EFFECT OF WEATHERING ON STRENGTH AND DEFORMATION OF SEDIMENTARY ROCK

A DESSERTATION

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS

FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY

IN

GEOTECHNICAL ENGINEERING

Submitted by: -

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CANDIDATE'S DECLARATION

I, Mohd Anas, 2K17/GTE/12 of M.Tech (Geotechnical Engineering), hereby declare that the major project titled "Effect of Weathering on Strength and Deformation of Sedimentary rock" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original -and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associate ship, Fellowship or other similar title or recognition.

Anas.

Place: Delhi (MOHD ANAS)

Date: 01/09/2020

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CERTIFICATE

I hereby certify that the minor project titled " Effect of Weathering on Strength and Deformation of Sedimentary rock " which is submitted by Mohd Anas, 2K17/GTE/12 (Civil Engineering Department) Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the him under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi — Prof. A. K. Srivastava

Date:31/08/2020 — (SUPERVISOR)

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Abstract Weathering is a natural process in all type of igneous, sedimentary and metamorphic rock occurring more than great many years under fluctuated ecological conditions. Weathering can be physical, chemical or biological in various natural conditions in gentle to outrageous environmental factors. Sedimentary rocks are itself formed by erosion, weathering followed by lithification of pre-existing rocks and modifies its physical and chemical properties. Further weathering in sedimentary rock, physical or chemical alter its composition and effect the strength and chemical properties of the rock, thus laboratory-based tests are carried out to know about the soundness of rock. This study is principally credited to examine the strength of sedimentary rock simulating sea condition and its impact on the strength of the rock because of variation in salinity of sea water, along these lines it could help in evaluating the strength which would be valuable in different applications, for example in deep drilling aquifers for extraction of oil and gases.

This investigation in this way plans to perform tests on sedimentary rocks of Vindhyan range extending close to Kota city and study the uniaxial unconfined compressive strength test with changing concentrations of the saltiness levels (10%, 20%, 30%) of NaCl arrangement with time variation. The tests were performed in time gaps for example after 30, 60, 90 and 300 days to check the impact of time and salinity on quality of the stone in the research work. In spite of the fact that it is hard to make a similar level of confinement and pressure conditions, efforts were made to simulate sea-salt weathering conditions by putting the rock samples in cannisters of saline solution arrangement of 10%, 20% and 30% for long timespans.

1. Introduction

1.1 General

The study presents research work based exploratory examinations in the rock mechanics area with an emphasis on the effect of weathering and sea-salinity on the strength and deformation of sedimentary rock. Sedimentary rocks exposed in high saline sea environment are affected causing decrease in strength due to chemical weathering of the rock mass over the time. Some of the applications like deep drilling in bed rocks are required for extraction of oil and gases from their reservoir beds below sedimentary rock layers for which the layers are drilled in-situ to reach the underlying beds. Thus, extensive information about the mechanical practices of rock materials in sub-fluidly profound well boring applications is compulsory for the exact estimation of the stress and deformation. The presence of salinity because of sea water in the sedimentary rocks cause its weathering over the time which modifies the rock properties. The focus of study is to conclude the effect brought about by the sea salt weathering on the strength, stress and strain properties of the rock.

The rocks selected for the condition is type of a sandstone from the mines of *Dabi* near *Kota* city are identified as rock range of the Upper Vindhyan Supergroup (as refer in *GSI, 2012* No. 30, part 12). These rocks shown below in fig 1 were mined from site by various mining agencies and kept in workshops for engineering purposes.

Fig:1 A site of rock after mining in Kota, Rajasthan

Fig:2 A block of Sedimentary rock

In Fig 2 above shows sedimentary rock with thin bedding layers across the cross section of the rock block. The sedimentary rock has visible bedding planes on it along which it shows very weak shear strength. A low impact could result in tearing of a thin rock slab due to presence of weak bedding planes in the rock mass. Some sediments in the form of thin layer between the layers of rock of soil, i.e. clay and sand is observed while drilling the rock.

The Unconfined Compressive Strength is one of the most significant parameters to characterise the rock materials and it plays an important role in predicting the bore ability of the material. Bore ability is used widely in analysis, design and classification of rock materials and is expressed by the maximum principal stress that the material can sustain under uniaxial compression. Due to this, a precise approach for UCS measurement is necessary in most fields of rock mechanics. Basically, a cylindrical specimen loaded by two compressive platens in parallel to its main axis is considered conventionally as the configuration of unconfined compression test. This conventional test suggested by the standard ASTM D7012-04 (2004) and BIS 9143 (1979).

1.2 Objective of Research

The following is the objective of this study: -

- Conduct various tests to find out the strength and durability of sedimentary rock.
- To find the effect of salinity on the Unconfined compressive strength of sedimentary rock. Unconfined compressive strength is obtained on compressive testing machine using data logger for finding the peak stress at failure of the rock sample following standard code BIS 9143 (1979) or ASTM D7012-04 (2004).
- To study the effect in weathering of the sedimentary rock simulating sea-salt conditions. The extracted samples from sedimentary rock mass are kept in cannisters with brine solution of different concentrations i.e. 10%, 20%, 30% and have to be tested for UCS in specific time intervals of 30, 60, 90 and 300 days.
- To study the effect of weathering on strength and deformation of the sedimentary rock. Saline water alters the mineralogical composition present in the layers of sedimentary rock and degrade its mechanical strength. Thus, variation of stress with strain deformation is studied under different salinity conditions causing chemical weathering of the sedimentary rock.

2. Literature review

2.1 Weathering of sedimentary rock

Weathering is a natural process of disintegration of rocks into tiny particles by various types of erosion through wind, water, animals etc. Different agents in the process can be physical, chemical and biological causing weathering of rock.

Various variables influencing weathering are a) temperature and atmospheric conditions, b) appearance or nonappearance of sea or marine water in the rock surrounding, c) presence of oil or other characteristic happening gases causing chemical weathering. Presence of natural life in or close to the site of the rock without light and with less air and moistness conditions is a case of biological weathering. These factors cause decay in rock and alter with the sediments and mineralogy present in the rock. Atmosphere plays significant job in procedure of weathering by changing the pace of freeze-thaw cycles and chemical responses with corrosive downpour. The minerology of the sedimentary rock effects in controlling the deformation procedure, little minuscule minerals will be defenseless more for chemical weathering than physical weathering while course grained rock structure will be progressively vulnerable for physical weathering. Cantisani et al (2013) featured the mineralogical, petrological, physical and mechanical properties of some Italian sandstones and the impact of weathering on the sandstone by contrasting the marine condition influenced sandstone and those utilized in the avenues of Rome. The weathering close to the shore because of wind and salinity of sea-water broke down rock at faster rate. The picture appeared in fig 3 are the surface pavement in the city of Italy of sandstone, the pictures compare the degradation of sandstones at various environmental conditions and their weathering effect on the rock pavement.

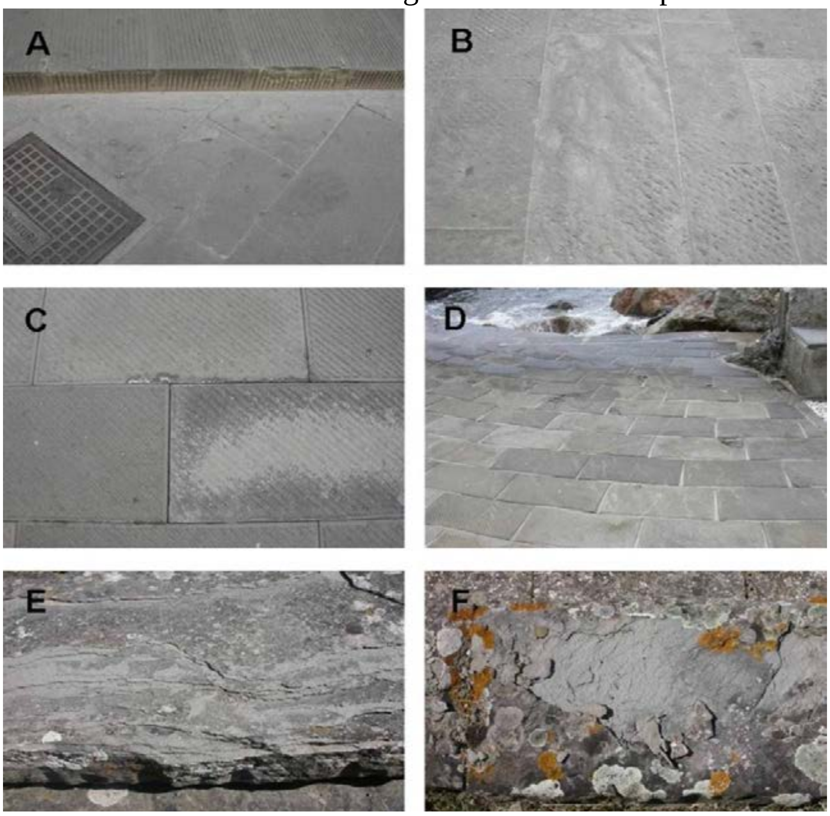

Fig:3 decay of sandstone A&B in urban environment; C&D in marine environment; E&F in mountainous environment, Cantisani (2013).

2.1.1 Analytic study of weathering of sandstone

Cantisani et al (2013) in his investigation demonstrated that for the chosen layers of the rock sample of $2cm^3$ were taken and porosity test was performed using hydrostatic balance method applying formula based on Archimedes' law. The samples were exposed to 48 cycles, every one of which comprises of 6hr of freezing in air at a temperature of - 12°C, trailed by 6hr of defrosting in water at temperature of 20°C. All test methodology was done as depicted in EN 12371:2010. Salt crystallization test were played out, each cycle comprises of 4 hr at a temperature of 35°C in a drying chamber with a sodium sulphate solution and 8hr of wetting at a temperature of 70°C-60 cycles followed by a somewhat long salts purification period was performed. Preliminary laboratory tests were performed so as to understand the ageing test with acid rain. The chose cycle plan that the examples ought to be kept presented to sulphuric acid solution in pH go 3-4 for 3hr at a temperature of 20°C followed by temperature of 70°C. This cycle was rehashed multiple times.

Baiyegunhi (2017) in his paper examined the weathering effect on some sedimentary and igneous rock in Karoogroup of Eastern Cape territory of South-Africa. The study depended on some weathering indices evaluated by considering the chemical weathering of mineralogical change of the rock over the period of change in climatic conditions. The mixture of compounds like K_2O/Na_2O variate with time causing chemical weathering of rock mass. The proportion of difference of the mixes yield to conclude up the severity of weathering on rock type whether igneous or sedimentary.

2.2 Effect of weathering on strength of rock

Due to chemical weathering over an extensive stretch of decades, change in climatic conditions and presence of humid condition with rainstorm winds break down the rock particles and adjust its minerology at base level. As, if there should arise an occurrence in limestone, $CaCO_3$ compound of the limestone gets deteriorated influencing its minerology and decreasing its strength. Modulus of rigidity and other physical attributes gets influenced by these reactions. Qi et al (2009) in his paper learned about the weathering effect on thick argillaceous limestone and its impact on the strength of the rock estimating unconfined compressive strength near Three Gorges reservoir in Central China.

Mechanical properties of thick argillaceous limestone apparently worsened because of chemical degradation. The decrease in its unconfined compressive strength and modulus of rigidity was seen up to 45% and 75% respectively for extremely weathered limestone. The strength and deformation of the limestone changes with the calcite mineral content of the rock. The advancement of thick weathering of the rock is because of the joints and gaps present in the structure of the mountain profile.

The weathering follows the joint structure with exceptionally wide spacing and the mountain slope. Human factors, for example, removal of the rock framing rugged slope and joints is a significant reason for the breaking down of the rock particles. The joints give good channel to water to go through, invade into rock and ground adding to profound chemical weathering of rock mass in general.

The image shown in fig 4 shows physical and chemical degradation due to process of weathering. Due to change in wind profiles and climatic conditions large gaps and channel joints are developed causing deep weathering and decay of rock effecting large mountain profile.

Fig:4 Mechanical and chemical degradation of argillaceous limestone on mountainous slope in three Gorges reservoir, Central China, Zhang Qi (2009).

