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CASE STUDY



Relationship between petrography and geomechanical properties of the sandstone: A case study from Wadi Halfa, North Sudan

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ABSTRACT

The investigation of the effect of petrography and diagenetic features on the geomechanical properties of the sandstone and their relationship to rock failure are of vital importance for different construction projects. The present study involves analyzing multi-vertical lithofacies profiles around the region of Wadi Halfa, North Sudan. The sandstone is dominantly composed of monocrystalline quartz grains (60%) accompanied by some polycrystalline quartz, feldspars, lithic fragments, micas, and heavy minerals. Iron oxides are the main type of cementing materials (14%), with some (2%) of carbonates and clay minerals. The average porosity of all studied samples is 12%. The compressive strength ranges widely, influenced by weathering, grain size, cementing materials, and bedding planes. The uniaxial compressive strength is more influenced by wetting when the load is parallel to bedding planes. Sandstone anisotropy is suggested by a U-shaped curve, with lower values at 45° and higher values at 90° and 0°. The geomechanical behavior of rocks masses in Wadi Halfa was evaluated through a combination of field and laboratory analyses which revealed a variable Rock Mass Rating (RMR) ranging from 58 to 92 and a Geological Strength Index (GSI) ranging from 33 to 61.

KEYWORDS

sandstone, compressive strength, anisotropy, post-specimen failure, softness coefficient, RMR, GSI

1. INTRODUCTION

Sedimentary rocks naturally occur in different textures and structures, this heterogeneity comprising mineral composition, grain size, shape, orientation, and anisotropy highlights the significance of considering the impact of petrography on the geomechanical behavior which is vital for civil and construction engineering projects, so the composition and petrographic properties of sedimentary rocks especially sandstone are essential for assessing important information such as strength-deformation characteristics, failure mechanisms, slope instability, and other engineering purposes [1–4].

The behavior of petrographical characteristics of the sandstone such as different quartz grains, cementing materials, matrix, and intergranular and oversized pores are crucial for various physical and geomechanical properties like elastic properties (γ), ultrasonic pulse velocity (UPV), and uniaxial compressive strength (UCS), understanding these factors is

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essential, as they can affect the stability of large engineering projects and potentially lead to hazardous situations like rockfalls, causing risks to human safety [5–9].

Bedding planes, joints, and fractures, contribute to weakening and significantly influence overall strength response leading to decreased strength properties of sandstone [10–13].

The selected study area presents dissected Wadi Halfa Oolitic Ironstone Formation (WHOI) outcrops potentially valuable for engineering and construction purposes, such as building materials, ornamental stones, slope stability, foundations, and road bases. While regional and project-specific geotechnical data for Nubian Sandstone Formation (NSF) rocks are available, there is a lack of information on the unique WHOI formation geomechanical properties and rock failures in the study area [14].

The purpose of the present study is to conduct a comprehensive examination of the sandstone within the WHOI formation, with the goal of understanding the relationship between its petrographical characteristics on geomechanical parameters to evaluate the strength of both intact rock and rock mass by utilizing Rock Mass Rating (RMR) and Geological Strength Index (GSI) methods in accordance to petrography and diagenesis affecting these geomechanical properties and to investigate the different types of rock failure occurring around the region of Wadi Halfa, northern Sudan.

2. STUDY AREA & GEOLOGY

Wadi Halfa town is situated near the Egyptian-Sudanese border, close to the Nubian Lake (Fig. 1a), characterized by Paleozoic and Mesozoic sedimentary rocks overlaying the Pre-Cambrian basement complex rocks. The prominent sedimentary formation, known as NSF or recently WHOI formation, exhibiting loose to highly consolidated sandstones, siltstones, mudstones, barite concretions and oolitic ironstone [15, 16].

The Precambrian basement complex found in the southern part consisting different lithological units of high-grade metamorphic rocks followed by syn to late tectonic intrusives, ophiolites and immature sediments [17].

The term 'WHOI' has been assigned to the NSF around Wadi Halfa with a variety geological history ranging from Upper Carboniferous to Lower Jurassic age [16] as indicated in Fig. 1b. The lithofacies of this formation encompass different deposition environment type including fluvial, glacial, fluvioglacial, and shallow marine sediments, with primary sedimentary structures of sandstone facies (trough and planner cross bedded, rippled sandstone, horizontally stratified sandstone) and mudstone facies (fine and massive mudstone), along with barite concretion facies [15, 16, 18] as shown in Fig. 2.

The selected profiles generally consist of fine- to coarse-grained yellowish, brownish, whitish, and reddish ferruginous sandstone. However, some profiles exhibit three layers of oolitic ironstone with varying thicknesses, while others

contain features large, silicified tree trunks embedded in different parts. Some profiles are characterized by intercalations of siltstone, sandstone, and siltstone with approximately the same sizes and quantities.

3. DATA & METHODOLOGY

3.1. Field observations

Identification and selection of fifteen representative vertical profiles, each representing distinct lithofacies associations within the WHOI formation. These profiles underwent field description, sampling, and reclassified into six main profiles representing as the major constituent of other profiles (Fig. 3).

Other field trips were done for detail geomechanical survey for measuring of rock quality designation (RQD) and GSI following charts suggested by [19, 20]. RQD estimated in the field using modified Eq. (1) suggested by [21, 22]:

$$RQD (\%) = 115 - 3.3 J_v \quad (1)$$

Where J_v is the sum of the number of joints per unit length for all joint (discontinuity) sets known as the volumetric joint count.

