Chemical, Mineralogical, Geological and Physical Properties of Sandstones

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Abstract

The sedimentary are commonly encountered during various civil, mining, tunneling, activities and oil and gas exploration activities. three principal sedimentary rocks viz. Sandstones, limestones and shales constitute over 80% of all sedimentary rocks. The chemical, mineralogical, geological and microscopic properties of rocks plays an important and dominant role in their behavior and response under varying stress conditions and environmental surroundings. This paper presents experimental studies on 8 sandstones from central part of India pertaining to their chemical, mineralogical, geological and microscopic properties experimentally determined. The paper also analyses the interrelation among various properties and their influence on behavior and response of these rocks under varying stress and environmental conditions.

Keywords: Chemical Properties, Mineralogical Properties, X-ray Diffraction, Scanning Electron Microscopy, porosity

1. Introduction

The sedimentary rocks are commonly encountered during various civil, mining and tunnelling engineering construction activities. In terms of area of coverage, they constitute about 75% of all rocks. Further the three principal sedimentary rocks viz. sandstone, limestone and shale account for above 80% of all sedimentary rocks as reported by Pettijohn (1984) and are extensively encountered during various mining, tunneling, civil engineering activities and oil and gas exploration activities. In a coalmine sandstones and shales are encountered as alternate layers referred as seams.

The various factors affecting rock behavior are presented in Table 1. As can be seen from this table that various geological factors such as geological age and weathering and other alterations and lithological factors such as mineral composition, cementing material, grain size, texture, fabric, anisotropy etc. significantly influence the response or rocks to varying loading conditions and surrounding environmental conditions. Geological factors like age of formation, weathering and alterations affect strength and deformational behaviour of rocks. For the sedimentary rocks, which are derived through the secondary processes, the age of their formation influences their engineering behaviour.

Sandstones occur prominently in India. They are extensively encountered during various mining, tunnelling and civil engineering, construction activities. Sandstones exhibit several verities of structure and texture and are considered· as problematic rocks due to large variations in their physical and geotechnical properties basically due to its varying chemical and mineralogical composition and formation.

Table 1: Factors Affecting Rock Behaviour

Geological	Lithological	Physical	Mechanical	Environmental
Geological age Weathering Other alterations	Mineral Composition Cementing material Grain size Texture Fabric Anisotropy	Specific gravity Unit weight Porosity Void index	Sampling technique Specimen preparation Specimen geometry and size End contacts and constraints Rate of loading	Confining conditions Moisture content Relative humidity Nature of pore fluid pH value and dielectric constant Temperature

2. Literature Review

The present study concentrates on two main factors namely geological and lithological factors.

2.1 Geological Factors

Vutukuri et. al. (1974) reported a band of linear increase in age of the rock with void index on semi-log plot for sandstones, shale and other argillaceous rocks. With age, the increasing overburden pressure due to further deposition of layers results in denser grain packing, resulting an increase in density and a decrease in void index and porosity of rock formation. The increase in density and decrease in voids leads to increase in strength of rocks. Hoshino et al. (1972) studied the tertiary sedimentary rocks of Japan and observed increase in strength with geological age. The increase in strength thus noticed was highest for argillaceous rocks (shales, siltstones), medium for arenaceous rocks (sandstones), and least for pyroclastic rocks (tuffs). It is well established that the weathering decreases the competency of the rock. A number of investigators (Bell, 1992; Gupta, 1997 and others) noticed that weathering reduces strength and increases deformation, porosity and permeability.

2.2 Lithological Factors

The lithological factors like texture, mineralogical composition, cementing material etc. significantly influences the engineering behaviour of rocks. The texture deals with the microgeometry of the rock e. g. size, shape, interlocking and mutual arrangement of various mineral components etc. in the rock. Most of the sedimentary rocks consist of transported grains and cementing material, which binds them together. Thus, the strength behaviour of sedimentary rocks in general is a function of the strength of individual constituent grains and extent of their cementation. Some researchers tried to explain strength changes in rocks in terms of their mineralogical composition. Price (1960) studied number of coal measures rocks (quartz calcite, sandstone, quartz clay and siltstones) and observed that the compressive strength was directly proportional to their quartz content.