2.3 Effect of weathering on strength and deformation of rock

Weathering process modifies the mineralogy of the rock by degrading them chemically because of progress in climatic conditions. The fine grained are progressively susceptible to chemical modification of the sediment layers of the sedimentary rock. This influences the strength and some physical attributes of the rock like porosity. Villarraga et al (2018) in his paper learned about the impact on strength of some sedimentary and metamorphic rock examples because of mechanical degradation brought about by patterns of temperature change.

2.3.1 Laboratory study of rock parameters

Some rock parameters were measured to study the effect of weathering i.e. by taking the rock through 1000 of thermal cycles from 10-50°C in dry conditions on unconfined compressive strength and p-wave velocity distribution in rock. Measure of deformations were also measured axially and radially and how it is affected by the thermal cycles was studied by ASTM D7012-

10 standard. Axial deformation was measured by using LVDTs on 5 cylindrical samples. P-wave velocity was studied before and after compressive test.

Large amount of strains was observed on the sample with values as 2.2×10^{-3}. P-wave reduces across the samples. The conclusion lead to analyse the effect was due to global expansion of the microscopic particles of the rock sample due to thermal cycles causing expansion and drastic reduction of the p-wave velocity.

The plot shown in fig 5 is stress-strain variation of sedimentary and metamorphic rocks after given number of cycles of temperature change, thaw-freeze cycle shows dip in stress level with almost same strain values.

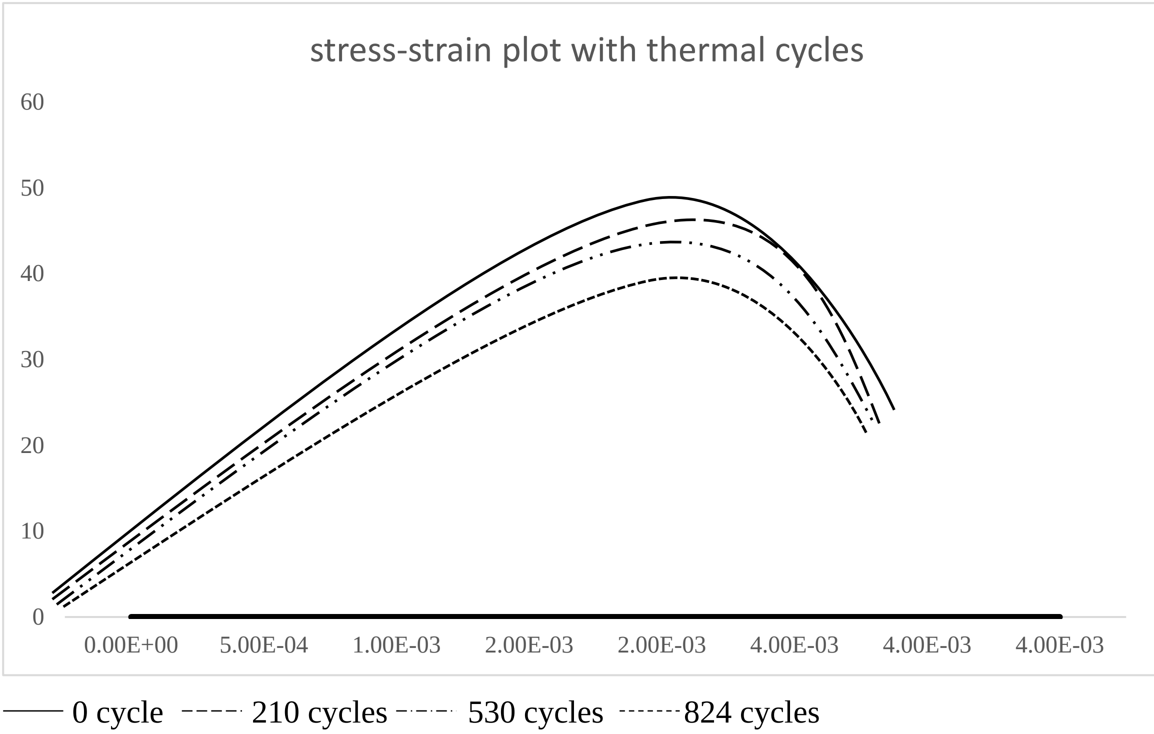

Fig 5: stress-strain with effects of thermal cycles and weathering on sedimentary rocks samples, Villarraga (2018).

2.4 Permeability of rocks

Permeability in sedimentary rocks depends on the resistance of flow of the sediment layers in the rock type and few interconnected voids, viscosity of the fluid present and rock temperature.

2.4.1 Co-efficient of Permeability

Jumikis (1983) studied the permeability of different rock masses i.e. igneous, sedimentary and metamorphic rocks. Table 1 shows approximate values of permeability for various rock mass

According to Barton (2008), the permeability of the rock mass is roughly given as below at 20°C -:

$$k \approx \left(\frac{0.002}{Q}\right)\left(\frac{100}{JCS}\right)\left(\frac{1}{H^{5/3}}\right), m/sec \quad (1)$$

where,
Q = in situ rock mass quality (Q = 0.1 to 100) = (RQD/J_n) (J_r/J_a) (J_w/SRF)
JCS = joint wall compressive strength in MPa,
H = depth of a point under consideration
below ground surface.

the permeability of sandstone lies in range 10^{-2} to 10^{-4} cm/s with minimum value across the sediments of the sedimentary rock. Thus, the height of 78 cm long sample will take maximum of almost $78*10^4$ seconds approximately making 9 days for water to reach the bottom the rock sample

Table 1: Approximate Coefficient of permeability of Rocks and Porosity at 15°C, Jumikis (1983).

In situ rock	Coefficient of permeability (cm/s)	Porosity (%)
Igneous rock	-	
Basalt	10^{-4} to10^{-3}	1 to 3
Gabbro	10^{-5} to 10^{-7}	0.1 to 0.5
Granite	10^{-3} to 10^{-5}	1 to 4
Sedimentary rock		
Dolomite Limestone	10^{-2} to 10^{-4}	5 to 15
Sandstone	10^{-2} to 10^{-4}	4 to 2
Slate	10^{-3} to 10^{-4}	5 to 2
Metamorphic rocks		
Gneiss	10^{-3} to 10^{-4}	----
Marble	10^{-4} to 10^{-5}	2 to 4
Quartzite	10^{-5} to 10^{-7}	0.2 to 0.6
Schist	10^{-4} to $3.0x10^{-4}$	----
Slate	$10^{-}4$ to 10^{-7}	0.1 to 1

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2.4.2 Permeability determination test

Permeability of in-situ soil or rock determined is by pumping test or water pressure test which is known as “Lugeon test”. This test is performed in a drill-hole and does not give value of coefficient of permeability but gives the in-situ comparison of the permeabilities of the rock masses, it is mainly accounted for grouting of rock masses.

Table 2 shows the classification of rocks on Lugeon value and joints present in the rock mass whether weak or heavily jointed

Table 2: Classification of rock on Lugeon value of permeability, Houlsby (1977).

Lugeon value 1 lugeon = 10^{-7} m/sec	Strong, massive rock with Continuous jointing	Weak, heavily jointed rock
0	Completely tight	Completely tight
1	Sometimes open joints up to About 1mm	Sometimes open to hair crack size of 0.3mm
3.5	Occasionally open to 2.5 mm	Occasionally open to 1.2 mm
20	Often open to 1.2 mm	Often open to 1.2 mm
50	Often open to 2.5 mm	Often open to 2.5 mm
100	Often open to 6.2 mm	Often open to 6.2 mm

2.4.3 Hydraulic conductivity of sedimentary rock

The prime factors for sea-salt water absorption to rock samples is to acknowledge about the permeability and hydraulic conductivity of the sedimentary rock.
Mehbratu et al (2019) in his paper showed the range of hydraulic conductivity of sandstone is of $3*10^{-10}$ to $6*10^{-6}$ m/s from unconsolidated to fractured sandstones respectively depending upon the geology of the sedimentary rock origin.
The image shown in fig 6 shows the hydraulic conductivity of water through the rocks and soil. As we can see the extreme conditions increase leads to decrease in the conductivity of the rock and make it more difficult for water to permeate through rock.

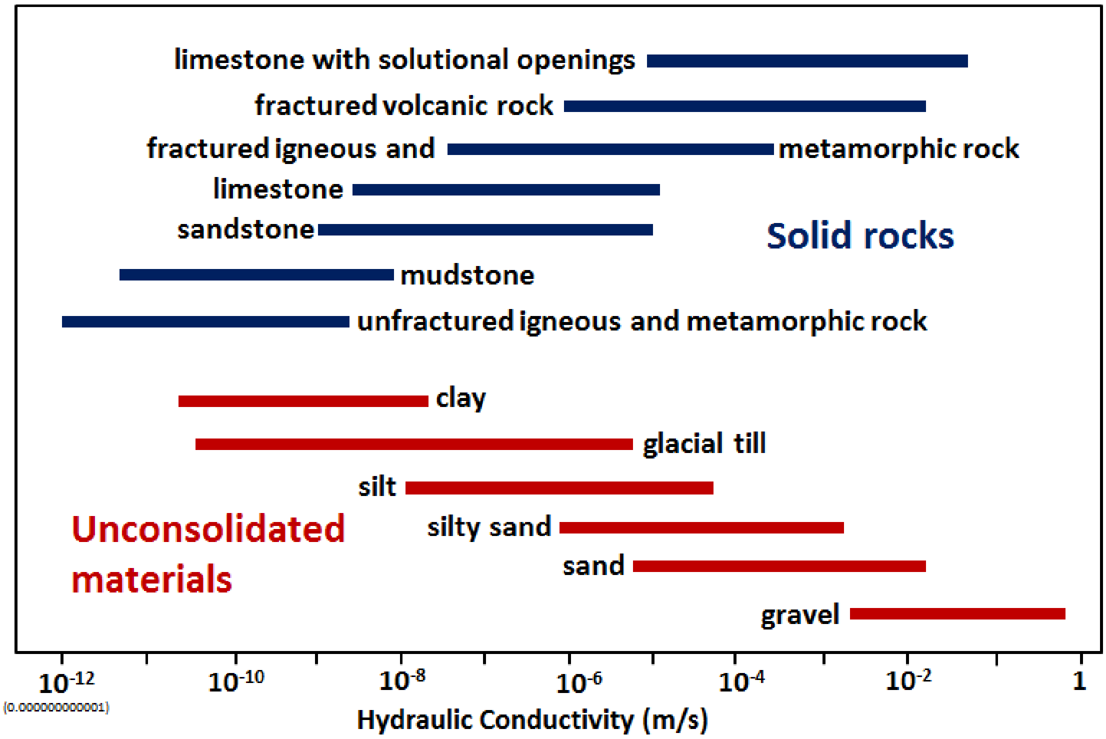


Fig:6 Hydraulic conductivity, Mehbratu (2019).

Quite a number of studies was done to understand the hydraulic conductivity and water permeability of the *Dabri* sandstone on which our tests were conducted which belongs to lower Vindhyan supergroup range. Dutta (1983), based on the permeability studies also showed by water absorption and porosity tests performed in the lab that the sandstone has a conductivity range of $10^{\wedge -8}$ ~ $10^{\wedge -6}$ m/s.

2.5 Sea-salt Weathering of Sedimentary rock

Weathering in sedimentary rocks along an sea coast experiences pressure and enduring because of water leaking in the rock pores and because of salt present in it which causes the rock structure to decay influencing its strength. Salt takes shape in the rock pores causing its rot at that point follow to its interruption, or break down the calcareous concrete in limestones. Cardell et al (2002) in his paper contemplated the sea water impact on weathering of some granite and sedimentary rocks and distinguishing the harm designs under a similar condition. He utilized a saline spray ageing test to simulate the field situation of seaside condition on various examples of some granite and sedimentary rocks (calcarenite, breccia, limestone). Physical procedures were associated with the enduring of stone examples, though disintegration of calcite was additionally engaged with the deterioration of calcareous rocks.

2.5.1 Intrinsic parameters of stone implicated in the weathering process

By the examination done by Cardell (2002) in his investigation the perception prompts set up that the microstructural parameters assume significant job in salt degradation. The pore structure assumes significant job in the porosity of the rock type. Ageing tests were performed on crystals of granite rock for example, Muros is a fine grained, two mica anataxis rock with an inequigranular anhedral surface and slight direction of its mineral segments.