- Measuring of RQD by scan line methods of all selected profiles.
- Elaboration of measurement of primary structures including cross bedding for describing their thickness and inclination.
- Study of surface condition of discontinuities which include the dip direction and angles of each bed, discontinuities spacing and weathering and alteration of discontinuity surface for GSI classification.
- Description of block size and shape bounded by discontinuities of rock masses.

3.2. Laboratory analysis

Twenty-one samples were systematically collected from all the previously described lithological units to facilitate laboratory investigations for the detailed mineralogical and geomechanical properties including:

3.2.1. Mineralogy. The selected representative samples were petrographically analyzed according to the methods suggested by [23]. The petrographic characteristics were determined by using a Leitz Laborlux 12 microscope (PL) to determine the rock constituents and the different porosity types. All selected samples were point-counted (300–500 points per thin section) by point counting stage and J Micro Vision program were used to classify the clastic sediments according to Folk's classification. This technique is standardized in geology as described by [24].

Representative twenty samples were prepared at Electron Microscope Unit, Faculty of Sciences Alexandria University for the Scanning Electron Microscopy (SEM) to study micro-textures using a JEOL-JSM-5300.



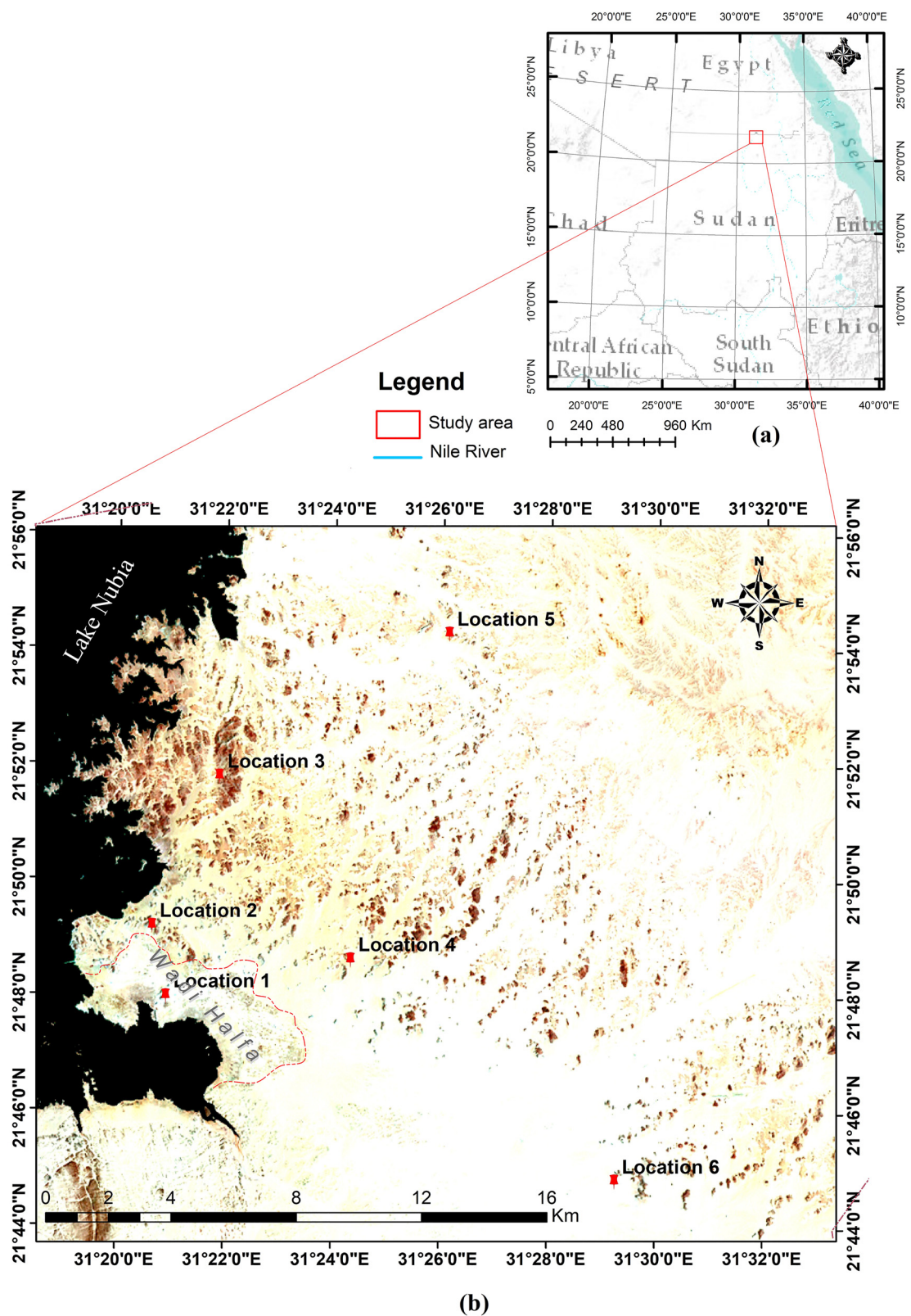


Fig. 1. Location map (a) of the study area; (b) satellite image showing locations of the selected profiles

