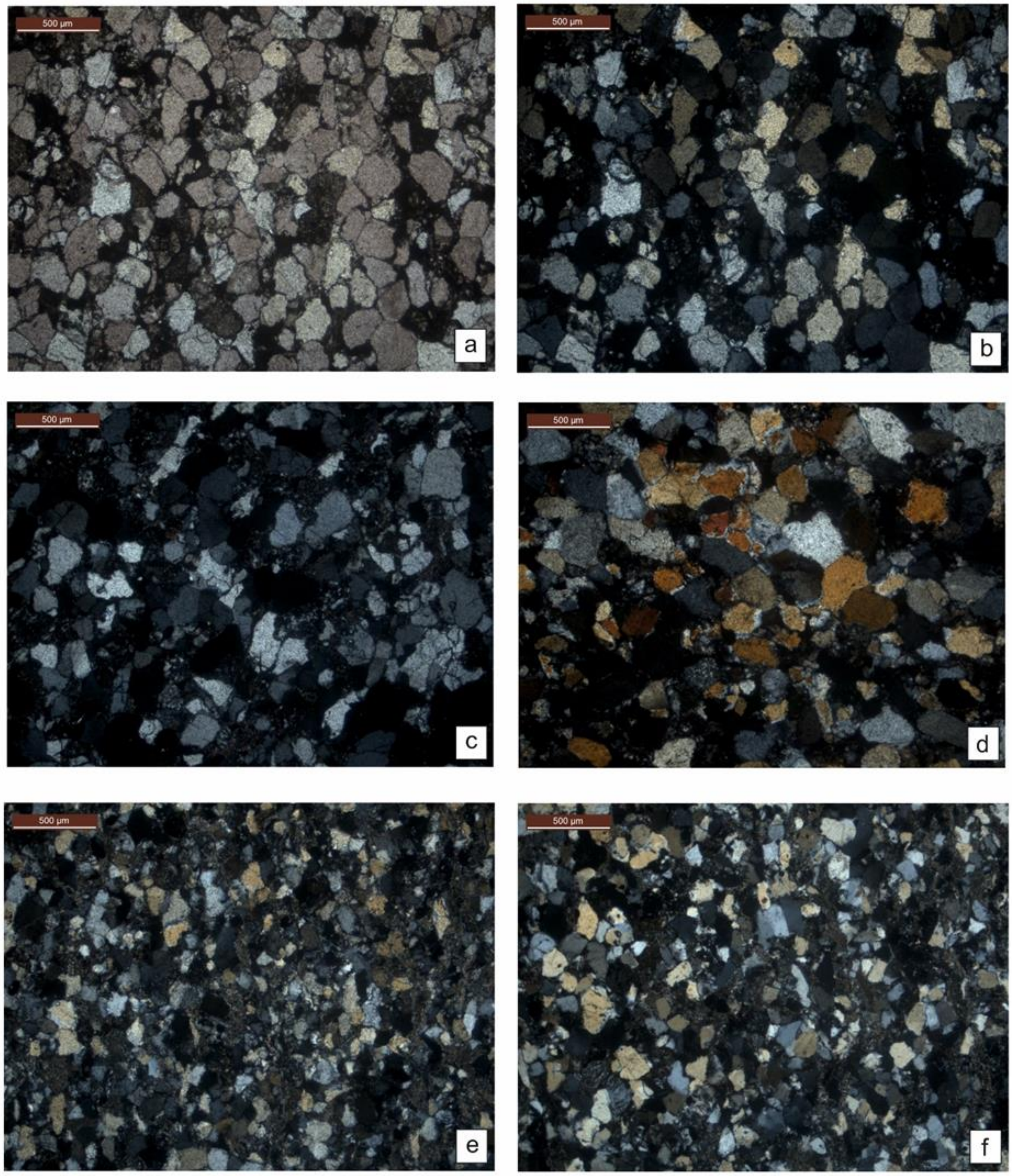

Fig. 2. Petrography of the sandstones from Lakhaniya Dari (a & b), Chunar (c & d) and Ahraura (e & f)

microscope studied are packing density, grain area ratio and form factor.

The modal composition analysis was performed with traditional point counting method, 500 points were counted for each thin section, with appropriate spacing greater than the size largest grain. The proportion of Quartz, Felspar & lithic fragments was calculated in percentage for 500 counts.

Table 1. shows the statistical data of petrographical analysis. IQR stands for inter-quartile range, Min for minimum, Max for maximum, St. Dev. for standard deviation, Qt and RF for quartz and rock fragments.