Roan is another stone with medium to fine grained two mica layered structure contains xenoliths. It is a homogeneous stone with no ordinary directions of the mineral segments. Between the quartz grains intergranular gaps are available mostly influencing feldspar with incorporations present in these minerals, for example plagioclases (related with sericitization) and micas (muscovite and biotite).

Calcareous rocks from Apulia (Italy) are coarse grained homogeneous limestones made out of sparytic calcite (grain size > 10μm). Limestone from Salerno have high intergranular porosity with very much associated pores containing both quartz and micas and fossil bryozoans, though limestone from Gargano is a brecciate limestone made out of large sparry calcite gems and homogeneous biomicrites with fossils all around solidified with micrite (grain size < 5μm).

2.5.2 Salt-spray ageing test

Test crystals were exposed to ageing test utilizing controlled chamber. This chamber is modified electronically to create spray of salt solution for 1 min and for other 29 mins controlled drying in temperature scope of 35-40°C and with relative dampness of 49 percent. The spray delivered is through the capillary tube of containing sea water associated with standard spraying gun. The test outcomes concluded that the drying temperature, nature of arrangement of the salt kind (blended or unadulterated) affects type of weathering delivered on the calcareous (Cardell et al, 1998) and granite rocks (Rivas et al, 2000).

2.6 Vindhyan supergroup formation in Rajasthan

Rajasthan is partitioned into four principle locales physio graphically for example Aravalli scope of mountains, Eastern fields, Vindhyan supergroup, Western deserts.

Gupta et al (1999) in his paper learned about the mineralogy and sediment bedding of the formation.

Aravalli go extends from west to east part of the states separating Rajasthan into inconsistent regions, whole range is extensively isolated into other slope ranges like of Jaipur area, Alwar region, Mewar slopes, Udaipur, Sirohi regions, Mt. Abu slopes and similarly.

Western desert planes establish ridge fields and rough asphalts and is influenced by almost no precipitation.

Eastern fields are in upper east and eastern pieces of the state where northern limit is meeting the Gangetic fields in area Bharatpur; though south eastern limit is meeting the Vindhyan level busy with gneisses and schists, the territory is sedimented with thick layer of alluvium blown sand.

The Vindhyan supergroup is the territory covering Bundi locale, Kota area including three gatherings for example Bhander bunch which is in north-east locale, Rewa gathering toward the south of the area and some eastern parts, and the Kaimur bunch which circles these two gatherings. Eastern fields and Vindhyan share intersection set apart as Great Boundary Fault (GBF). The locale different streams running towards north-eastern side of GBF is Berach waterway which stream in Chambal stream at long last. Ranthambore Group was considered as the arrangement of basal piece of Vindhyan supergroup by Guha and Rai Chowdhury (1999), This gathering contain exchange succession of sandstone, shale with less carbonate and basal polymictic and lenticular aggregate beds.

2.6.1 Field investigation of Vindhyan range of Rajasthan

Vindhyan supergroup involve right around 25,000 sq. km of territory in the south eastern pieces of the state, it overlays the metamorphites of Bhilwara Supergroup and the rocks of Berach with sharp unconformity of the syn-sedimentary volcanoes and broken collections of aggregate of the basal Khardeola Sandstone and Bhagwanpura Limestone arrangement. Two fundamental subgroups partitioned are Lower-Vindhyan gathering and Upper-Vindhyan gathering, where lower Vindhyan for the most part establish calc-argillaceous and upper Vindhyan comprise of arenaceous.

a) Lower Vindhyan

The sedimentation of the Vindhyan occurred in two unique bowls one is Chittorgarh-Jhalawar sub-bowl in southwest with layers named Satola, Sand, Lasrawan and Khorip gatherings and the Sapotra-Karauli sub-bowl in the upper east, with fractional turn of events and later went under one front of silt which were isolated by an upland close Bundi where Lower Vindhyan is missing.

Chittorgarh-Jhalawar sub-bowl: The underlying sedimentation began with volcanic movement of the andesitic liking which was trailed by mixture and bedding of shale of the basal Khardeola Sandstone overlying the meta residue of Bhilwara gathering and Granite of Berach. This is then trailed by level stores of Bhagwanpura limestone through tides along the seaside system. The overlying layer is the of Lasrawan residue with kalmia sandstone and shale of Binota with glauconitic siltstone interbeds stored in profound water. Once more, kept are Khorip, Khori Malan aggregate alongside Jiran sandstone then Bari shale all stored in entirely temperamental state.

Sapotra-Karauli sub-bowl: Sediments of Khardeola and Bhagwanpura sandstones began with initiation of Basal aggregate, glauconitic sandstone and shale following Tirohan Limestone getting sedimented with development of green growth like Collenia, Conophyton and Crypto zoon. Tirohan Breccia with chert get kept over on Limestone at that point layered with Shale of Parli and sand gathering. Sedimentation happens quicker than the subsidence of the Basal aggregate, Tirohan Limestone with productive algal development is a proof of its statement under littoral marine condition. Autoclastic layer of Tirohan Breccia and porcellanite is layered over it and with the nearness of GBF profile syn-sedimentational tectonism supposedly takes place.

b) Upper Vindhyan

A checking change in the sedimentation is seen from calc-argillaceous to clastic in the timeframe of Upper Vindhyan go arrangement. Erosional exercises were seen among Lower and Upper Vindhyan scopes of Tirohan Breccia which is flimsy overlaid by Kaimur aggregate and Akoda Mahadev Sandstone. The strand line moved to north as the testimony of Chittorgarh-Jhalawar sub-bowl was occurring with Chittorgarh fortification Sandstone lies over Suket Formation and afterward the Akoda Mahadev sandstone was saved over the north of GBF, with a particular basal aggregate among Akoda and Bundi-Indargarh zone. The Kaimur bowl statement leads to finish up its littoral marine condition because of its orthoquartzite nature, develop surfaces, away from and advancement of wave marks. Confined ferruginisation of splits, engravings of downpour and intra-formational combination recommend advancement of neighborhood sub-aeronautical conditions towards the last sheet material of Khaimur sandstone.

The sedimentation in the Rewa gathering of exchange argillaceous and arenaceous facies shows the occasional shakiness off the bowl floor. Overly fine-grain Panna shale was stored locally in a shore-tidal pond condition. The glauconotic siltstone beds at Rawatbhata are shows decreasing condition. Indargarh sandstone shows its testimony is orthoquartzitic, developed texturally, implanted cross sheets and in littoral to neritic zone of ocean condition. At the hour of ocean offense, the Jhiri shale was kept covering past arrangements. The ruddy/purplish shade of glauconitic siltstone and Jhiri shale shows the depositional condition of warm-water conditions. The above overlaying layer of Taragarh Fort Sandstone which was likewise orthoquartzitic, texturally-developed and advancement of cross sheets and nearness of waves happened in a sweeping sort sedimentation under shallow-marine salt marsh conditions. The nearness of dainty layered aggregates proposes high-vitality states of the encompassing at the hour of affidavit. The relationship of orthoquartzite-carbonate-shale of the Bhander bunch is ascribed to stable system. Salt marsh affidavit was seen in Ganugarh Shale with bed waves and cross sheet material of combination at the base and breccia at the top with intraformational aggregate shows supratidal conditions.

During the affidavit of Sirbu shale, the two sub-bowls got joined in single storehouse while the other development for example Mihar Sandstone, Balwan Limestone and Dholpura shale in Bundi-Indargarh territory and upper Bhander sandstone in Sapotra-Karauli are were saved under shallow-marine condition. The normal paleocurrent course in the affidavit is towards the north. The arrangement is uniform and reliable implies a stable paleo-slant and general structural steadiness of the bowl. The most youthful layer of Dholpur shale was demonstrated to be stored in limited condition.

In the entirety of the Vindhyan supergroup sedimentation because of subsidence and height of the bowl the affidavits are fluctuating and because of nonstop offense and relapse of the ocean. Hint of natural life as small scale, large scale fossils were found in the Vindhyan. The age running from more than 1,300 Ma to under 600 Ma.

The image shown in fig 7 shows the layout of the supergroup range of rock mountains from the state of Rajasthan, India. The main focus of the study is from *Kota* district from where the sandstone samples were taken coming in *Vindhyan* Supergroup range. The geology study shows the manner of deposition of sedimentary layers occurred over millions of years over and above through weathering process in which a number of natural and man-made factors were involved.

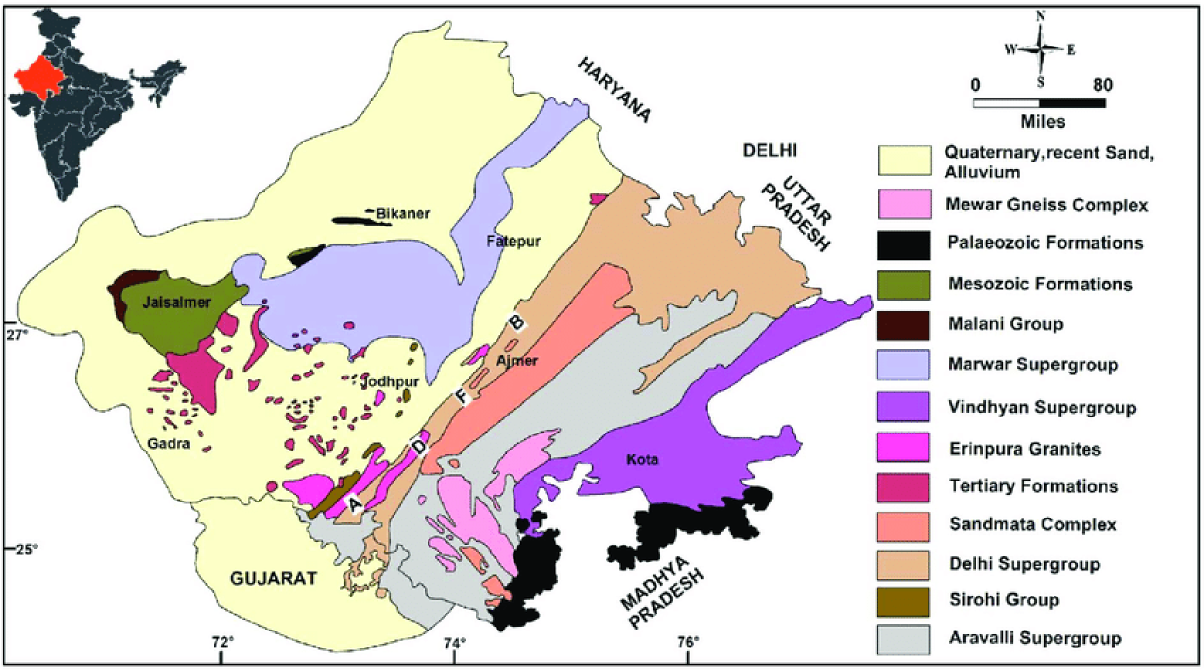


Fig:7 Geology of rock folds distribution of Rajasthan, Gupta (1999) (GSI No.30 part12. 3rd revised edition.)

The water permeates through the sedimentary layers of sand quartz between the high pressurised embedded layers of sandstone. Generally intact rock is very well cemented with mineral grains which contain tiny pores. The pores or voids are not interconnected however may represent at least very low permeability if rock is not fractured. Gupta (1999) in his study also showed the Sandstone geochemical characteristics similar to those of quartz wakes (SiO_2 = 74–76%, CaO = 0.16–0.17%, Na_2O = 0.11–0.12%, and P_2O_5 = 0.03%). Sandstone, which has intermediate chemistry with SiO_2 = 74–76% and Al_2O_3 = 13–14%. In general, the rocks appear to be a mixture of quartz and illite as end minerals. The rocks of the Vindhyan Supergroup are very little disturbed and have gentle dip towards south and south-east.