The amount and type of cementing material, influences not only the physical properties but also strength and elastic properties. Generally siliceous and ferruginous cementing material impart more strength than the other types (argillaceous, carbonaceous, calcareous etc.) cements. Significant increase in porosity with an increase of cement was observed by Bell (1978) for Fell sandstones. Subash babu et al. (1977) reported decrease in compressive strength with increase in amount of cement for Singrauli sandstones.

3. Experimental Investigation

The block rock samples for present study were collected from various places from three States of central India with three locations each from Madhya Pradesh and Uttar Pradesh and from two locations from state of Rajasthan. The Table 2 presents the details of locations of these rocks. For brevity, they are referred 3 letter symbols with first indicating it place of collection, second letter indicating the district and the third letter indicating the state. For example, AKR Sandstone implies that it is a sandstone collected from Aroli village in Kota district of state of Rajasthan.

Table 2: Location of Sandstones Samples collected

Sr. No.	Sandstone collection Location			Latitude	Longitude	Symbol adopted
	Village	District	State			
1	Aroli	Kota	Rajasthan	$25.5N^0$	$75.1E^0$	AKR
2	Bari	Lalitpur	Uttar Pradesh	$24.7N^0$	$78.2E^0$	BLU
3	Banmor	Morena	Madhya Pradesh	$26.3N^0$	$78.1E^0$	BMM
4	Dudichua	Sonebhadra	Uttar Pradesh	$24.5N^0$	$82.5E^0$	DSU
5	Ghatgaon	Gwalior	Madhya Pradesh	$26.1N^0$	$77.9E^0$	GGM
6	Malanpur	Bhind	Madhya Pradesh	$26.2N^0$	$78.2E^0$	MBM
7	Savla	Agra	Uttar Pradesh	$27.6N^0$	$77.5E^0$	SAU
8	Sirmuttra	Dholpur	Rajasthan	$26.5N^0$	$77.3E^0$	SDR

An elaborate experimental investigation programme was planned and conducted to determine various mineralogical and chemical and physical properties. The physical characteristics were assessed both at microscopic and macroscopic level.

In order to identify the rock forming constituents, the studies pertaining to mineralogy, petrography and chemical analysis of the rocks are very much essential. Keeping this in view various tests/studies such as X- ray diffraction analysis, the studies of thin sections under microscope at magnification of x20, scanning electron microscopy and chemical analysis was conducted following conventional and standard procedure and are described in brief herein.

3.1 Chemical Composition

The conventional titration method of rock/mineral analysis was used for the estimation of major and trace elements. Through these various elements namely Silica (SiO_2), Alumina (Al_2O_3), Iron Oxide (Fe_2O_3), Titanium Oxide (TiO_2), Calcium Oxide (CaO) and Magnesium Oxide (MgO) were estimated. The loss on ignition was determined by heating the powder sample in the furnace at 1400^0c for more than an hour.

3.2 Mineralogical and Petrographical Analysis

In order to identify the rock forming constituents, the studies pertaining to mineralogy, petrography and chemical analysis of the rocks are very much essential. Keeping this in view following tests/studies have been conducted on representative rock samples.

3.3 X- ray diffraction analysis

The powder method was adopted to obtain x-ray diffractograms (whole-rock analysis) of these rock samples. For this purpose, an advanced X-ray diffraction (XRD) instrument model GEIGERFLEX D/max-B, make Rigaku, Japan with Cukα (1.54Å) radiation was used. The representative rock samples were reduced to 10 μm powder by careful grinding. The partly oriented sample-mounts were prepared by smearing the acetone-powder paste on the sample holder. Each sample was scanned for diffraction angle (2θ) from 8^0 to 80^0 in the above mentioned XRD instrument to obtain x-ray diffractograms. The peaks of different minerals on diffractograms were identified using data cards published by JCPDS (1988) and other related references.