The rocks exposed in Lakhaniya Dari contain quartz ranging from 86 to 92%, Felspar content varies from 1 to 4 % and lithic fragments are less than 3%. The mean matrix is 24.7%. Grain to grain contact is quite distinct, and grain boundaries are subrounded to subangular. Mean grain area ratio (GAR) of Lakhaniya Dari samples is 71.07% (Table 1).

Table 1. Petrographical characteristics and modal composition of sandstones.

Sample		GAR (%)	PD (%)	FF (%)	Matrix (%)	Modal Composition			
						Qtz (%)	Felspar (%)	RF (%)	Others (%)
Lakhaniya Dari	Min	61.70	59.30	0.46	16.74	86.40	1.40	1.60	4.80
	Median	72.00	69.60	0.53	24.30	88.50	2.60	2.20	6.90
	Mean	71.07	70.69	0.53	24.70	88.78	2.52	2.20	6.50
	Max	79.10	84.40	0.63	34.04	91.80	3.60	2.80	7.60
	IQR	05.07	07.75	0.06	05.40	02.80	0.90	0.40	1.70
	St. Dev.	05.37	06.93	0.05	05.31	01.79	0.68	0.38	1.06
Chunar	Min	78.70	68.80	0.60	10.58	83.80	2.40	3.40	2.20
	Median	83.80	81.70	0.64	13.68	85.40	3.40	4.80	5.00
	Mean	83.22	80.75	0.65	13.88	86.56	3.33	4.80	5.31
	Max	86.80	90.10	0.71	18.76	90.20	4.20	6.60	8.00
	IQR	04.15	06.30	0.05	04.64	03.30	0.80	1.20	3.00
	St. Dev.	02.81	05.83	0.04	02.96	02.18	0.59	0.93	1.90
Ahraura	Min	64.60	59.70	0.47	11.71	84.20	2.60	3.20	4.60
	Median	76.60	77.10	0.56	19.85	85.20	3.80	4.20	6.60
	Mean	75.75	76.94	0.56	20.24	85.49	3.64	4.49	6.38
	Max	84.70	88.20	0.67	30.94	87.80	4.40	5.80	8.80
	IQR	10.00	11.35	0.11	09.97	01.80	0.80	1.40	1.60
	St. Dev.	07.09	08.73	0.07	6.81	1.16	0.59	0.90	1.29

Chunar sandstones have matrix range from 10 to 19%. The mean Quartz, felspar and rock fragments content are 86.6, 3.3 and 4.8% respectively. The mean GAR of Chunar samples is 83.2%. Grain boundaries are subangular to subrounded. Grain to grain contact is discernible (Fig. 3).

Ahraura rock samples have quartz content from 84 to 88%, felspar content ranges from 2 to 4% and rock fragments 3 to 4%. The mean matrix content of Ahraura rocks is 20.2%. Grain boundaries are subangular and matrix is found between the grains. The mean GAR is 75.8% (Table 1).

Most of the grains were subrounded, fewer were subangular. Lesser amount of felspar and subrounded grain boundary imply larger transportation has taken place before the submergence and deposition of sediments.

B. Microscopic Image Analysis

After Modal analysis, the images of thin sections were studied under the Leica image analysis software, to calculate the geometrical aspects of mineral grains. The properties determined through image analysis include packing density, grain area ratio and form factor.