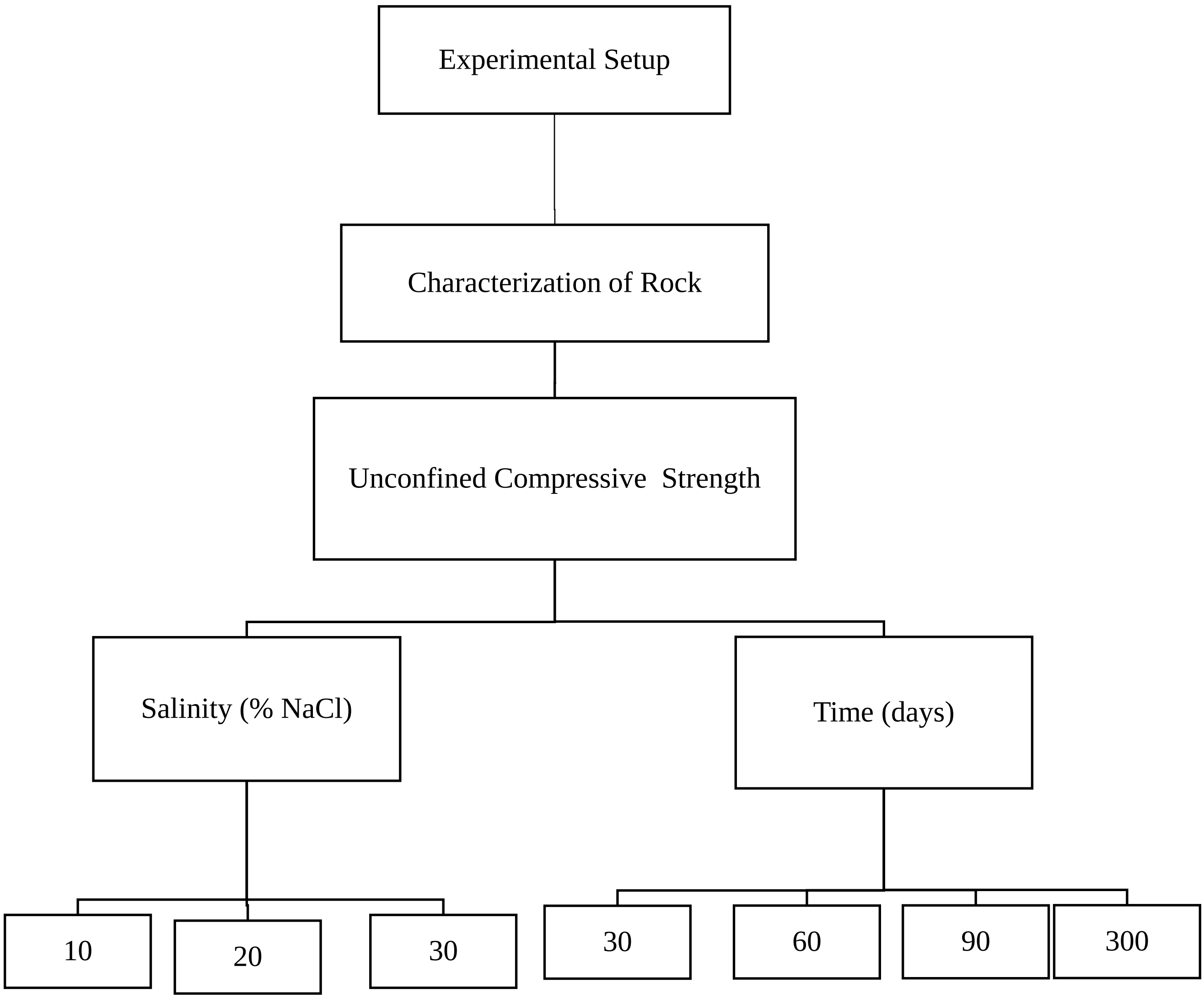
The image shown in fig 8 shows layer of SiO_2 which is deposited through small particles, showing the pattern of deposition containing other earth elements but with a clear layer of silica oxide. Quantity of some metals and non-metal oxides and fossils and their variation over time help to depict age of the rock through these layers.

Fig:8 layer of sand quartzite sediments in an intact sedimentary rock

3. Methodology

The flowchart below takes through the procedure to execute our lab-based objective of conducting characteristic index tests performed to study the physical characteristics of the rock. Further unconfined compressive strength test was performed on the sample followed through the weathering process by creating saline environment conditions. The strength test was carried out in some time gaps to study the sea-salt weathering effect on the UCS of the sedimentary rock.

Flowchart for experimental program



3.1 Sample Extraction

Core sample is extracted from the core of the block of sedimentary rock of internal diameter of 38mm ($\emptyset - 38$) by using diamond drilling bit of outer diameter of barrel 44mm.

Sample extracted is with the bedding planes being horizontal i.e. 0° inclination with horizontal so the loading applied would be across the bedding which would give the maximum possible compressive strength of rock.

Samples are also taken out at different angle of inclination with the bedding plane which could prove to be useful to account the shear strength of the rock along and across the bedding planes (i.e. $0°, 30°, 45°, 60°, 90°$). The images shown in fig 9 is core sample drilled from sedimentary rock block shown in fig 10 respectively.

Fig:9 Rock Core samples

Fig:10 Rock block used for drilling

The drilling was done using diamond drill bits of outer diameter 44mm and thickness of bit 3mm as shown in fig 11. The bit is fit in the core cutting machine as shown in fig 12 and core samples were extracted from sedimentary rock blocks as shown in fig 13.

Internal Dia of the bit = 44-2*3 = 38mm

~Diameter of the extracted sample

Fig:11 Drill bit ($\emptyset = 44mm$)

Fig:12 Core Cutting Machine

Fig:13 Samples with bedding planes

3.2 Fabrication of sample

The core sample taken out is fabricated as a standard sample of

Dia. of sample = 38mm

Height of sample =76mm

Using rock cutting machine as shown in fig 15. Fig 14 shows standard samples fabricated for UCS test according to code BIS 9143 (1979).

Fig:14 Core samples of standard dimension

Fig:15 Rock Cutting Machine

3.3 Creation of Saline Environment

Saline environment was prepared for the core samples simulating the field condition of sea-salt weathering. The peak stress and strain vary little with reservoir condition due to high effective stress present there. Brine solution of varying salt concentration were prepared (10%, 20%, 30%) as shown in fig 18 and the samples are kept for its saturation in the canisters to simulate field conditions as shown in fig 17. The core samples for various tests were extracted as shown in fig 16 shows both standard and non-standard dimensional samples for UCS and other characteristic Index tests performed.

The Unconfined Compressive Strength test is to be performed on the samples with time variation of 15days, 30 days, 60 days ,90 days and 300 days.

Time plot of strength with salt concentration is to be done with varying content of NaCl.

Fig:16 Core Samples of sedimentary rock

Fig:17 Samples placed in saline environment

Fig:18 Canisters with brine solution 10%, 20%, 30%

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4. Observation

4.1 Results and discussion

4.1.1 Characteristic index tests

In characterisation index test we inquire about the properties of rock i.e. water absorption, void ratio, dry unit weight, porosity with code provisions as shown in fig 17. Unconfined compressive strength, Oblique shear test, point load test values are experimentally calculated to study about the strength of rock.

1. Index properties – Density, water absorption, void ratio, porosity
   Code reference – IS 13030(1991)

As shown in fig 19 the sample is tested for water absorption, void ratio and porosity.

Weight of sample = 286gm (bulk weight)
Dia. of sample = 3.8cm
Height of sample = 10cm
Volume of sample = 110cc
Dry weight of sample = 282gm
(After 24-hrs of oven drying at 105degree Celsius)

Saturated weight = 287gm
(After 24-hrs of saturation in water)

Fig:19 rock core sample

Water content = (287 – 282)/282
= **1.77%**

Unit weight of rock = 282/110
= **2.56** gm/cc
Therefore, specific gravity of rock,
G_s = **2.56**

Void ratio

$$e.S = w.G_s \qquad (2)$$

e = 0.0177 * 2.56
= **0.045**

Porosity

$$N = e/(1+e) \qquad (3)$$

N = **0.043**

2. Point Load test
Code reference – IS-8764

As shown in fig 20, the point load test: -
Dia. of sample = 38mm
Height of sample = 11.5mm

H/D = {0.3 to 1}
Point load strength index = **2.69 MPa**
(axial strength)

Fig:20 - point load test apparatus

3. Unconfined compressive strength
Code reference – (IS 9143 (1979))
As shown in fig 21, a failed sample after UCS test
Standard sample dia. taken = 38mm
Height of sample = 76mm
Rate of loading applied = 0.5 to 1 MPa/s
Max compressive load recorded before failure = 156KN
Compressive stress calculated = **137MPa**

Fig:21 failure in UCS

4. <u>Oblique shear stress test</u>

Code reference – IS 7446:1991

Fig 22 & 23 shows oblique shear strength test apparatus and failure of sample across the bedding plane of the sedimentary rock sample.

Dia. of sample = 38mm
Height of sample = 58mm

Shear is applied across the bedding plane perpendicularly in this test

Value of loading recorded/ failure point= 39.6KN
Oblique shear strength calculated, thus= **18MPa**

Fig:22 oblique shear apparatus

Fig:23 oblique shear failure

5. <u>Brazilian test</u>

Code reference – IS 10082 (1981)

Dia. of sample = 50mm
Height of sample= 50mm

Tensile strength value = **16.7KN**

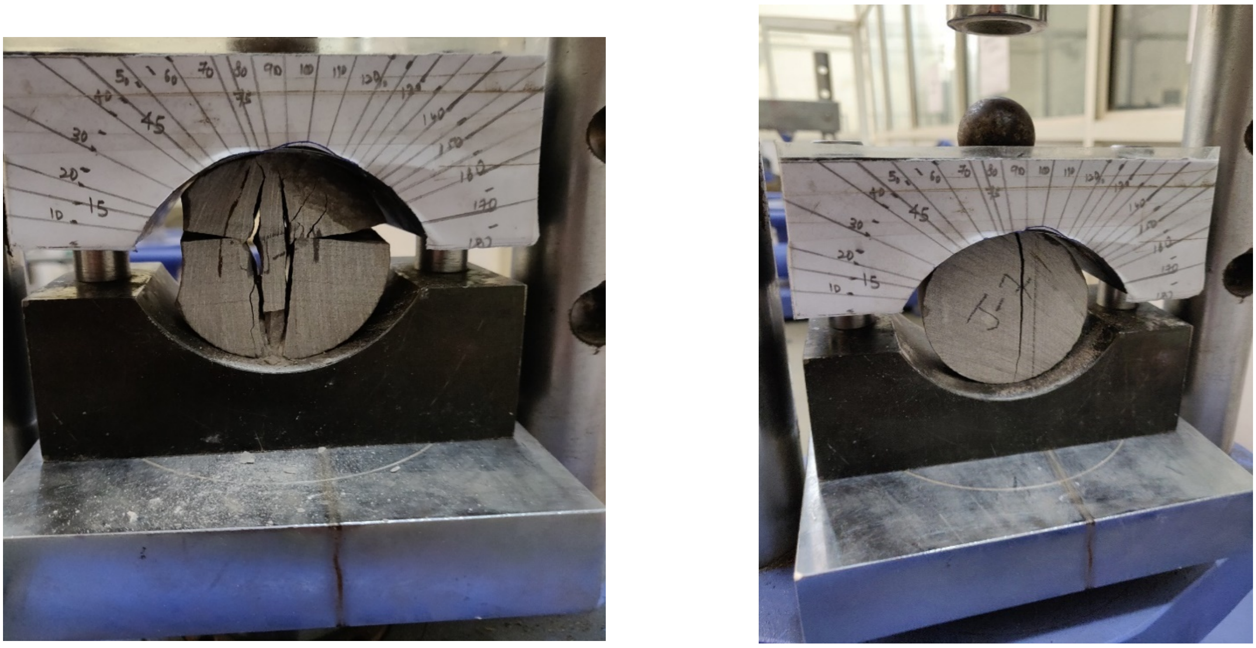

Fig:24 a) Brazilian test sample failure and b) Brazilian test apparatus and sample test

The images shown in figure 24 a) &b) shows the Brazilian test sample in the test apparatus with marking of angles along which the failure pattern follows. Crack starts generating from the top end of diameter following diametrical axis ending at the other end.