3.4 Microscopic study

The basic tool for the study of mineralogy and petrography is visual observations of thin sections under microscope. The thin sections of all these 8 rock types required for microscopic study, were prepared by adopting Beuler Petro-Thin section cutting system. The studies of these thin sections were carried out under Zeiss microscope at magnification of x20.

3.5 Scanning electron microscopy

Scanning electron microscopy is extremely useful tool to study the samples under very high magnifications. In the present study, the rock samples in the form of small chips were mounted on a stub after ultrasound cleaning, vacuum-heating and coating with a conducting material. These samples were studied under a highly sophisticated Scanning Electron Microscope (Cambridge Instrument Stereo scan 360, model S360) at magnifications as high as x3500.

3.6 Physical Properties

The macroscopic physical properties such as specific gravity, dry & saturated unit weights, effective & total porosities (n_e and n_t) and water absorption (w_s) have been determined in the laboratory for all the sandstones following the procedure as per ISRM as described by Brown et. al. (1982). The specific gravity was determined by conducting minimum 5 tests on each rock type until reproducible results were obtained. The tests to determine unit weights, porosities, degree of saturation have been conducted on all the specimens of both the rock types. In addition, effective water evaporation index (I_{we}) is determined following procedure reported by Gokhale (1999).

4. Result and Discussion

The typical experimental data are presented and analyzed so as to assess geological, chemical and microscopic characteristics and its interrelation and or influence on physical properties which affect the strength and deformation behavior of rocks.

4.1 Geological Formation

The samples of sandstones studied in the present investigation were collected from different geological formations in central India. The geological formation details of these sandstones are illustrated in Table 3. It can be seen from this table that except MBM other 7 sandstones belong to geological Upper Proterozoic geological age group (550-1000 million-year-old). Whereas, MBM belongs to Middle Proterozoic geological age group (1000-1500 million-year-old). As far as stratigraphic unit is concerned, except DSU which belongs to Gondwana sequence, remaining 7 sandstones belong to Vindhyan super group. As far as sub stratigraphic unit is concerned 3 sandstone namely AKR, SAU and SDR belong to Bhander sub group, 3 sandstones namely BMM, BLU and GGM belong to Rewa sub group and remaining two sandstones namely MBM and DSU belong to Gwalior sub group and Talchir sub group.

Table 3: Geological Formation Details of Sandstones Studied

Sl. No.	Sandstone Symbol	Geological age	Stratigraphic unit	Stratigraphic sub unit
1	AKR	Upper Proterozoic	Vindhyan Super Group	Bhander Group
2	BLU	Upper Proterozoic	Vindhyan Super Group	Rewa Group
3	BMM	Upper Proterozoic	Vindhyan Super Group	Rewa Group
4	DSU	Upper Proterozoic	Gondwana Sequence	Talchir Formation
5	GGM	Upper Proterozoic	Vindhyan Super Group	Rewa Group
6	MBM	Middle Proterozoic	Vindhyan Super Group	Gwalior Group
7	SAU	Upper Proterozoic	Vindhyan Super Group	Bhander Group
8	SDR	Upper Proterozoic	Vindhyan Super Group	Bhander Group

4.2 Chemical Composition

The results of chemical analysis are presented in Table 4. It can be observed from the data presented in this table that the main chemical Constituent SiO_2 for sandstones studied falls in very narrow range of 86.42% to 92.22% except for DSU for which value is 52.10%. Similarly, the second main constituent Al_2O_3 is also observed to be less than 10% except for DSU which has a value of over 30%. Here it may be noted that DSU belongs is only sandstone which belong to Gondwana Stratigraphic unit while remaining 7 sandstone belong to Vindhyan Super Group. Further while loss on ignition (LOI) for 7 sandstone is observed to be very low (below 2%), for DSU it has a high value of 11.52%. Here it is pertinent to note that DSU belongs to a coalmine area.