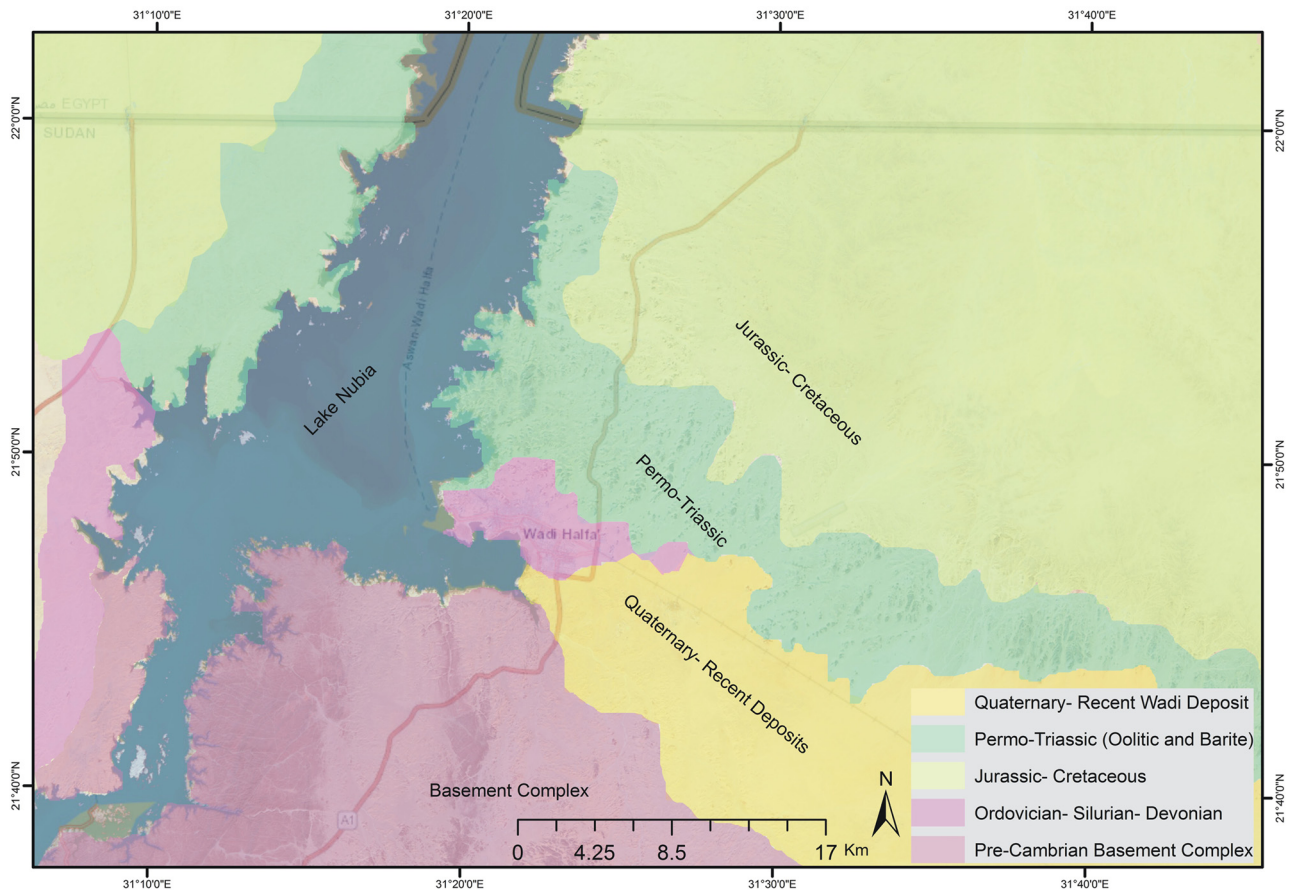


Fig. 2. General geological map showing the WHOI Formation compiled by using own field observations and data published by [16]

According to results of textural, petrographic analysis and scanning electron microscope analysis ten representative samples were carefully selected from all profiles and prepared for two steps of analysis; the first being the bulk mineralogical composition and second step is prepared for fractions less than 2 μm for clay mineralogy. XRD study was carried out using X- ray diffraction unit Philips PW-3710 with generator PW-1830, Cr target and Ni at 40 kV and 30 mA. Nuclear Materials Authority, Egypt.

3.2.2. Physical and mechanical properties. Various physical tests were conducted on all samples, encompassing unit weight (ρ), specific gravity (G_s), porosity (n), void ratio (e), and moisture content (M_c), these tests were performed using standard methods outlined in ASTM standards and procedures [25–30].

Rock samples were cored in three directions: parallel (0°), inclined (45°), and vertical (90°) to bedding planes for measuring geomechanical properties of intact rock including UCS and UPV.

Elastic modulus (E) of intact rock and rock masses was estimated and calculated according to given UCS, UPV, ρ , and gravity (g).

As the water absorption test (W) is the most important factor that effect on the geomechanical properties of rocks [31–33], all samples tested for compressive strength under-went water absorption test.

4. RESULTS

4.1. Field observations of rock masses

Geological and geomechanical data were gathered through various methods to describe the rock masses in the field. Parameters such as color, structure, degree of weathering, fabrics, bedding characteristics, block size and shape, roundness, discontinuity spacing, and rock strength were assessed for all selected profiles.

Wadi Halfa Oolitic Ironstone Formation exhibited distinct structures, including bedding planes (planar, cross bedding, and trough crossbedding), weathering-induced structures (caves and honeycomb formations), and vertical/horizontal joints. The degree of weathering varied across profiles, with 50% slightly weathered, 33.3% moderately weathered, and 16.75% highly weathered.

Profiles 1, 3, and 5 showed slight weathering, indicating no significant loss of strength or discoloration. **Profiles 2, 4, and 6** exhibited increased rock joints and falling rocks due to high weathering. Bedding inclinations were predominantly sub-horizontal [$0-5^\circ$], with some gently inclined layers. All profiles had thick rock beds ($>2\text{ m}$) with large block sizes ($>2\text{ m}$) (Fig. 4).