6. Slake durability test

Code reference – IS 10050 (1981)

10 samples of 40-60gms as shown in fig 26 are taken rounded edges to make 400-600 gm of sample and put in the apparatus, the apparatus as shown in fig 25 is set for 10 min of 20 rev per min. and results are recorded.

Slake Durability Index calculated = **99.61%**
Classification of strength index – Very high (95-100%)

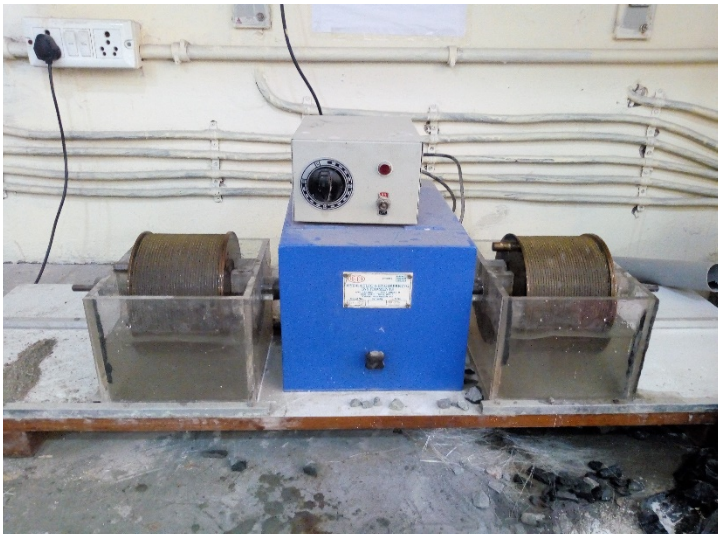

Fig:25 slake durability apparatus

Fig:26 10 Rock lumps

A comparison of stress-time behaviours obtained from the experimental shows the relation of stress with time variation and a certain break point to be obtained where there could not be any further effect of the brine solution on the load bearing capacity of the sedimentary rock. Table below shows the unconfined compressive strength of the sedimentary rock kept in the solution with the progression of days.

From table 3, it could be seen that the compressive strength of the rock sample is decreasing with passage of days. The strength is deteriorated at not any certain rate but initially it falls down more for the sample of 30% brine solution than that for 10% or 20%.

Table 3: Change in compressive strength of the rock samples in brine solution with time

Strength of brine solution (MPa)	10% NaCl	20% NaCl	30% NaCl
Time (days) 0	137	137	137
30	90.5	67.84	56.31
60	61.88	48.87	38381
90	43.49	37.03	30
300	36.15	21.69	19.66

The strength of the rock sample decreases uniformly for 10% NaCl brine solution when it is kept, whereas the strength variation for 20% NaCl solution decreases at a slightly greater rate for first 15 days and then follow the same order as that of 10% NaCl solution. For 30% solution the rate of decrease in strength is slightly higher even than 20% and then follow the same order as of 10% and 20% NaCl solution. The strength degradation for 30% NaCl solution is the highest, thus indicating as the percentage of salt content in the brine solution increases, the strength decreases. The decrease in strength in the *sandstone* rock sample reaches the strength of certain *limestone* rock in their state of no salt content.

The sample in the UCS testing machine fails producing cracks across the bedding plane. The 0-degree angle of the bedding plane provides the maximum strength of the sedimentary rock through the test.

The image shown in fig 27 are of a standard cylindrical sample for UCS test and the failure when load applied is across the bedding plane

Fig:27 0-degree bedding plane

The cracks produced initiate at the top of the sample and progresses down across the sample to the bottom as shown in fig 28. No failure takes place along any of the weak plane defined in the sample along the bedding plane. Thus, the strength produced is the core compressive strength of the rock block without confinement.

Fig:28 progression of crack across the plane

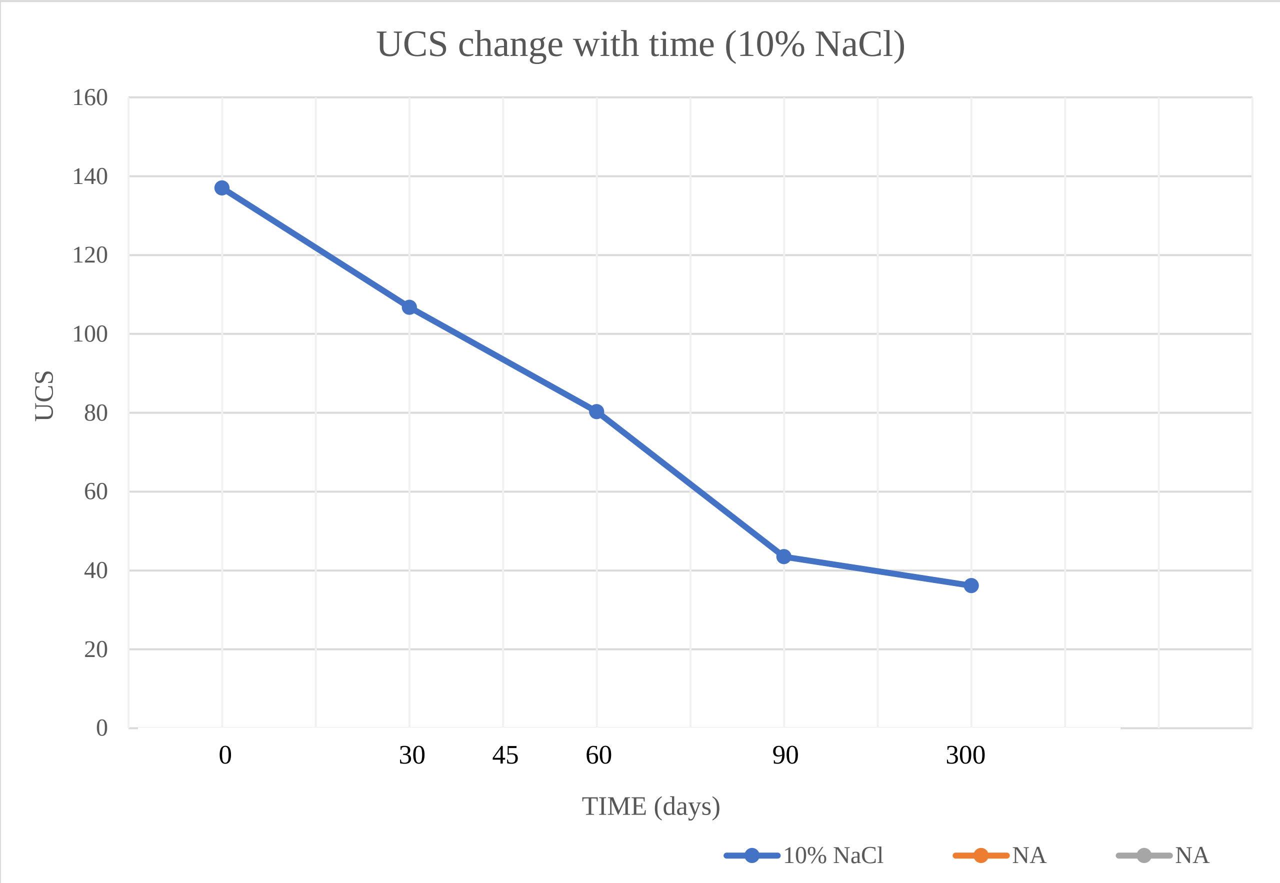

Fig:29 strength vs time graph
(10% NaCl)

The graph above shown in fig 29 is the plot of stress variation against time for the samples kept immersed in the salt solution of concentration 10% NaCl. The samples are tested in time duration of period of 30-60-90-300 days to study the behaviour of the salt weathering effect on the UCS of the sedimentary rock and the results are thus plotted respectively.

It could be concluded from the graph the rate of decreasing for initial period of time is high and that is low for the period afterwards

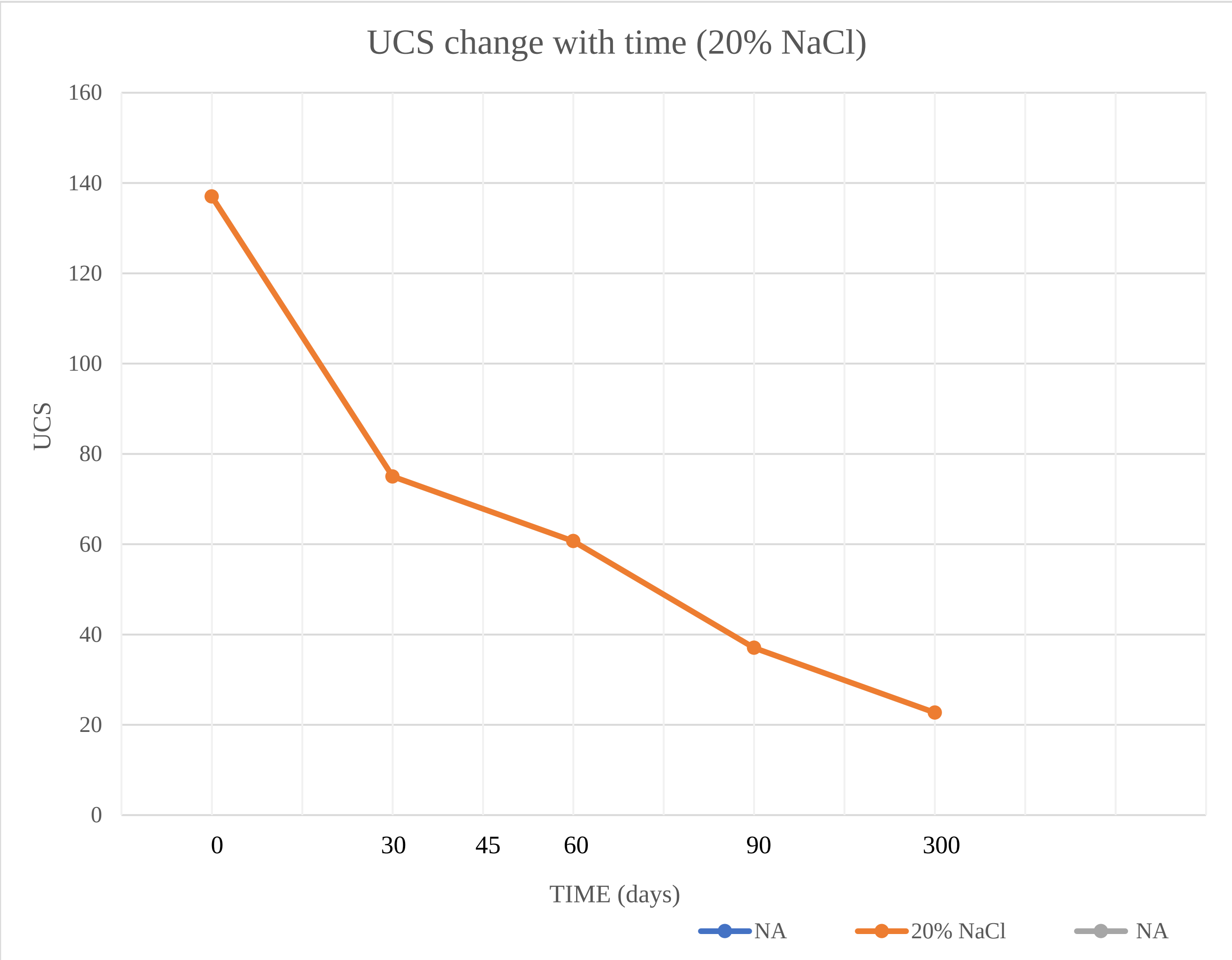

Fig:30 strength vs time graph
(20% NaCl)

The graph above shown in fig 30 shows the plot of the stress variation against time for a salt concentration of 20% NaCl solution by weight. The tests were performed on the same pattern of duration of 30-60-90-300 days.

The concluded result shows the falling stress values against time, where the initial rate is very high even than the sample tests for 10% NaCl solution but in the latter part the rate decreases and is least for the end period of the tests performed.