1) Packing density

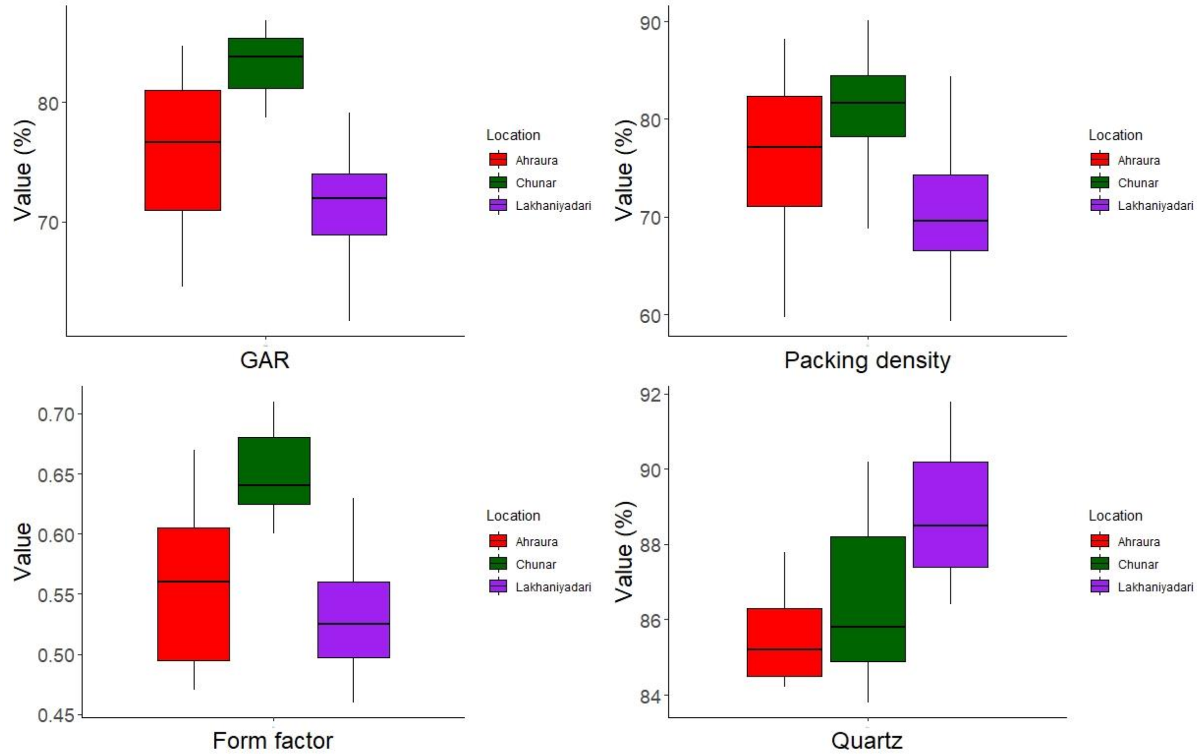

Fig. 3. Statistical representation of petrographic parameters

Packing density (PD) in thin section is defined as ratio of total length occupied by the grains in a specific traverse to the total traverse length (Eq. 1) (Kahn, 1956, Jeng et al., 2004). It is a significant parameter which is studied under the microscope and influences the strength properties of rocks (Bell, 1978, Howarth and Rowlands, 1987).

$$PD = \frac{\sum g_n}{t} \quad (1)$$

Where n is number of mineral grains present in a traverse of length (t) and g_n is the length of n^{th} grain.

2) Grain area ratio

Grain area ratio (GAR) is defined as ratio of area occupied by grains (A_{grains}) to the total area (A_{total}) of the selected image boundary (Eq. 2) (Weng and Li, 2012).

$$GAR = \frac{A_{grains}}{A_{total}} \quad (2)$$

3) Form factor

Form factor refers to the variation of grain shape from circularity. Its value ranges between 0 to 1. The elongated grains&rough grain perimeter have FF value near 0 whereas circular grains have FF value close to 1 (Ersoy and Waller, 1995). Form factor (FF) is calculated from the grain area (A) and grain perimeter length (l) using Eq. 3.

$$FF = \frac{4\pi A}{l^2} \quad (3)$$

C. Physical and mechanical Properties

Physical properties including porosity, density and specific gravity of the rock samples were ascertained in rock mechanics laboratory of department of mining engineering (Fig. 4).

1) Dry density

The samples were dried at 105± 3^0C for 24 hours, then dried mass (M_{sd}) was measured, bulk volume of the samples is determined using Caliper method by measuring volume of rock cores through Vernier caliper. (ISRM, 1977). Dry density of the rocks was enumerated using Eq. (4)

$$\rho_d = \frac{M_{sd}}{V_t} \quad (4)$$

where M_{sd} mass of dried samples in grams, V_t is total volume of the samples in cm^3.

2) Porosity

The rock samples were saturated in water and saturated mass of the samples (M_s) was measured, then samples were oven-dried and dried mass of the sample (M_{sd}) was also determined. Pore volume was calculated using ratio of differences between masses and water density (ρ_w) from Eq. 5.

$$V_v = \frac{(M_s - M_{sd})}{\rho_w} \quad (5)$$

Total volume of the samples was measured using Vernier caliper scale of cylindrical core samples. Porosity was determined using the following Eq. 6 (ISRM, 1977).

$$n = \frac{V_v}{V_t} \quad (6)$$

Where, n is porosity in %, V_v is volume of voids and V_t is Bulk volume of the sample.