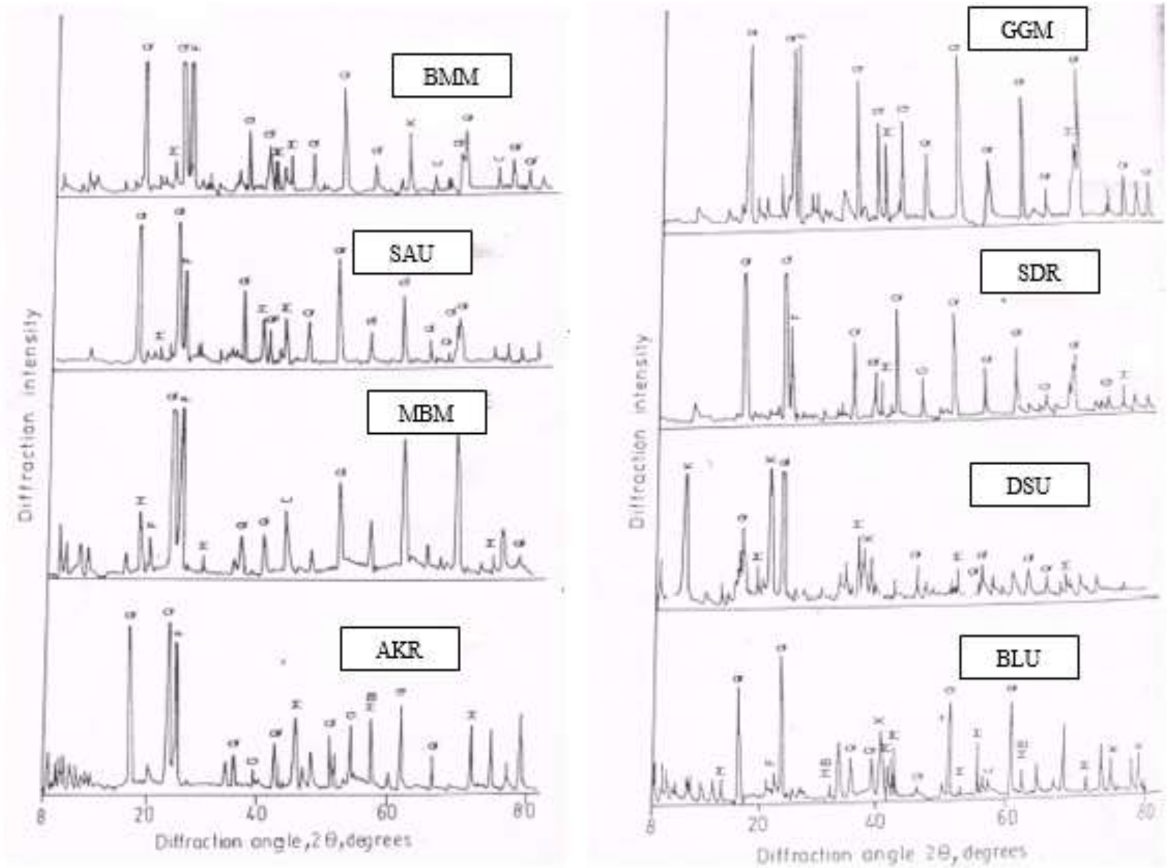
Table 4: Chemical Analysis Results Sandstones Studied

Type of Sandstone	Chemical Constituents, %						
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	LOI
AKR	88.00	7.44	0.84	0.40	0.56	1.00	0.92
BLU	88.48	8.62	0.56	0.16	Trace	Trace	1.04
BMM	92.22	2.72	0.98	0.16	0.28	0.42	0.68
DSU	52.10	33.16	1.70	0.48	0.28	Trace	11.52
GGM	86.42	7.85	1.27	....	0.84	0.20	1.64
MBM	91.26	4.90	0.42	0.40	0.56	0.60	0.88
SAU	92.58	1.02	2.38	0.32	0.28	0.42	0.70
SDR	87.92	7.79	1.13	....	0.84	0.20	0.98