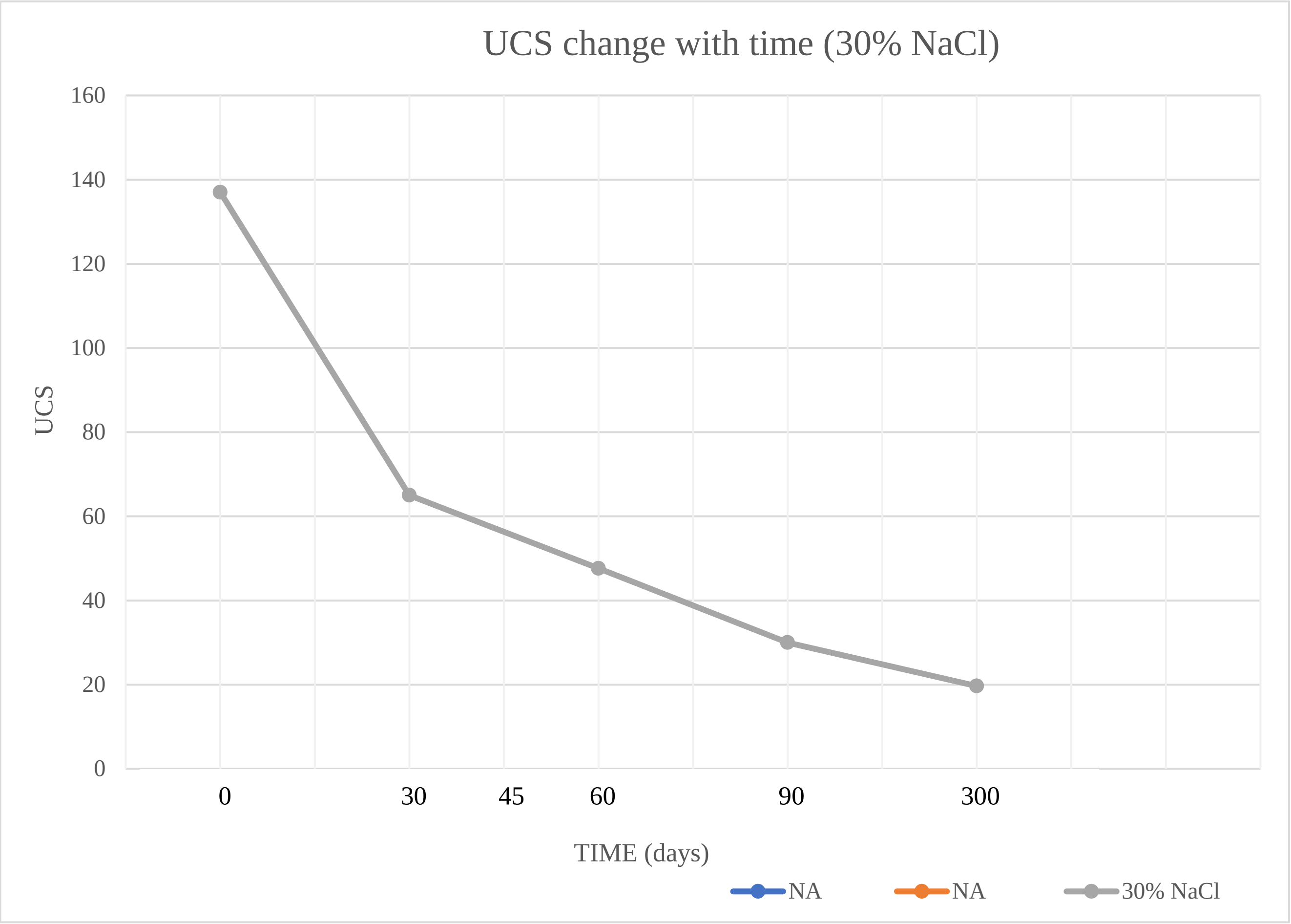

Fig:31 strength vs time graph
(30% NaCl)

The graph plotted above in fig 31 shows the stress variation against time for the samples kept immersed in salt solution of 30% NaCl salt concentration by weight and were tested following the same pattern of duration i.e., 30-60-90-300 days and the results obtained were thus plotted.

The conclusion observed was that the stress is ever decreasing as the period of the test increases but the falling rate is highest as compared with the 10% and 20% salt solution and the rate is least for the latter duration of the test.

A graph is prepared showing the trend of the strength of rock that is followed with time

Co-relation of Various Salt Concentrations

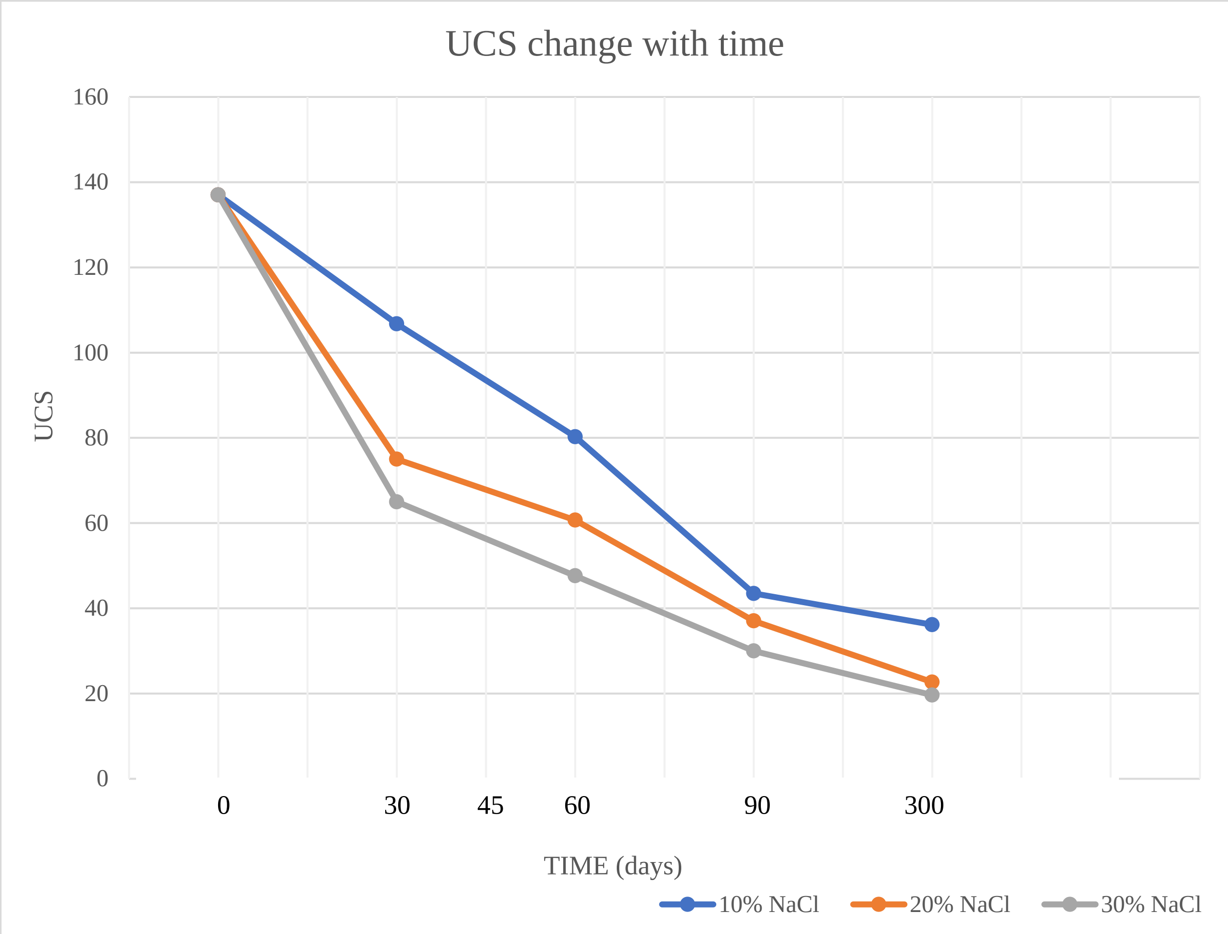

Fig:32 strength vs time graph

(co-relation of concentrations)

The above graph in fig 32 plotted with the results that followed and it can be concluded that the rate of change of stress with passage of time is decreasing. The initial rate of decreasing stresses is high for 20% and further higher for 30% salt concentration as compared to 10% salt concentration solution.

Rate decreases for the period of 30-60 days for 20% and 30% salt concentration but is almost constant for 10% salt solution but the stresses are ever decreasing.

For the period of 60-90 days rate is almost constant for 20% and 30% salt concentration samples but increases a little for 10% salt concentration samples.

For the last period which is almost 200 days long it could be seen that the rate of change in stresses decrease for all the salt concentration samples and the stresses converge at the end of

$300 day^{th}$ test to achieve the breakpoint where there would be negligible effect of the salt concentration on the unconfined compressive strength of the sandstone.

4.1.4 Variation of stress with strain

A group of samples with varying salt content i.e., for 10%, 20% and 30%NaCl concentration is analysed for strain also and further stress-strain graphs for the specimens and the test are plotted accordingly. Due to very brittle nature of the sedimentary rock there can be seen very minute difference of weathering effect of the saline environment on the strain property of the rock.

Strain gauges of 350 micro ohm(Ω) are used to account for the strain recorded in stress-strain analysis of the rock sample as shown in fig 33.

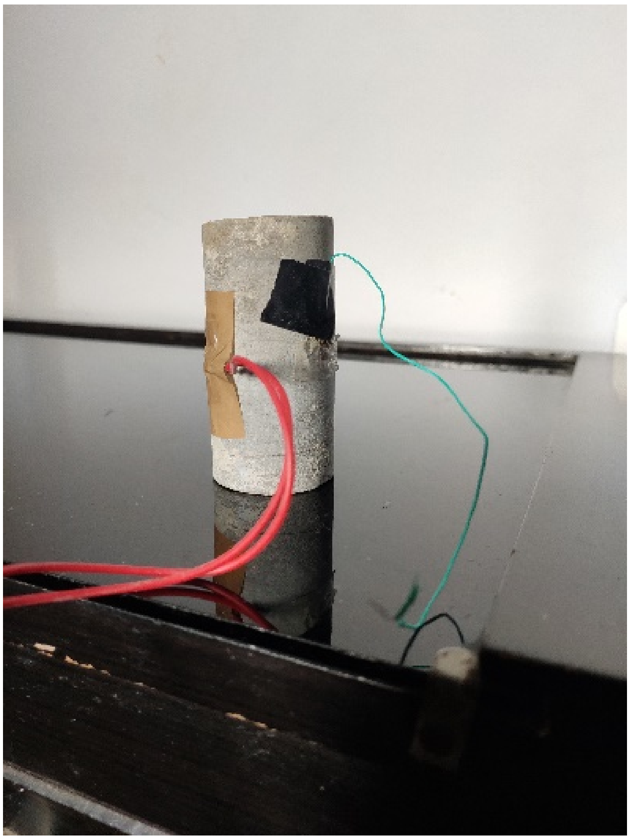

Fig:33 strain gauges connected to sample

The analysis has done for the axial deformation of the sample, two longitudinal strain gauges were connected along the axis of the sample opposite to each other and the strains with change in stress were recorded after a period of weathering for 300 days. Following were the results:

Table 4 shows strain readings for sample with 10%NaCl salt concentration

Table 4: strain gauge readings (10% NaCl)

Strain channel	**Beginning (μs)**	**Failure (μs)**
Channel-1	-80	-370
Channel-2	+630	-2570

Average strain recorded at failure - 1745μs

Maximum stress recorded at failure – 36.15MPa

Table 5 shows strain reading for sample with 20% NaCl salt concentration

Table 5: strain gauge readings (20% NaCl)

Strain channel	**Beginning (μs)**	**Failure (μs)**
Channel-1	+1145	+3685
Channel-2	-290	-685

Average strain recorded at failure – 1467.5μs

Maximum stress recorded at failure – 21.69MPa

Table 6 shows strain reading for sample with 30% salt concentration

Table 6: strain gauge readings (30% NaCl)

Strain channel	**Beginning (μs)**	**Failure (μs)**
Channel-1	+360	-410
Channel-2	-760	-3755

Average strain recorded ay failure – 1882.5μs

Maximum stress recorded at failure – 19.66MPa

Variation of strain on opposite faces of the sedimentary rock sample is observed due to non-isotropic application of forces due to tilting of the upper plate of the compressive testing machine when the load is applied. To overcome this uncertainty average of the strains of the two face is calculated to get strain along the central axis of the sample which is the axis of the failure plane.