3) Slake Durability Index

Slake durability index (I_d) test was performed on small blocks (40-60 grams) of sandstone samples (Eq. 7). In each testing total

Table 2. Physical and mechanical properties of rock samples

Sample		n (%)	G_s	Density (gm/cm^3)	UCS (MPa)	I_{d2} (%)	E (GPa)
Lakhaniya Dari	Minimum	3.37	2.49	2.47	51.20	94.55	6.27
	Median	4.21	2.53	2.50	59.80	96.42	6.48
	Mean	4.23	2.53	2.50	60.60	96.27	6.51
	Maximum	5.21	2.57	2.54	70.10	97.27	6.83
	IQR	0.92	0.03	0.04	7.68	0.51	0.24
	Standard Deviation	0.60	0.02	0.02	5.75	0.78	0.18
Chunar	Minimum	2.33	2.53	2.50	60.10	95.37	6.48
	Median	2.87	2.56	2.52	71.20	97.43	6.63
	Mean	2.90	2.56	2.53	70.38	97.26	6.89
	Maximum	4.21	2.61	2.57	82.40	98.81	7.19
	IQR	0.63	0.05	0.03	9.70	1.28	0.37
	Standard Deviation	0.56	0.03	0.02	6.47	1.11	0.24
Ahraura	Minimum	2.76	2.49	2.49	47.10	93.41	6.23
	Median	3.85	2.54	2.52	62.40	97.29	6.64
	Mean	4.00	2.54	2.52	61.06	96.45	6.67
	Maximum	5.94	2.60	2.57	71.10	98.40	7.01
	IQR	0.79	0.06	0.04	8.05	2.70	0.28
	Standard Deviation	0.86	0.04	0.03	7.28	1.76	0.23

8-10 samples of cumulative weight 450-550 grams were kept in the drums and were dried in oven for 6 hours then Mass of drum and samples after drying in the oven (M_a) was measured. The samples were revolved in half water immersion for 10 mins at revolution rate of 20 rpm/min and dried after cooling then retained dried mass of drum and samples after two cycles of revolution of samples (M_c) were weighed. After cleaning and removing the samples from drum, mass of drum was measured (ISRM, 1981).

$$I_{d2} = \frac{M_c - M_d}{M_a - M_d} * 100 \quad (7)$$

Where, I_{d2} is slake durability index after two cycles.

4) Uniaxial Compressive Strength

The rock cores of 54 mm diameter with length/diameter ratio 2.5-3.0 were prepared (ISRM, 1977). The samples were tested in Universal testing machine (UTM) in the department of mining engineering laboratory, IIT B.H.U. Uniaxial compressive strength was determined after determining the load at the failure (Eq. 8).

$$\sigma_c = \frac{4P}{\pi D^2} \quad (8)$$

Where, P is failure load in Newtonand D is diameter of core samples in mm.