4.3 Petrographical and Mineralogical

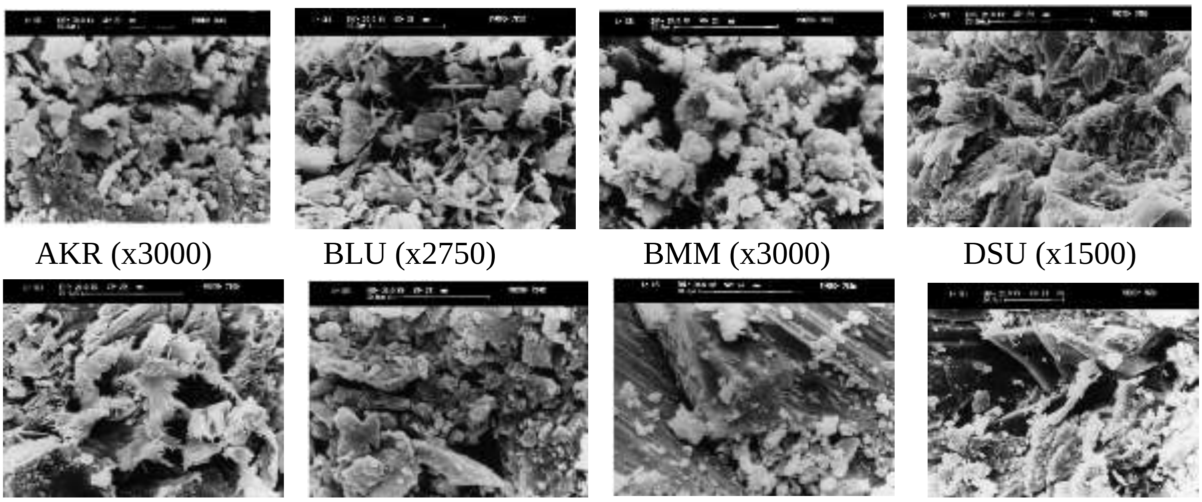
The petrographical and mineralogical studies were conducted using petrographical microscopy (PM) of thin sections, x-ray diffraction (XRD) and scanning electron microscopy (SEM). The x-ray diffractograms of the sandstones studied obtained are presented in Figure

1. Various minerals observed to be present and identified are also indicated therein. The scanning electron micrographs obtained through SEM are these 8 sandstones reproduced in Figure 2. While 4 sandstones namely AKR, MBM, SAU and BMM provided clarity at magnification of X3000, BLU provided it at X2750, DSU and GSS at X1500 and SDR at X900.



(Q=Quartz, C=Calcite, H=Hematite, F=Feldspar, K=Kaolinite, HB=Hornblende, M=Mica, G=Geothite, MO=Montmorillionite)

Fig. 1. X-ray diffractograms of the sandstones studied



AKR (x3000) BLU (x2750) BMM (x3000) DSU (x1500)

GGM (x1500) MBM (x3000) SAU (x3000) SDR (x900)

Fig. 2. Scanning Electron Micrographs for Shales studied

The dominant mineral present in each rock type identified on the basis of these studies and its approximate percentage (obtained through petrographic study) is presented in Table 5. It can be observed from the data given in this table that for all 8 sandstones the Quartz (Q) is most predominant mineral, which is quite obvious. The second dominant mineral is observed to be Feldspar (F) in 4 sandstones, followed by Kaolinite (K) in 3 sandstones and Mica (M) in one sandstone and third dominant mineral is observed to be Mica (M) in 5 sandstones, followed by Kaolinite (K), Feldspar (F) and Hornblende (H) in 1 sandstone each. A close scrutiny indicates that mineral Hornblende (H) is present only in one sandstone namely BLU and that too as third dominant mineral.

Table 5: Predominant Minerals observed for Sandstones Studied

Sl. No.	Sandstone Symbol	Three Prominent Minerals observed
1	AKR	Q: Quartz, F: Feldspar, M: Mica
2	BLU	Q: Quartz, F: Feldspar H: Hornblende,
3	BMM	Q: Quartz, F: Feldspar, M: Mica
4	DSU	Q: Quartz, K: Kaolinite, F: Feldspar,
5	GGM	Q: Quartz, M: Mica, K: Kaolinite
6	MBM	Q: Quartz, K: Kaolinite, M: Mica
7	SAU	Q: Quartz, F: Feldspar, M: Mica
8	SDR	Q: Quartz, K: Kaolinite, M: Mica

Based on studies of scanning electron micrographs, x-ray diffractograms and thin sections brief description of these sandstone is presented below.