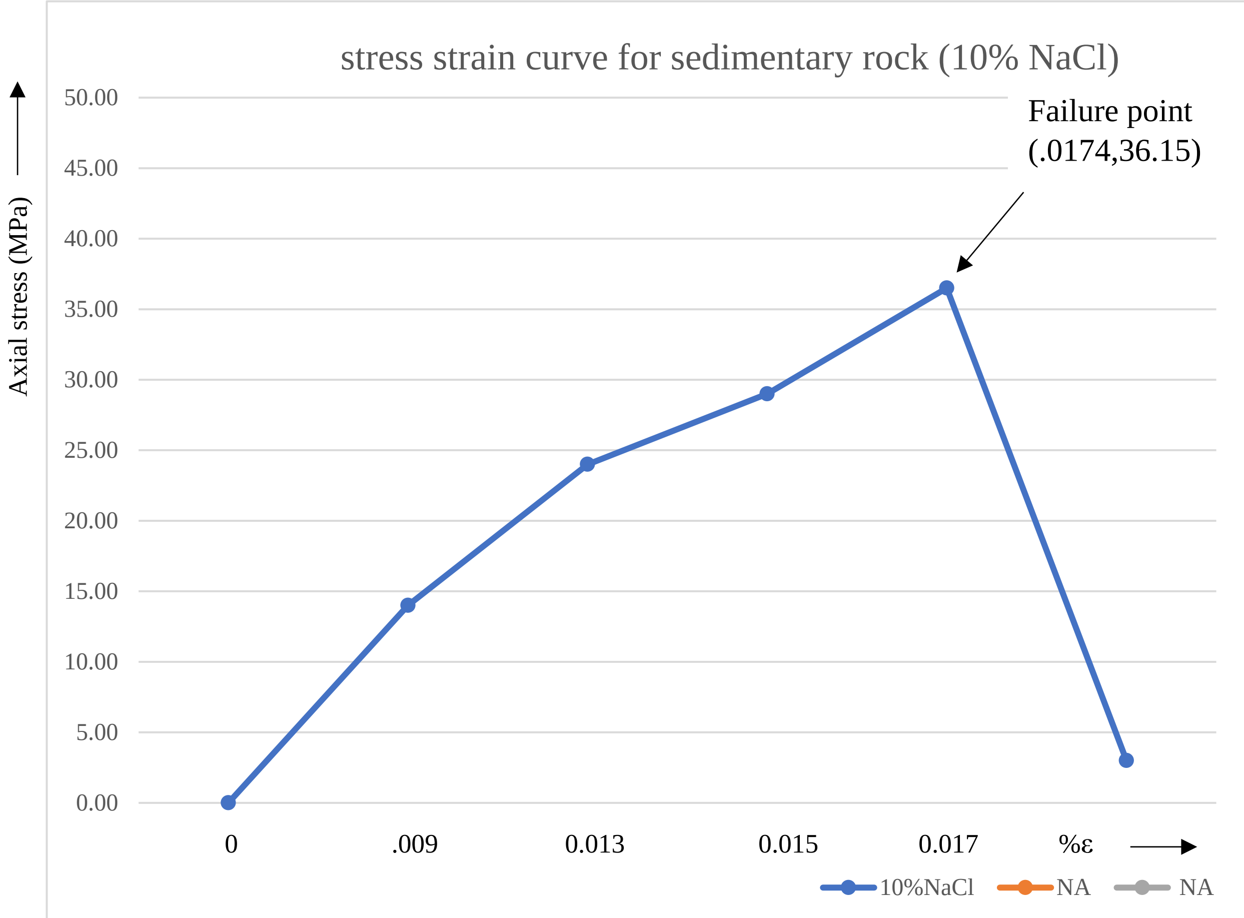

Fig:34 stress vs strain

(10% NaCl)

The curve shown in fig 34 is plot of the stress-strain for the samples kept under salt concentration of 10%NaCl solution. The values were obtained performing the test in laboratory in CTM machine after keeping the samples immersed in the salt solution for period of 300 days to simulate the field conditions as nearly as possible but under very little or negligible confining pressure. The data recorded is thus plotted.

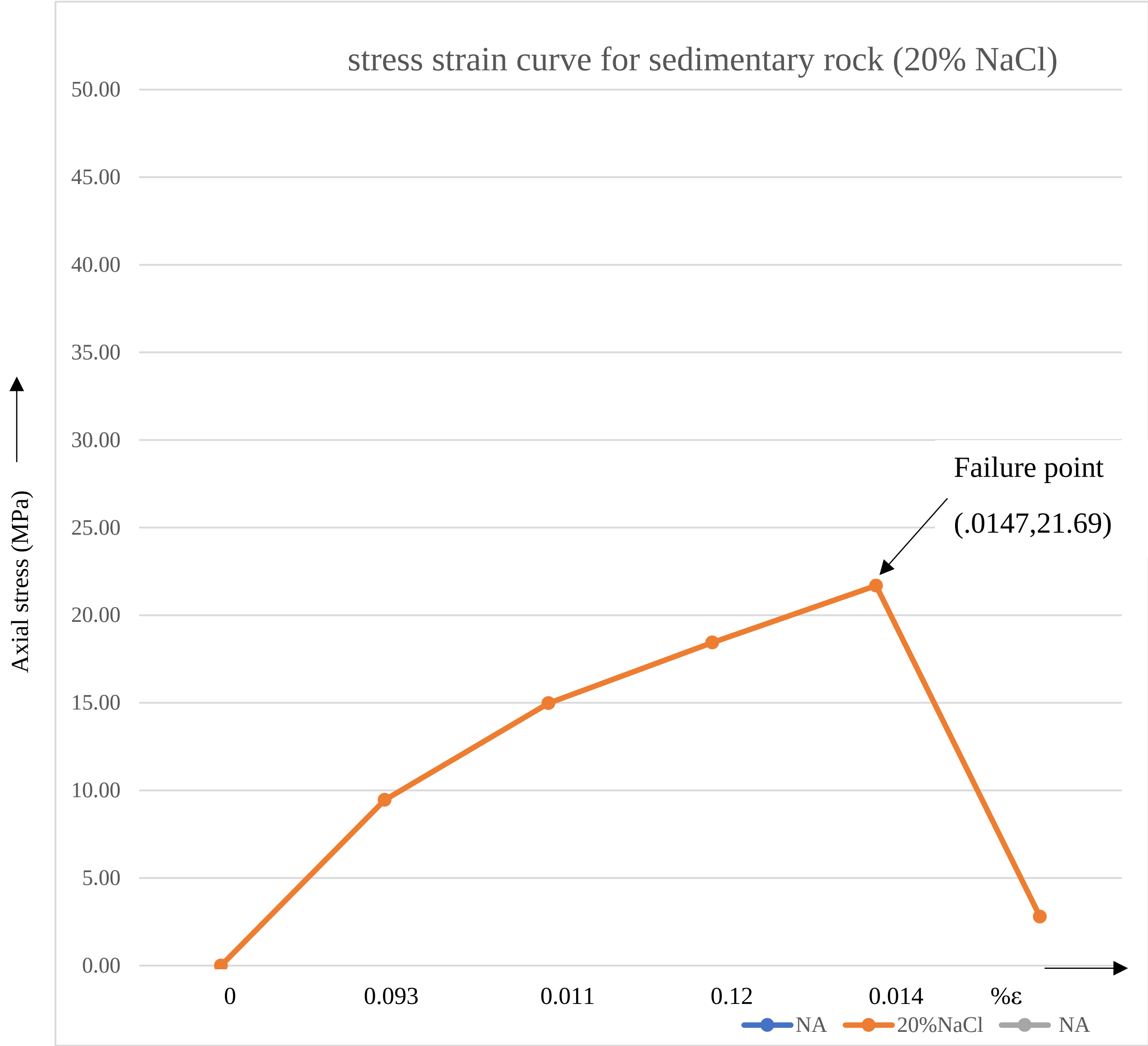

Fig:35 stress vs strain

(20% NaCl)

The above curve shown in fig 35 is the plot of stress-strain of the samples kept immersed for 300 days in a salt solution with concentration of 20% NaCl by weight. The values obtained after performing the test in laboratory in CTM machine and results obtained are thus plotted. It can be seen that the values obtained are little less than the values of 10% NaCl salt concentration samples.

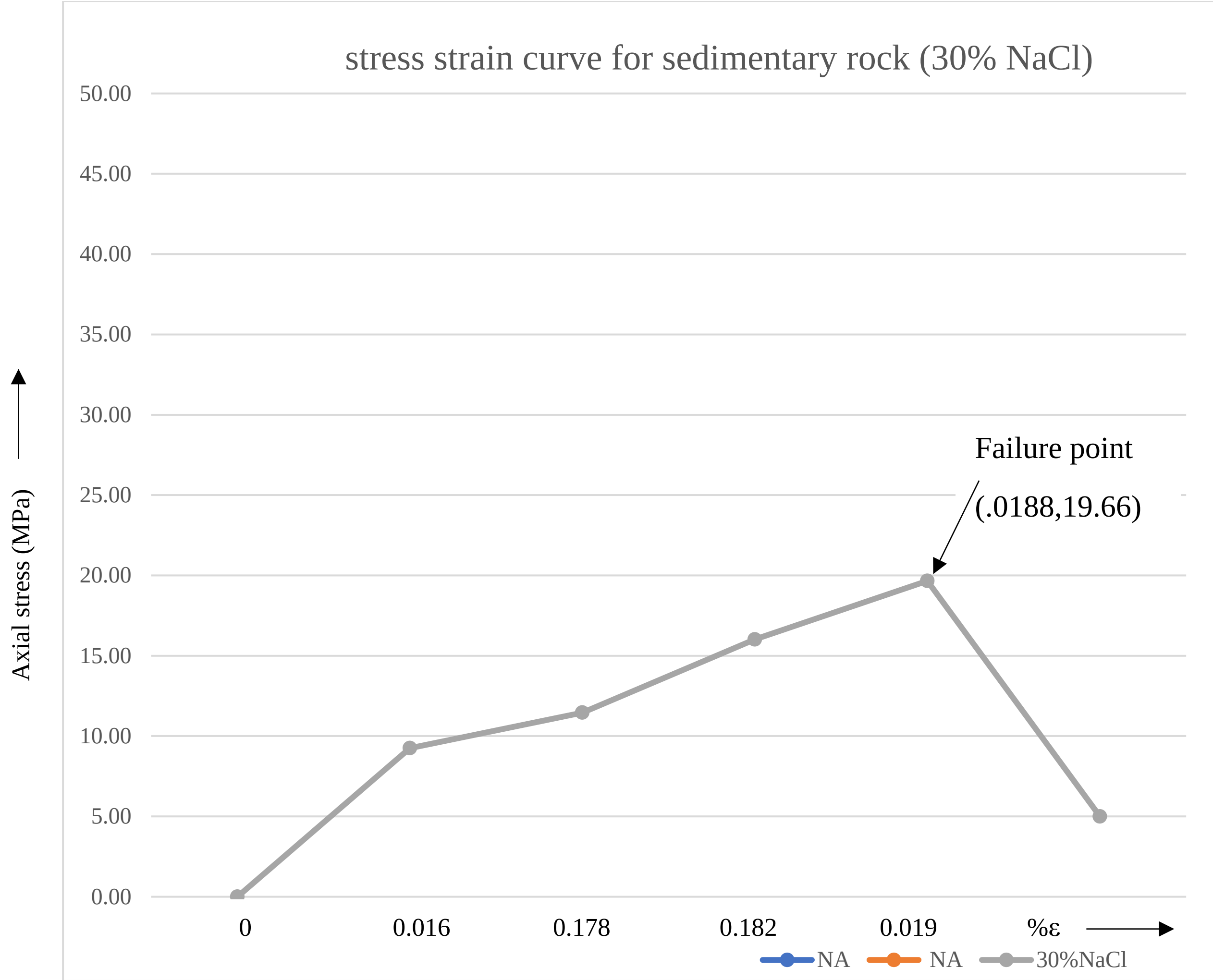

Fig:36 stress vs strain

(30% NaCl)

The above curve in fig 36 plotted shows the test results of the stress-strain on the samples kept immersed under salt solution of concentration with 30% NaCl by weight. The test was performed after 300days from the start when the sample was kept in the solution. The results came out showed us that the values of stresses for this concentration of salt solution is reduced than the other salt solutions of 10% and 20% NaCl.