Block masses were characterized by dominant parallel bedding planes, non-continuous discontinuities, and three orthogonal sets of discontinuities with irregularities.

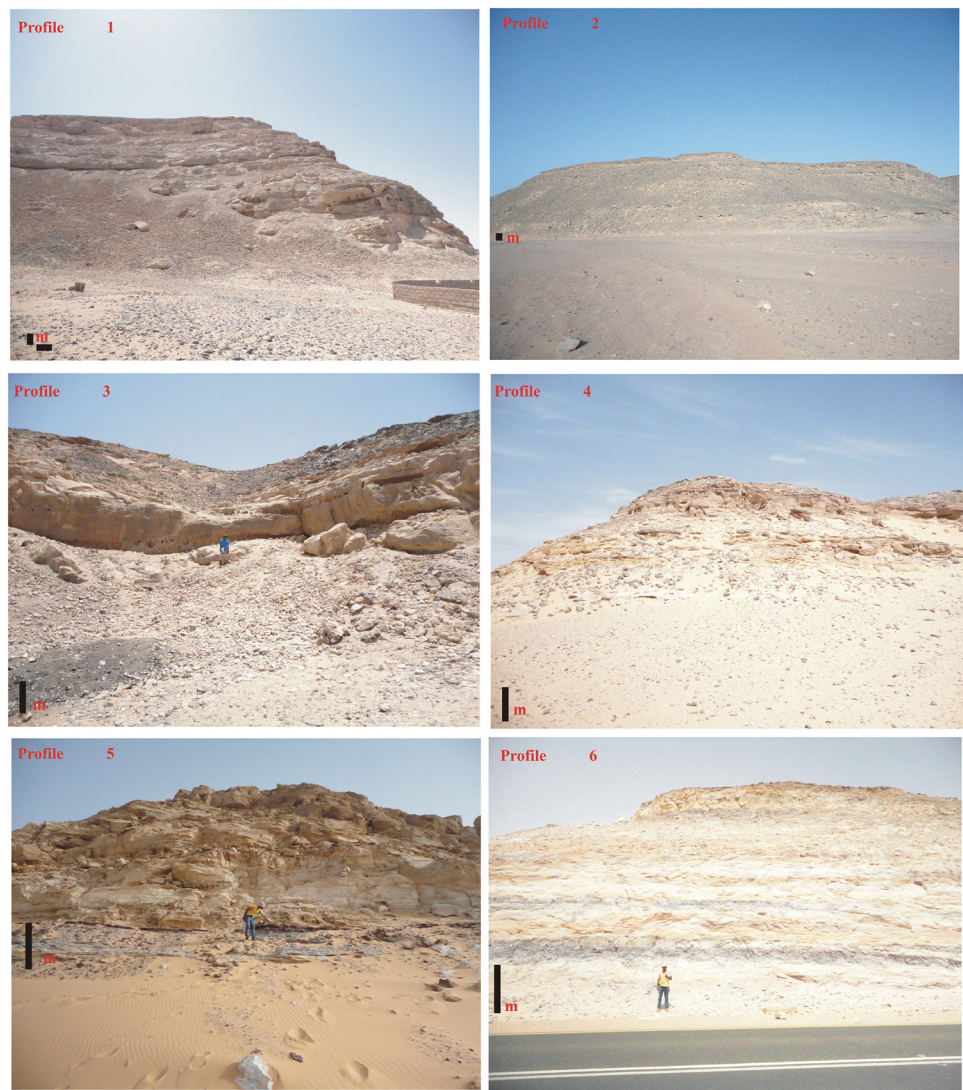


Fig. 3. Representative lithofacies profile around the region of Wadi Halfa

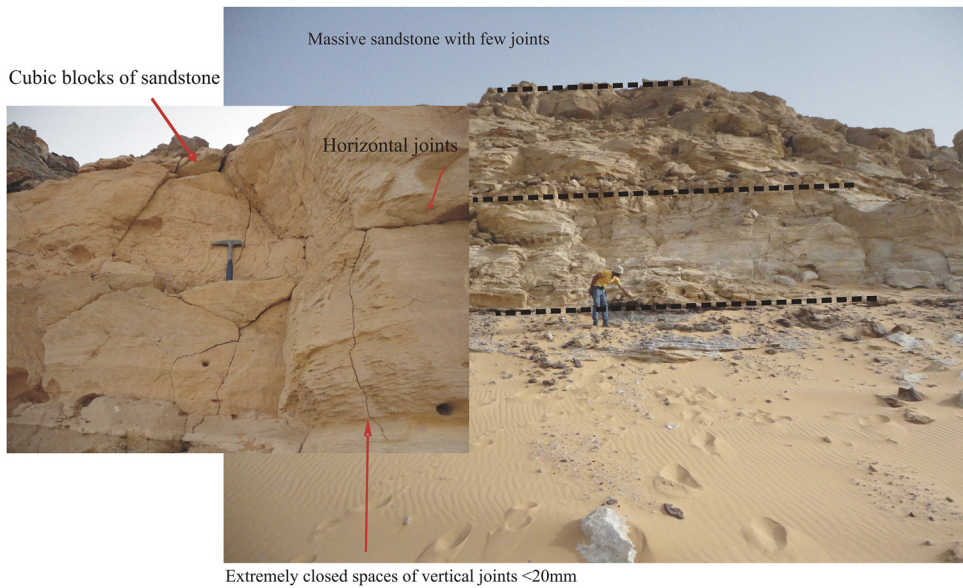


Fig. 4. A massive sandstone showing vertical and horizontal joints with extremely closed spacing of joints, found in Profile 5

Discontinuity spacing varied, with extremely close spacing (<20 mm) in some profiles and closely to very closely spaced (20–200 mm) in others as shown in (Fig. 5).