AKR: The colour of this rock is variegated shades of red or buff, mottled or speckled owing to the variable dissemination of the colouring matter or its removal by de-oxidation. The SEM and PM studies indicate that this rock mainly consists of moderately sorted, well-cemented, fine to medium, rounded to sub-rounded sand grains with moderate packing. The XRD shows predominance of quartz. It contains around 85% of quartz and the presence of feldspar, mica, hornblende and iron oxides are also identified. The void spaces appear to be filled up with secondary minerals. It also shows high relief with red colour, which may be due to altered clay minerals. The cementing matrix is observed to be of ferruginous nature with traces of siliceous materials.

BLU: This rock of moderately sorted, loosely packed, rounded to sub-rounded coarse to medium sand grains exhibits pale white colour. The grains are cemented together with siliceous and argillaceous cementing material. It has unconsolidated rock fragments too. The rock shows convex-concave grain contact boundaries at few places whereas boundaries not so clear at some other places. Sutured boundaries with larger void space are also observed. The rock contains around 78% quartz, 5% mica and 8% feldspar. It also shows presence of hornblende and variety of clay minerals.

BMM: The light green-brown colour sandstone contains fine to coarse; sub-rounded to angular closely packed sand grains cemented together with calcareous and siliceous cementing material. At some places, smaller grains are preferred in one direction. In this rock of high matrix, smaller grains are occupying the space between larger grains. This rock which contains about 89% of quartz shows presence of cleavage in feldspar and its alteration. The alteration of mica to sericite in small amount has also been noticed in this rock. The rock minerals like kaolinite, hornblende, calcite along with some opaque minerals are present in this rock.

DSU: This dull white coloured sandstone with some black fine speckled contains very coarse, rounded to angular, poorly sorted sand grains. The cementing material is observed to be argillaceous in nature. The clay matrix present in high proportion mostly contains kaolinite. The rock contains around 40% of quartz and 50% of kaolinite. The presence of mica and feldspar has also been noticed in this rock. The separated grains and frequently floating contact between grains leads to higher porosity. A few of the grains are observed in the broken state.

GGM: This mud-coloured rock contains moderately to closely packed medium to fine, rounded to sub-rounded sand grains cemented together with siliceous and ferruginous cementing materials. The presence of mica, feldspar and opaque minerals is also noticed. The fine grains are observed to occupy void space between medium size grains.

MBM: The studies show that, this earthy white to dull colour rock contains moderately sorted angular to sub-angular fine grains cemented together with siliceous cementing material. In this moderately packed rock, the void spaces are filled up with fine rock fragments and clay matrix. The presence of detrital rock fragments has also been noticed. The rock contains around 88% of quartz. The minerals like mica, feldspar, hornblende is also present in this rock. It also shows presence of opaque minerals.

SAU: This red buff colour (with white speckled) rock consists of well sorted, closely packed, mixture of angular, sub-rounded and rounded fine sand grains cemented together by ferruginous cementing material. It shows cluster of grains with some elongated grains. The rock contains mostly quartz (around 91%) and rock minerals such as feldspar, hornblende, mica, hematite and opaque minerals are also present. Probably alteration of feldspar material imparts white speckled appearance to this rock.

SAR: The colour of this sandstone is light yellow with red-grey speckled. It contains moderately sorted and packed, medium to fine grains of sand particles. These grains are cemented together mainly with ferruginous material. The traces of argillaceous cementing material have also been noticed in this sandstone. This rock containing around 75% of quartz also shows presence of feldspar, mica, calcite and opaque minerals. Some overgrowth and elongated grains have also been noticed in this sandstone.