Further the recorded strains are plotted on the stress-strain graph to study the behaviour of the sandstone.

Co-relation of Various Salt Concentration

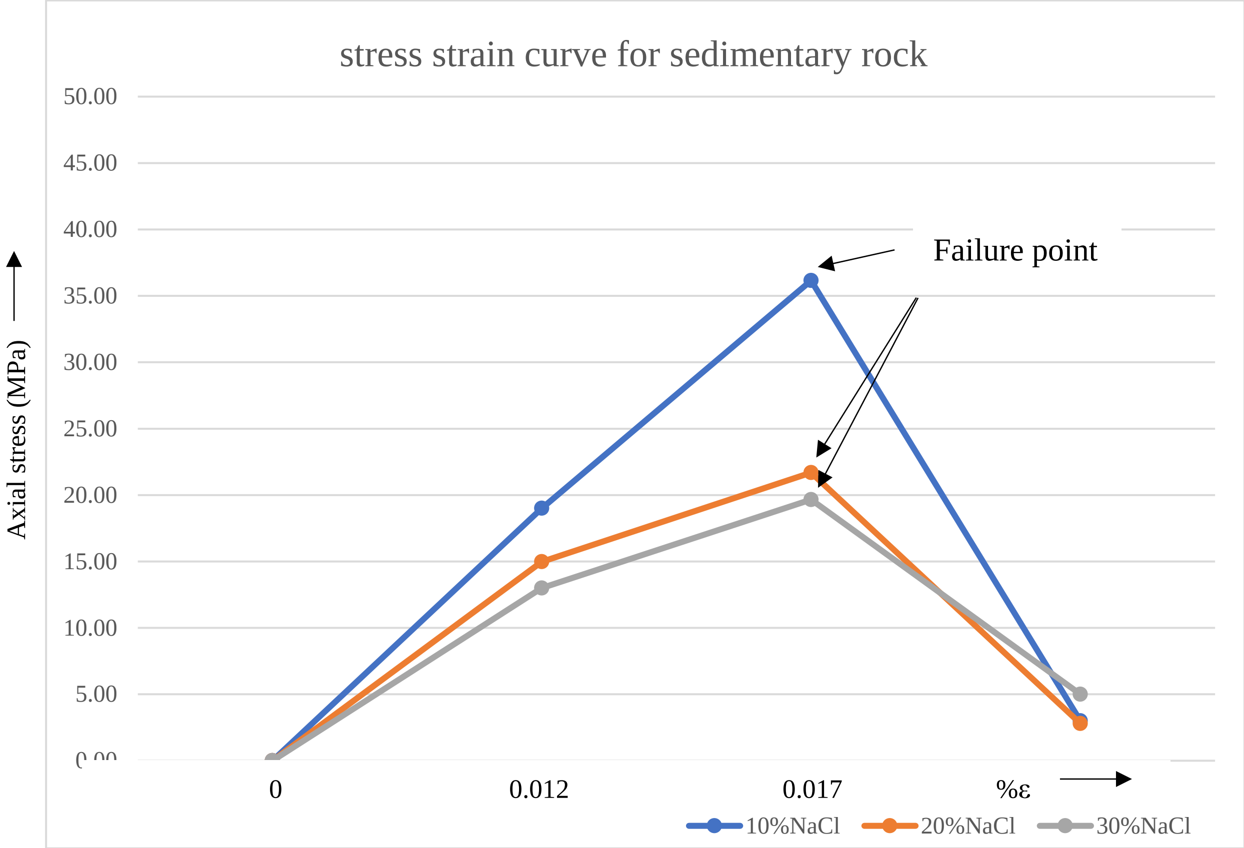

Fig:37 stress vs strain

(co-relation of concentrations)

As we can see from the above stress-strain in fig 37 that the change in stress for sample of 10%NaCl solution is more than the sample of other two solutions i.e., 20% and 30% NaCl solution. The stress strain curve follows almost same trend for all the samples and the samples fail nearly at a strain range of 0.016% -- 0.018% (avg. of 0.017% is shown) and there is no certain relationship of the failure strain with the salt concentration of the rock sample as it is in the case of stress we analysed before i.e., load bearing axial stress decreases with the increase in salt concentration of the sedimentary rock samples.

Fig 38 shows the failure of sample in UCS test and fig 39 shows the failure pattern with the crack across the bedding plane, crack initiates from the top surface and end at bottom of the rock sample causing its failure. Stress and strains are analysed when the first crack is induced in the sample and value of stress or strain changes abruptly in either increasing or decreasing values. Fig 40 shows the failure plane of the sandstone with bedding plane across the failure and crack pattern.

Fig:38 failure of sample with recording stress and strain

Fig:39 progression of crack across the plane

Fig:40 failure plane across the bedding plane of the sedimentary rock

4.1.5 Stress analysis of samples with bedding plane at an angle

Some samples were also analysed for the stress at some angle of bedding plane, i.e., 90-degree and 75-degree as shown in fig 41.

For sample with 10% salt concentration, failure stress value recorded for 75degree bedding plane at the end of 300 days comes out to be 36.32MPa

Fig:41 bedding plane at an angle of 75°

The fig 41 shows test result showed that the failure plane corresponds with the bedding pane at an angle of 75° with the vertical. The cracks develop at bedding plane angle and comes parallel to the bottom surface along the plane.

For sample of same salt concentration of 10% NaCl content with bedding plane along the line of load application in the CTM machine i.e., 90° the stress comes out to be 30.86 MPa.

Fig:42 failure along the bedding plane for 10% NaCl

As shown in fig 42 the cracks developed is along the bedding plane which is parallel to the axis of load applied, the crack progresses along one of its weak planes i.e., bedding plane and forms a failure surface from top of surface to bottom.

As shown in fig 43 for the sample with salt concentration of 30% NaCl solution UCS test was performed with bedding plane at 90° for the sample. The strength under CTM machine and unconfined compressive strength were recorded and observed.

Fig:43 failure of sample with 30% NaCl

The observation showed that the recorded stress at failure for the 30% NaCl salt solution for perpendicular bedding plane i.e., 90° (load along the weak plane of failure) is 20.36 MPa. The failure surface builds along one of the bedding planes and the portion is chipped of from the sample.

4.2 Scope of Research

1. The Triaxial test could be performed with confining pressure to simulate more accurate field conditions and the effect of depth and confinement on its strength could be studied.

2.The effect of weathering on the mineral composition and its alteration could be studied on different types of igneous, sedimentary or metamorphic rock.

3. Apart from exposure to sea and marine environmental conditions weathering of sedimentary rock by physical processes like wind and river could be studied, and also slope stability of hill ranges exposed to atmosphere and high velocity wind condition could be analysed.

4. Estimation of Young's modulus and other elastic properties of the sedimentary rock type could be studied and the effect of physical or chemical weathering on it.

5. Conclusion

The paper presented is a study of the effect on the strength of the sedimentary rock due to weathering process over the time, the saline environment and its concentration of the brine solution causing chemical weathering and degrading their physical strength with time. Following conclusions can be drawn from the study:

1. Characterisation Index test were performed in laboratory on some standard and non-standard samples reveals the physical properties about the sedimentary rock. The strength of rock is anisotropic, i.e. high across the bedding planes and weak along the planes due to slipping of layers on each other with low shear strength. The sandstone has high value of slake durability thus concluding that the sedimentary rock is susceptible to chemical degradation more than its physical degradation in sea and marine conditions.

2. Salinity effect on UCS: - With the effect of weathering in saline environment the UCS strength was seen to be decreasing with time and with increasing content of NaCl (%). Although it is difficult to create the same degree of confinement and extreme pressure due to depth of the rock as in reservoir, we have tried to simulate field conditions by placing the rock samples with 10%, 20% and 30% brine solution in cannisters. The decrease in failure strength was seen up to 57% for 10% NaCl and that for 30% NaCl salt content strength decreased up to 65% of UCS. As the timespan of tests were increased rate of decrease in strength also decreases and approach its minimum value after which there would be negligible effect of time on stress value of the sedimentary rock. Almost after 300 days the slope of stress-time graph approach constant stress value asymptotically.

3. Salinity effect on strength and deformation: - The conclusion drawn from stress-strain curve shows that due to weathering in saline environment conditions the stress decreases with time and increasing salt content as the peak at failure point is falling. Sample fails with almost similar strain values for each of 10%, 20% and 30% brine solution. Thus, weathering effect on rock solutions was seen to not affect strain values at the same extent.

4. Effect of weathering on strength along bedding planes: - The strength of sedimentary rock is weaker along the bedding plane than across it, due to the fact that shear strength along bedding planes is less. The weathering effect on the sample with inclined bedding plane i.e. 90° when tested for UCS test with load being applied along the bedding plane also shows the decreasing UCS value by 34% for 30% brine solution as compared to 10% brine solution sample.

5. Reference

1. Azimian, A. and Ajalloeian, R., 2015. Permeability and groutability appraisal of the Nargesi dam site in Iran based on the secondary permeability index, joint hydraulic aperture and Lugeon tests. *Bulletin of Engineering Geology and the Environment*, *74*(3), pp.845-859.

2. Cantisani, E., Garzonio, C.A., Ricci, M. and Vettori, S., 2013. Relationships between the petrographical, physical and mechanical properties of some Italian sandstones. *International Journal of Rock Mechanics and Mining Sciences*, *60*, pp.321-332.

3. Cardell, C., Rivas, T., Mosquera, M.J., Birginie, J.M., Moropoulou, A., Prieto, B., Silva, B. and Van Grieken, R., 2003. Patterns of damage in igneous and sedimentary rocks under conditions simulating sea-salt weathering. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *28*(1), pp.1-14.

4. Datta, A.K., 1983. Geological evolution and hydrocarbon prospects of Rajasthan basin. *Petroleum Asia Journal, Oil and Natural Gas Commission*, *6*(4), pp.93-100.

5. Hoek, E., Marinos, P.G. and Marinos, V.P., 2005. Characterisation and engineering properties of tectonically undisturbed but lithologically varied sedimentary rock masses. *International Journal of Rock Mechanics and Mining Sciences*, *42*(2), pp.277-285.

6. Khosla, A. and Verma, O., 2015. Paleobiota from the Deccan volcano-sedimentary sequences of India: paleoenvironments, age and paleobiogeographic implications. *Historical Biology*, *27*(7), pp.898-914.

7. Mebrahtu, G., Abay, A., Hailu, G. and Hagos, M., 2019. Electrical resistivity imaging and engineering geological investigation of Gereb Segen dam, northern Ethiopia. *Bulletin of Engineering Geology and the Environment*, pp.1-13.

8. Qi, S., Yue, Z.Q., Wu, F. and Chang, Z., 2009. Deep weathering of a group of thick argillaceous limestone rocks near Three Gorges Reservoir, Central China. *International Journal of Rock Mechanics and Mining Sciences*, *46*(5), pp.929-939.

9. Rathnaweera, T.D., Ranjith, P.G., Perera, M.S.A. and De Silva, V.R.S., 2017. Development of a laboratory-scale numerical model to simulate the mechanical behaviour of deep saline reservoir rocks under varying salinity conditions in uniaxial and triaxial test environments. *Measurement*, *101*, pp.126-137.

10. Raza, M., Ahmad, A.H.M., Shamim Khan, M. and Khan, F., 2012. Geochemistry and detrital modes of Proterozoic sedimentary rocks, Bayana Basin, north Delhi fold belt: implications for provenance and source-area weathering. *International Geology Review*, *54*(1), pp.111-129.

11. Roy, A.B. and Jakhar, S.R., 2002. *Geology of Rajasthan (northwest India): Precambrian to recent*. Scientific Publishers (India). Geological Survey of India.

12. Villarraga, C.J., Gasc-Barbier, M., Vaunat, J. and Darrozes, J., 2018. The effect of thermal cycles on limestone mechanical degradation. *International Journal of Rock Mechanics and Mining Sciences*, *109*, pp.115-123.