A comprehensive summary of field descriptions and observations for all six profiles is presented in Table 1.

Profiles one and three show little numbers of discontinuities more than 10 cm length and give values of RQD more than 60%, that means the RQD values of 60% refer to fair qualitative description. Profile six shows low values of RQD due to high joints and intercalations of sandstone, siltstone, and claystone layers with similar amounts.

In accordance with the structure and composition section of the GSI classification chart and referenced in the field observations, the profiles can be categorized into different types (A, B, C, and D):

1. Profiles 1, 3, and 5 fall into the type categories A and B. These profiles exhibit thick bedded, very blocky sandstone, and sandstone with interlayers of siltstone. In some cases, the bedding planes of the sandstone may contribute to structurally controlled instability. The discontinuity surface conditions are good, characterized by a rough, slightly weathered surface. These profiles consist of fine- to medium- to coarse-grained sandstone layers in shades of yellow, red-brown, and white-grey. They also feature well-developed bedding planes, along with thin laminated mudstone and siltstone layers.
2. Profiles 2 and 4 are classified under type category B and C, characterized by sandstone with thin layers of claystone and siltstone in similar amounts. In profile two, there is also sandstone with oolitic ironstone in comparable proportions. The surface conditions of the

Open aperture or discontinuity in sandstone layers filled by loose sands



Fig. 5. Vertical, oblique, and horizontal open joints, indicated by red arrows. These discontinuities are filled with loose sand, as seen in Profile 2

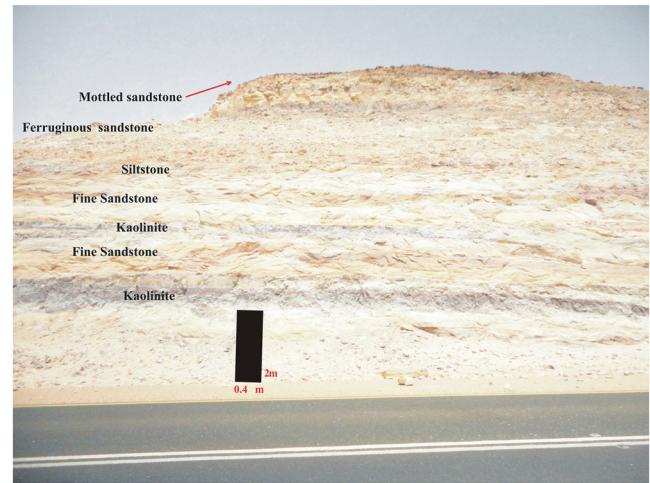


Fig. 6. The similarity amounts of intercalation layers corresponding to type (D) type category in the Geological Strength Index determination (Profile 6)

Table 1. The summary of field observations and descriptions of rock masses for each profile

Rock mass description	Profile1	Profile2	Profile3	Profile4	Profile5	Profile6
Structure	Bedding, cross bedding, trough cross bedding, joints caves and honeycombs					
Color	Yellowish, brownish, reddish, pinkish, greyish, and whitish					
Weathering	Slightly (SW)	Highly (HW)	Slightly (SW)	Moderately (MW)	Slightly (SW)	Moderately (MW)
Fabrics	Massive	Fine	Massive	Coarse	Medium	Fine
Bedding inclination	Sub horizontal and gently inclined.					
Bedding thickness	Very thick (>2m), thick and moderately thick (0.2 – 0.6 mm)					
Rock strength (geological hammer)	Strong	weak	Extremely strong	Very strong	Strong	Moderately strong
Roundness	Planer rough (VII)	Planer rough (VII)	Smooth (VIII)	Rough (VII)	Planer rough (VII)	Rough (VII)
Block size	Very large, Medium, and Large					
Block shape	Tabular	Equidimensional	Tabular	Prismatic	Equidimensional	Polyhedral
Discontinuity spacing	Extremely closed	Closely to very spaced	Extremely closed	Extremely closed	Extremely closed	Closely to Very closely spaced
Filling materials	Soft filling including sand, silt, and clay					
Rock Quality Designation (RQD %)	60	66.3	100	86.8	85.4	45.7

Table 2. The petrographic point counting results of the studied samples from Wadi Halfa