5) Young's Modulus

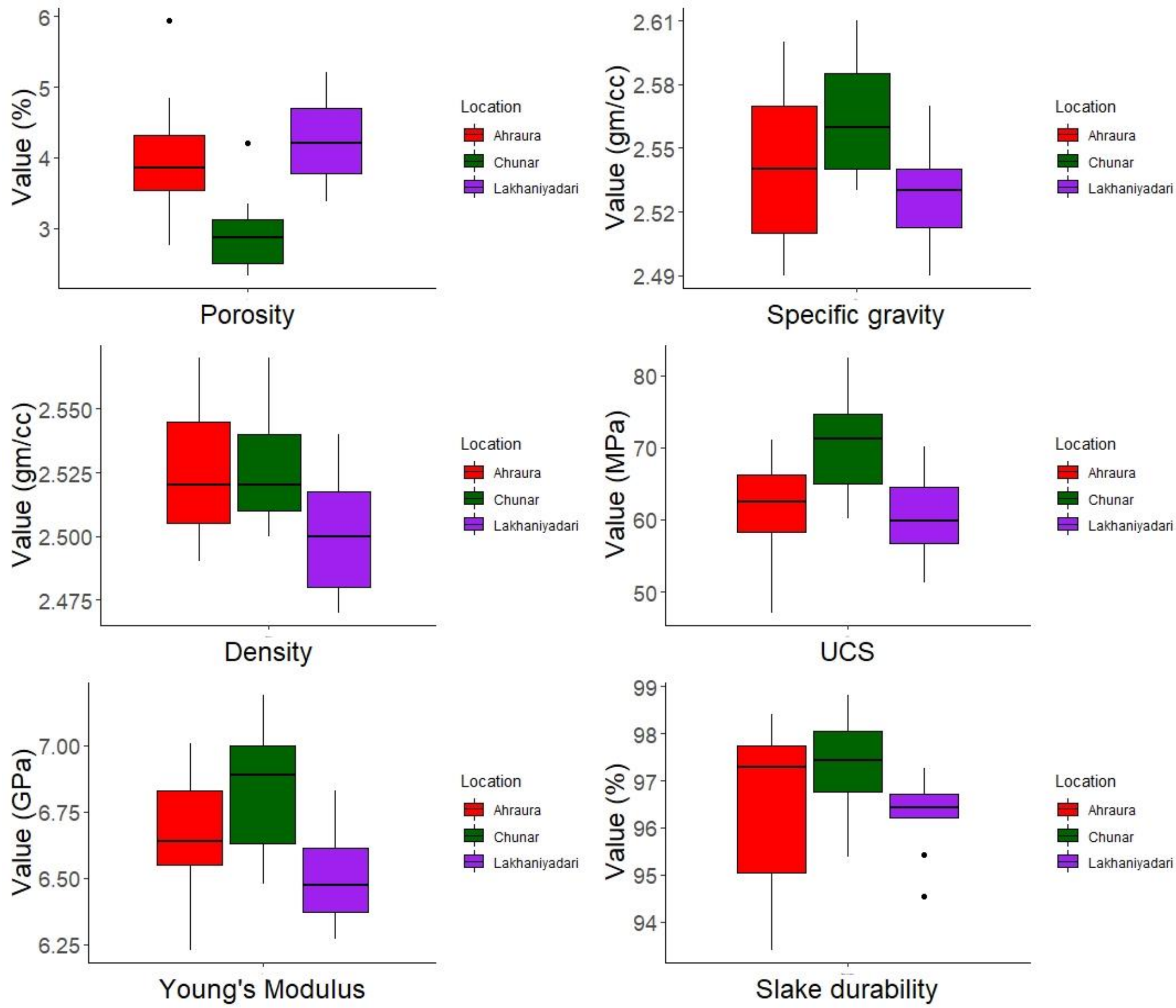

Fig. 4. Statistical representation of physical and mechanical parameters

Young's modulus (E) is ratio of stress to strain. The variation of stress with strain was calibrated using strain gauge (Eq. 6).

$$\boldsymbol{E} = \frac{\boldsymbol{Stress}}{\boldsymbol{Strain}} \qquad (9)$$

The matrix of the rock samples was determined from the following relation given in Eq. 10 (Jeng et al., 2004). Total 10 samples from Lakhaniya Dari location, 11 samples from Chunar, and 11 samples from Ahraura locality in Mirzapur district were tested for each physical and mechanical property test. Statistical data of test results is shown in Table 2.

$$GAR + Porosity + Matrix = 100\% \qquad (10)$$

IV. Statistical Analysis

Simple linear analysis has been conducted to know the correlation of petrographical properties (GAR, PD and FF) with physico-mechanical constants (n, G_s, UCS, E). The impact of petrographical parameters on physical and mechanical properties was analyzed through simple linear regression model. Simple linear model describes the dependent variable as a function of an independent variable through straight line equation (Eq. 11) (Montgomery et al. 1982).

$$y = \alpha_0 + \alpha_1 x + \in (11)$$

Where y is dependent variable or output variable, x is independent variable, α_0 is intercept, α_1 is slope of line and ϵ is error.

Correlation matrix has been shown to know the strength of correlation and its direction whether it's positive or negative (Fig. 5). In the matrix, orange colour is used for positive correlation and blue is used for negative correlation. All the statistical analysis is done using R programming software (R core team, 2021).

Initially, null hypothesis was assumed that there is no relation between petrographical parameters and physico-mechanical properties of rocks. Slope of regression line defines y is function of α_1, its value within confidence interval of 95% should be zero if the null hypothesisis true and p-value should be less than 0.05.Since, p-value for the tested parameters is less than 0.05 and the value of α_1 is non zero within confidence interval of

95%, we can reject the null hypothesis and it can be established that correlation between the tested parameters statistically significant.