4.4 Physical Properties

The experimentally determined values of various physical properties viz. specific gravity (G), dry unit weight (γ_{dry}), saturated unit weight (γ_{sat}), total porosity (n_t), effective porosity (n_e) and water absorption (w_s), void index (I_v), second cycle slake durability index (I_{sd2}) and water evaporation index (I_{we}) for the rocks studied are presented reported in Table 6. The table 6 also presents effective degree of saturation (S_{re}) obtained as (n_e/n_t) x100.

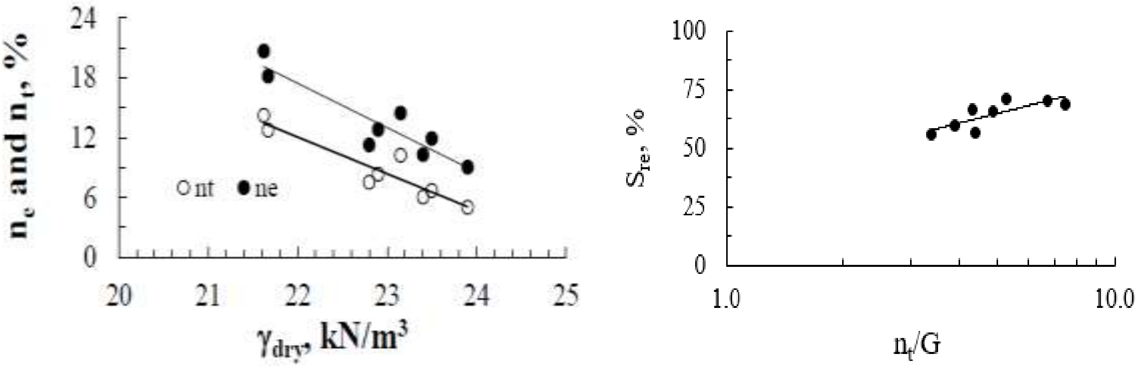
Table 6: Physical Properties of Sandstones Studied

Rock Type	G	γ_{dry}	γ_{sat}	n_t	n_e	w_s	I_v	I_{sd2}	I_{we}	s_{re}
		KN/m^3	KN/m^3	%	%	%	%	%	%	%
AKR	2.63	22.90	23.27	8.36	12.83	3.64	2.98	99.15	1.13	65.65
BLU	2.70	21.67	22.92	12.77	18.19	5.78	4.08	98.22	2.19	70.22
BMM	2.68	23.90	24.40	5.03	9.06	2.06	1.71	98.36	0.63	55.90
DSU	2.78	21.62	23.01	14.25	20.71	6.46	6.21	74.74	2.50	68.78
GGM	2.72	23.50	24.16	6.70	11.93	2.81	2.00	98.43	0.97	56.38
MBM	2.62	22.80	23.53	7.54	11.28	3.21	2.51	99.52	1.19	66.37
SAU	2.66	23.40	24.00	6.07	10.31	2.54	1.59	99.20	0.73	59.17
SDR	2.76	23.15	24.16	10.25	14.48	4.35	3.40	97.68	1.41	70.91

It can be observed from the data given in Table 6 that while values of G, γ_{dry} and γ_{sat} and I_{sd2} Vary within a narrow range, the values of other properties very in moderate to high range. For illustration n_t ranges from 6.07% for SAU to 14.25% (almost 2.35 times) for DSU. Further values of n_e are observed to be 1.4 (for SDR) to 1.8 (for BMM) times higher that of n_t. Conversely the values of S_{re} ranges from a low of 55.90% for BMM to a high of 70.91% for SDR. The values of I_{we} are observed to ranges from a low 0.63% for BMM to a high of 2.5% for DSU.