Number	Samples	Roundness	Textural Data				Detrital Grains						Cement/Matrix				Pores	
			G. Contact				Quartz		Feldspars	Rock Frag.	Heavy M.	Micas	Iron Oxides	Carbonates	Clays	Others	Intergranular	Oversized
			Point C.	Conc. C.	Over G.	Straight	Mono	Poly										
1	P1S1	A-SA	4	–	–	–	43	5	0	2	0	0	16	0	4	0	25	5
2	P1S2	SA-SR	1	–	1	–	69	1	1	4	0	0	8	3	4	0	9	2
3	P1S3	SA-SR	2	1	–	–	64	0	0	0	0	0	6	0	16	0	12	2
4	P1S4	SA-SR	6	2	–	1	63	1	0	1	0	0	12	0	0	0	12	0
5	P1S5	A-SA	7	8	1	–	64	0	0	0	1	0	10	0	14	0	12	0
6	P2S1	SA-SR	3	1	2	–	67	0	2	1	1	0	19	6	0	0	4	0
7	P2S2	R-SR	4	1	0	0	61	0	2	1	1	1	16	2	2	0	11	3
8	P3S1	A-SA	5	0	3	–	63	4	1	1	1	0	5	0	13	1	11	0
9	P3S2	SA-SR	6	4	–	–	67	2	4	1	0	0	14	0	6	0	5	0
10	P3S3	A-SA	6	3	1	–	59	3	3	1	0	0	14	0	16	0	5	0
11	P4S1	A-SA	2	2	4	1	50	8	2	1	0	0	5	9	1	0	18	7
12	P4S2	SA-SR	5	3	–	–	61	0	2	4	1	1	0	6	2	0	23	0
13	P4S3	A-SA	2	–	–	–	40	3	1	2	0	0	37	0	1	0	16	0
14	P4S4	A-SA	21	4	–	–	57	1	1	1	0	0	17	1	1	0	15	6
15	P5S1	R-SR	4	1	1	1	56	10	0	2	0	0	5	0	4	1	16	6
16	P5S2	R-SR	3	1	1	1	60	4	1	1	1	1	29	3	0	0	0	0
17	P5S3	SA-SR	5	–	–	–	50	0	1	0	0	0	49	0	0	0	0	0
18	P5S4	SA-SR	8	–	–	–	62	0	0	3	1	0	3	0	3	0	21	7
19	P6S1	A-SA	5	–	–	–	69	1	3	0	1	0	7	2	8	0	8	0
20	P6S2	SA-SR	3	–	–	1	65	1	3	1	0	0	8	0	11	0	10	1
21	P6S3	SA-SR	1	–	–	–	61	2	2	0	0	0	19	11	2	0	2	0

G. contact: grain contact; Point C.: Point contact, Conc. C.: Concavo-convex; Over G: Overgrowth; **A-SA:** Angular to sub angular; **R-SR:** Rounded to sub rounded; **SA-SR:** Sub angular to sub rounded; **Heavy M:** minerals.



discontinuity are considered fair, displaying a smooth, moderately weathered, and altered surface.

3. Profile 6 falls into type category D, featuring sandstone with silty shale and claystone layers in similar amounts. The surface conditions of the discontinuity in this profile are also considered fair, displaying a smooth, moderately weathered, and altered surface (see Fig. 6).
4. Different types of rock falling have been detected and observed via detailed field investigations which are mainly related to bedding planes of sandstone, include plane failure and toppling failure.

4.2. Mineralogy

The grains of sandstone from WHOI Formation consist of monocrystalline and polycrystalline quartz, along with feldspars, lithic fragments, opaques (iron oxides), clays, carbonates, micas, and heavy minerals as described in Table 2.

4.2.1. Detrital framework grains. The detrital quartz grains exhibit angular to subangular quartz (62%) and rounded to subrounded shapes (38 %). Quartz grain sorting ranges from poorly to moderately sorted, with the majority being medium- to coarse-grained and minor amounts being medium- to fine-grained. The contacts between grains include point contacts, straight contacts, quartz overgrowth, concavo-convex contacts, and sutured contacts (Fig. 7a and b).

The Folk's classification of sandstone from WHOI Formation based on mineral composition (quartz (Qz), lithic fragments (L), and feldspars (F)) reveal that most of the samples are classified as quartz-arenite 67%, with less amounts of sub-lithic arenite 20% and sub-arkose 13%.

4.2.2. Cement and matrix. Authigenic minerals resulting from the alteration of detrital material are present as matrix or grain replacements and cement in the sandstone from the study area. These minerals include carbonates, iron oxides, barite, pseudo matrix, clays, and opaque minerals. The percentage of iron oxides in the studied samples varies from 0.3%–49%, with an average value of 14 %, primarily acting as cement in most samples (Fig. 7c and d).

The study area exhibits more than six layers of clays, commonly found in sandstones as matrix or cement constituents. Optical, X-ray, and SEM analyses reveal a clay mineral assemblage dominated by kaolinite, with minor amounts of illite, montmorillonite, and chlorite (Fig. 8). The diverse cementation materials significantly impact the geo-mechanical properties of the sandstone.

4.2.3. Pores. The studied samples display various types of pores, categorized as intergranular pores (between sand grains), oversized pores (larger than normal intergranular pores, comparable to sand grain size), and intra-granular pores (within grains). Most of the studied samples show medium to high porosity. The porosity of the selected samples ranges from 2% to 30%, with an average of 12% (refer to Table 1).