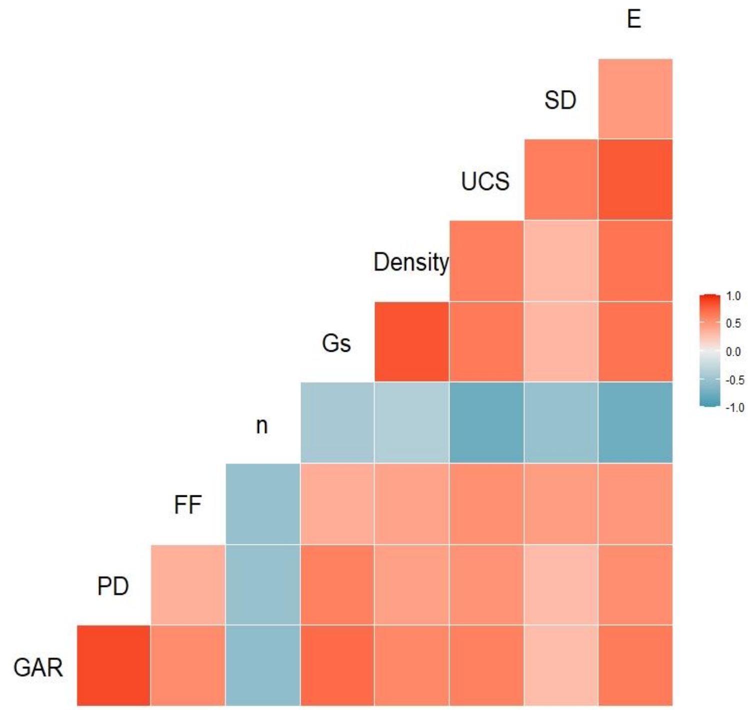

Fig. 5. Correlation matrix with blue colour for negative and orange colour for positive correlation coefficient

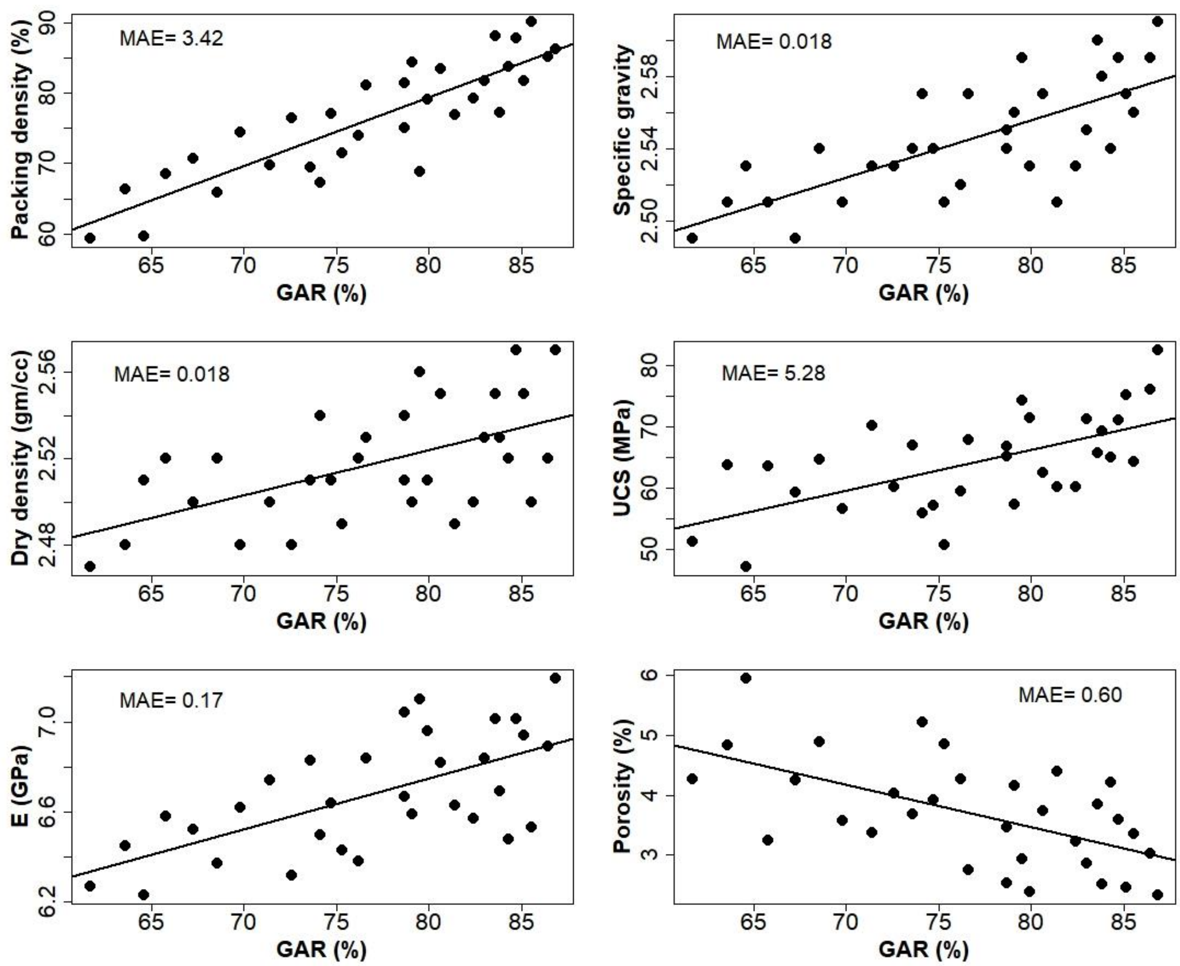

Fig. 6. Linear Regression analysis of different parameters with GAR

The model fit of regression model was tested with Mean absolute error (MAE) value and residual standard error of the equation (Fig. 6). MAE is the absolute difference between predicted value and actual value of independent variable. The residual standard error describes the undefined proportion of independent variable byregression model.

relationship and their variation with physico-mechanical properties of rocks.