4.5 Interrelationships

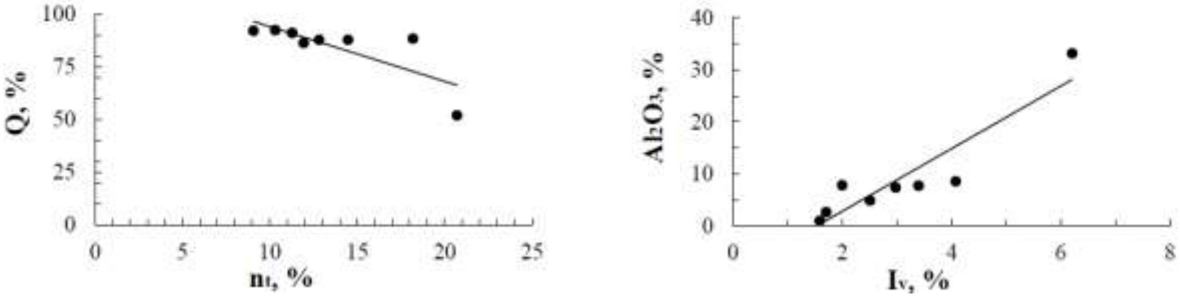
In order to investigate interdependence regression analysis of data was carried out. While Figure 3 (a) presents variation of effective porosity (n_e) and total porosity (n_t) with dry unit weight (γ_{dry}), Figure 3 (b) presents variation of effective degree of saturation (S_{re}) with ration of total porosity (n_t) and specific gravity (G).



(a) Variation on n_t and n_e with γ_{rdy} **(b) Variation of S_{re} with n_t/G**

Fig. 3. Interalationship between physical properties

In order to investigate influence of physical properties on rock forming minerals regression analysis of data was carried out with reference to two predominant minerals found in the sandstones studied. While Figure 4 (a) presents interrelation of quartz (Q) with total porosity (n_t), Figure 3 (b) presents interrelation between Alumina Oxide (Al_2O_3) with void index (I_v).



(a) Interrelation of Q with n_t **(b) Interrelation of Al_2O_3 with Iv**

Fig. 4. Influence of Physical Properties on Rock forming Minerals

It can be clearly delineated from Figure 3 that rock forming minerals have significant dependence on their physical properties. While with increase in porosity magnitude of main mineral quartz decreases on the other hand magnitude of second main mineral namely alumina oxide increases with increase in void index.

5. Conclusions

This paper presents experimental studies on 8 sandstones from central part of India pertaining to their chemical, mineralogical, geological and microscopic properties experimentally determined. The paper also analyses the interrelation among various properties and their influence on behavior and response of these rocks under varying stress and environmental conditions. The major conclusions arrived at are

(i) Geological 7 out of 8 sandstones studied belong to Upper Proterozoic geological age group and one sandstone (MBM) to Middle Proterozoic geological age group.

(ii) In terms of stratigraphic unit, except one sandstone (DSU) which belongs to Gondwana sequence, remaining 7 sandstones belong to Vindhyan super group. As far as sub stratigraphic unit is concerned 3 sandstone namely AKR, SAU and SDR belong to Bhander sub group, 3 sandstones namely BMM, BLU and GGM belong to Rewa sub group and remaining two sandstones namely MBM and DSU belong to Gwalior sub group and Talchir sub group respectively

(iii) The main chemical constituent for the sandstone is silica followed by alumina. The silica is observed to be above 85% except for DSU for which value is 52.10%. The he second main constituent alumina observed to be less than 10% except for DSU which has a value of over 30%. Here it may be noted that DSU is only sandstone which belong to Gondwana Stratigraphic unit while remaining 7 sandstone belong to Vindhyan Super Group.

(iv) Further while loss on ignition for 7 sandstone is observed to be less than 2%, for DSU it has a high value of 11.52%. Here it is pertinent to note that DSU belongs to a coalmine area.

(v) For the sandstones studied the quartz is primary mineral followed by two of the three minerals namely feldspar, kaolinite, mica, or hornblende.

(vi) The sandstones studied are observed to be moderately porous with total porosity ranging from 6% to 15%. The physical properties show fair interrelationship for example decrease in porosity with increase in unit weight and increase in effective degree of saturation with increase in ratio of total porosity and specific gravity.

(vii) Physical properties and rock forming minerals show significant interdependence. While with increase in porosity magnitude of main mineral quartz decreases on the other hand magnitude of second main mineral namely alumina oxide increases with increase in void index.

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