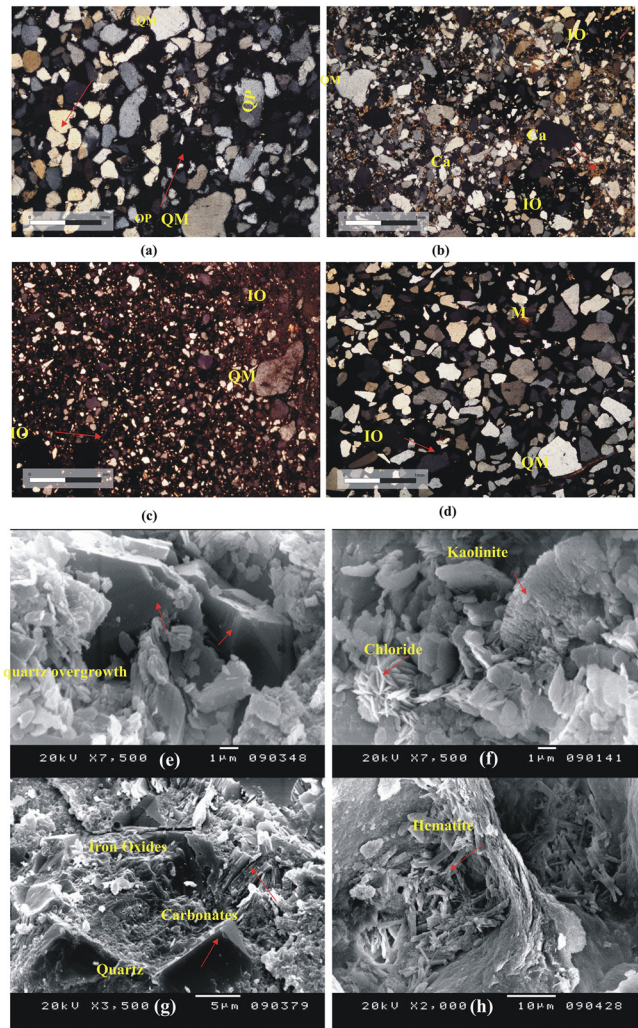


Fig. 7. Photomicrograph of detrital framework grains (a) angular to sub-angular monocrystalline (QM) polycrystalline (QP) quartz grains with straight and point contact between grains (red arrows) pores occurred between grains (P); (b) two types of cementing materials occurred iron oxides (IO) and carbonates (Ca) twined microcline occurred (F); (c) rounded to sub-rounded monocrystalline quartz grains with iron oxide occur as a main cementing material with clay matrix between grains; (d) iron oxide (IO) cemented quartz grains heavy minerals occurred (HM). OP refers to opaque minerals; (e) perfect crystal of quartz overgrowth observed under scanning electron microscope; (f) authigenic kaolinite well developed pseudo-hexagonal plates with rosette shape of chlorite; (g) iron oxides and carbonate within pores of sandstone; (h) elongated shape of hematite cement. (All photomicrographs were taken under crossed Nicols)

4.3. Geomechanical properties

The initial steps in studying the geomechanical properties of rocks involve examining their physical properties. These properties provide essential information for designing stable structures and constructions and establish a strong relationship with geomechanical characteristics.

Summarized results of the determined physical and engineering properties for dry intact samples are presented in Table 3.

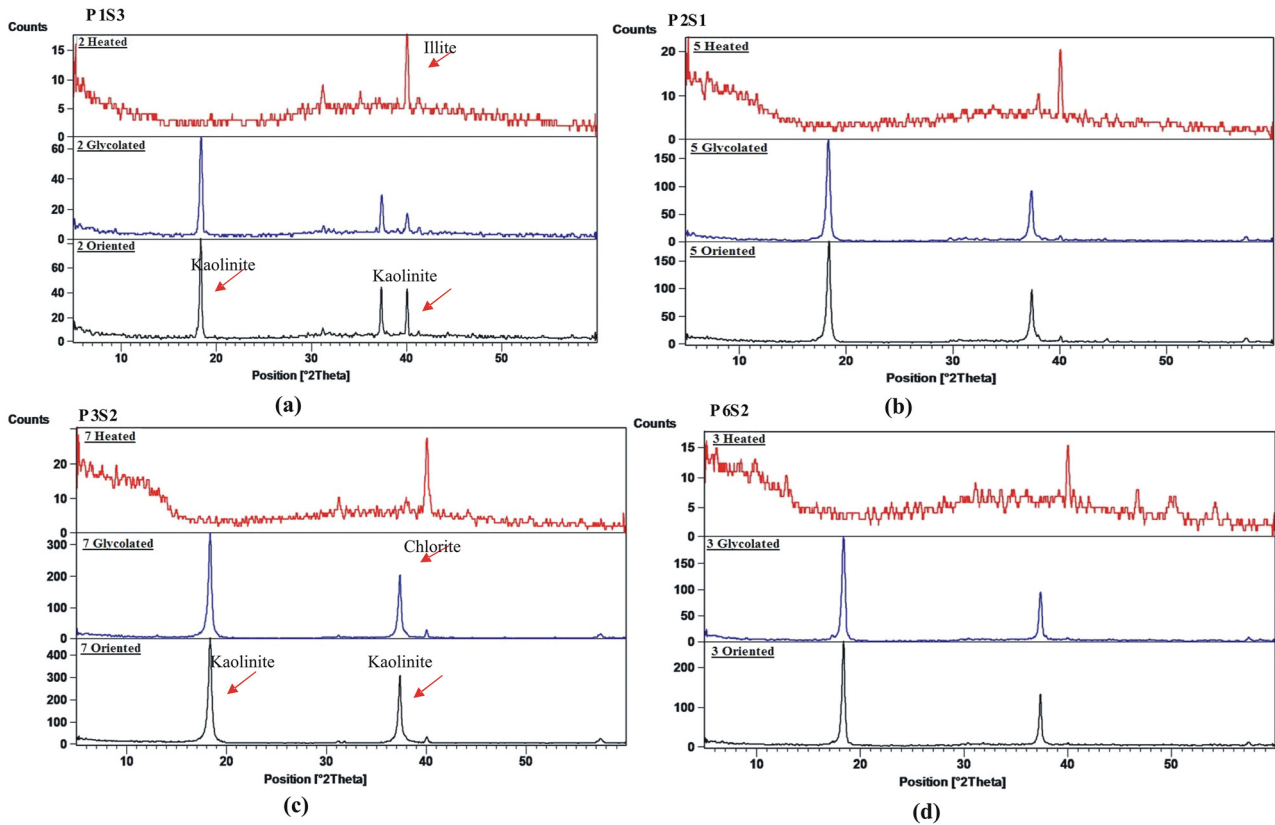


Fig. 8. Oriented (heated, oriented, and glycolate) XRD samples showing the dominance of kaolinite

The unit weight of sandstone is influenced by texture, mineral composition, and diagenetic processes in the rock's environment. The unit weight of the dry studied samples ranges from 2.13 to 2.76 g cm⁻³, with an average of 2.45 g cm⁻³.