Statistical analysis was performed to find the correlation between petrographical characteristics of the rocks and their physical & mechanical properties. The values of Pearson's*r* were positive for for all except porosity (Fig. 7). The results show that

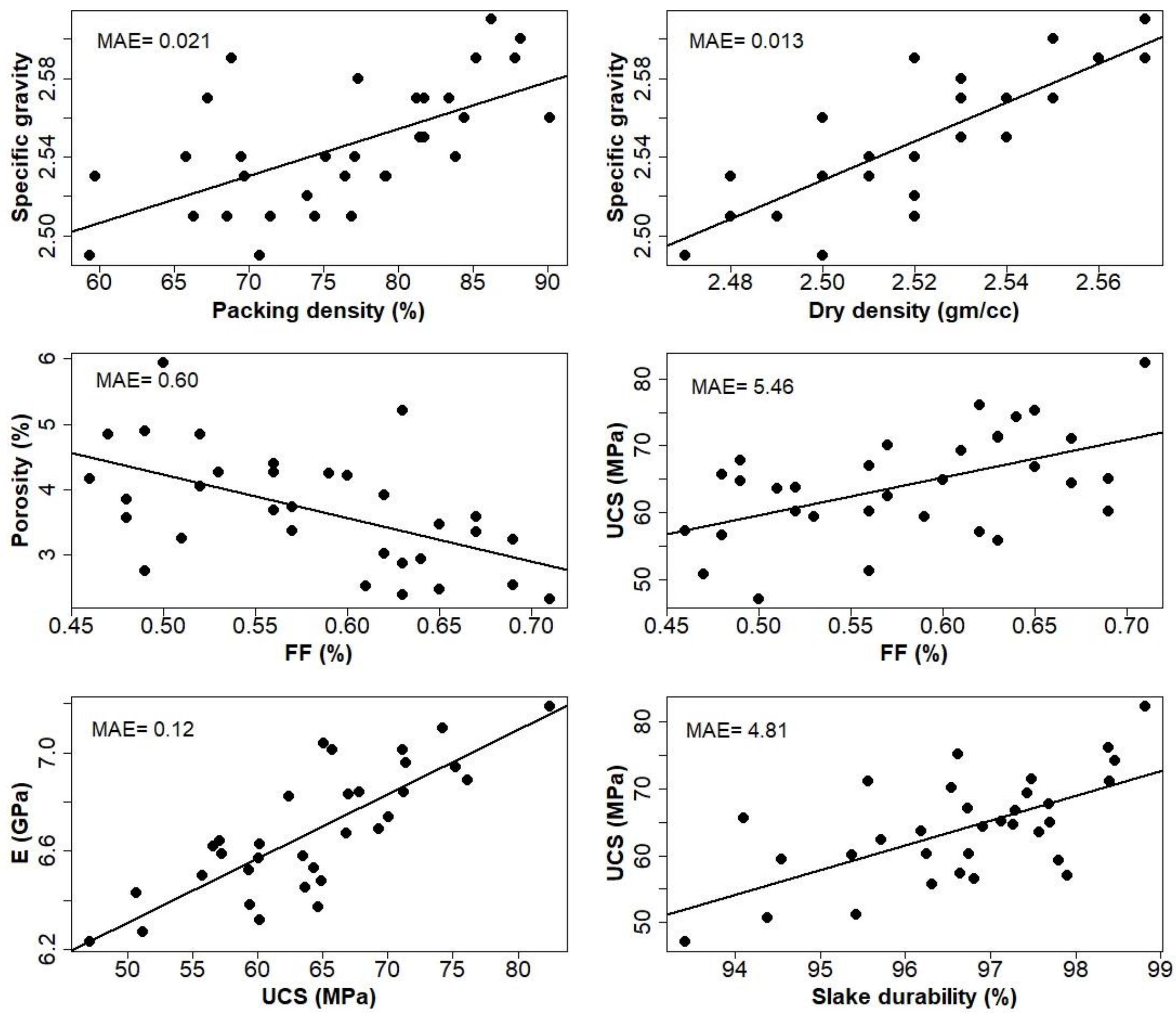

Fig. 7.Linear regression analysis between different parameters

V. RESULT AND DISCUSSION

The sandstone samples near Chunar region were studied under the microscope and modal composition of the rocks was determined through petrography. Afterwards, the laboratory tests were performed to determine their respective physico-mechanical properties. The modal composition study shows that rocks are enriched in quartz content and other components are in small quantity. The grain boundaries are subangular to subrounded which indicates that degree of transportation was moderate to higher. Geometrical parameters of mineral grains such as Grain area ratio (GAR), Packing density (PD) and Form factor (FF) were also determined to know inter-grain

parameters PD & GAR, Gs & GAR, Gs & ρ_d and E & UCS are strongly positively correlated.

Packing density and Grain area ratio both are functions of mineral grains percent in the rock. Therefore, PD & GAR are showing good positive correlation. Higher Grain area ratio refers predominance of mineral grains and lesser area occupied by pores, both resulting as increase in the unit weight of rock. Therefore, GAR has showed negative correlation with porosity and positive with specific gravity & density. Uniaxial compressive strength is a function of multiple factors including amount of mineral grains present, their composition, the kind of inter-granular bonding they are sharing, amount of pore spaces and degree of pore water pressure. UCS values have increased

Table 3. Predicted equations from present work

Parameters	Predicted equation	*r*	P-value	Standard error
PD and GAR	$\boldsymbol{PD = 0.98GAR + 1.31}$	0.87	'***'	4.140
Gs and GAR	$\boldsymbol{G_s = 0.003GAR + 2.30}$	0.72	'***'	0.022
ρ_d and GAR	$\boldsymbol{\rho_d = 0.002GAR + 2.36}$	0.57	'***'	0.022
UCS and GAR	$\boldsymbol{UCS = 0.66GAR + 13.34}$	0.62	'***'	6.300
E and GAR	$\boldsymbol{E = 0.022GAR + 4.96}$	0.63	'***'	0.200
n and GAR	$\boldsymbol{n = -0.071GAR + 9.14}$	0.57	'*** '	0.740
Gs and PD	$\boldsymbol{G_s = 0.002PD + 2.36}$	0.62	'***'	0.026
Gs and ρ_d	$\boldsymbol{G_s = 0.99\rho_d + 0.06}$	0.82	'***'	0.019
n and FF	$\boldsymbol{n = -6.61FF + 7.53}$	0.55	'**'	0.759
UCS and FF	$\boldsymbol{\sigma_c = 56.71FF + 31.22}$	0.53	'**'	6.744
E and UCS	$\boldsymbol{E = 0.026\sigma_c + 5.01}$	0.80	'***'	0.157
UCS & I_{d2}	$\boldsymbol{\sigma_c = 3.70I_{d2} - 293.32}$	0.62	'***'	6.211

with rise in GAR as GAR is function of mineral grains present in the rock.

Pearson's *r*value of correlation between packing density and grain area ratio is 0.87, with *p-value* less than 0.001, shows a significant correlation. The correlation between specific gravity and grain area ratio has *r* value 0.72 which is highly significant. Similar relation between PD & GAR has been established with *r*value of 0.56 for Tertiary sandstone Taiwan (Jeng et al., 2004). The present relation for Vindhyan sandstones is highly significant

with better *r* value. The correlation between dry density and grain area ratio is found good with *r* 0.57. Similar positive correlation was published for Paleocene sandstone with *r* 0.43 (Nespereira et al., 2010). The correlation between UCS and GAR have *r* 0.62. The similar correlation for Tertiary sandstone had *r* 0.75 (Jeng et al., 2004). The correlation between E and GAR is highly significant with *r* 0.63 and *p-value* with '***'.

Conclusion

Petrographical characteristics of rocks have strong influence on their mechanical properties. Kaimur sandstones are enriched in quartz content, therefore are highly resistant to weathering and have extremely high slake durability index. Simple linear regression is used to establish the correlation between the petrographical parameters and physico-mechanical constants. Statistically significant correlations have been established between Packing density and grain area ratio, Specific gravity and GAR, specific gravity and packing density.

The results depict high strength and lower water absorption potential making them quite valuable for construction purpose. The prediction equations have been given in the table 3. These equation models can be useful in forecasting the strength parameters and elastic constants of Proterozoic sandstonesand Eastern Vindhyan rocksto use as building materials, estimating load bearing capacity andfor preparing the design for underground structures.

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