The specific gravity of the samples varies from 2.65 to 2.72, with an average of 2.69%. Some samples (P1S2 and P3S1) exhibit elevated specific gravity values due to their high content of clays, iron oxides, and micas.

Compressive strength tests were conducted based on the angle between applied loads and bedding planes (anisotropy, angle β), samples were cored in three directions: parallel (0°), inclined (45°), and vertical (90°) to bedding planes.

Ultrasonic velocity tests were carried out on dry sandstone specimens cored parallel and vertical to bedding planes. The transit time for ultrasonic waves to traverse the sample was recorded, and UPV values were obtained.

The water content of the samples ranged from 0.10% to 0.24%, with an average of 0.17%. Mathematical relationships among unit weight, specific gravity, and moisture content were applied to calculate void ratio as shown in Eqs (2) and (3), porosity, and other weight-volume relations.

$$e = (Gs \times \gamma_w (1 + W) / \gamma) - 1 \quad (2)$$

And,

$$n = e / 1 + e \quad (3)$$

Where: γ_w refers to unit weight of water (1 gm/cm³), G_s specific gravity, n porosity, and e void ratios.

The wet compressive strength was determined for all selected profiles by choosing one sample from each profile, each representing a high content of clay matrix, carbonate and iron oxide cement and then submerging the samples in water for 24 h. The test was performed on specimens cored perpendicular (90°) and parallel (0°) to the bedding planes. Since the strength of wet sandstone (CS_{wet}) is often lower than that of dry sandstone (CS_{dry}), the softness coefficient (Sc) (Eq. (4)) indicates the reduction of strength due to wetting as shown in Table 4 and is determined using the formula:

$$Sc = UCS_{wet} / UCS_{dry} \quad (4)$$

Average values of ultrasonic velocity in the vertical and parallel directions to bedding planes are 2,293 m s⁻¹ and 2,340 m s⁻¹, respectively. Lower ultrasonic pulse velocity values in certain samples (P5S1, P5S3, and P6S1) correspond to high pore values and weak carbonate cementation. Additionally, the direction of bedding planes significantly influences ultrasonic velocity.

The strength varies between profiles of the studied samples from the Wadi Halfa due to geological and petrographic characteristics (e.g., bedding planes, sorting, types of cementing materials, roundness of quartz grains, clay content, and porosity) and their degree of weathering. The measured compressive strength ranges from weak (P5) to very strong (P2) [26].

Elastic modulus (E) of intact rock was estimated and calculated according to given ultrasonic pulse velocity (UPV), density (ρ), and gravity (g) as dictated in Eq. (5).



Table 3. Geomechanical properties of the selected intact sandstone samples

		Physical					UCS (MPa)			UPV (m s ⁻¹)			
Number Number	Samples	Porosity (n)	Specific Gravity (Gs)	Unit Weight (γ) g cm ⁻³	Void Ratio (e)	Moisture Content (%)	Anisotropy (β)			Vertical (90°)	Parallel (0°)	Water Absorption	Young's Modulus (E)
							Vertical (90°)	Inclined (45°)	Parallel (0°)				
1	P1S1	25.1	2.67	2.24	0.34	0.12	25.5	20.1	24.7	2,750	2,430	8.0	15.3
2	P1S2	18.7	2.65	2.38	0.23	0.10	112	78.7	97.3	3,500	3,110	7.1	26.6
3	P2S1	20.7	2.71	2.23	0.26	0.13	154	87.4	121	2,660	2,880	9.5	38.2
4	P2S2	13.1	2.74	2.20	0.49	0.12	116	66.1	93.6	3,100	2,970	6.2	20.7
5	P3S1	30.6	2.72	2.20	0.29	0.20	53.7	37.1	47.3	2,630	2,560	5.3	15.1
6	P3S2	8.2	2.66	2.76	0.34	0.15	66.4	42.7	50.0	2,650	2,550	8.2	19.2
7	P4S1	24.8	2.69	2.30	0.33	0.12	83.7	30.4	50.0	2,380	2,280	9.0	12.7
8	P4S2	19.4	2.66	2.20	0.24	0.11	86.4	40.5	55.5	2,840	2,800	8.9	17.8
9	P5S1	23.7	2.66	2.27	0.31	0.15	28.2	11.2	13.6	1830	1,570	10.3	26.8
10	P5S3	30.6	2.67	2.13	0.44	0.16	80.9	39.4	59.1	2060	1860	9.3	42.6
11	P6S1	19.4	2.67	2.36	0.24	0.10	82.8	53.3	79.1	2050	1960	9.6	48.2
12	P6S4	29.1	2.66	2.33	0.41	0.24	58.2	36.1	49.1	2,170	1940	12.2	48.8
13	Max.	30.6	2.72	2.76	0.49	0.24	154	87.4	121	3,500	3,110	12.2	48.8
14	Min.	8.2	2.65	2.13	0.23	0.10	28.2	11.2	13.6	1830	1,570	5.3	12.7
15	Av.	19.4	2.69	2.45	0.36	0.17	91.4	49.3	67.3	2,293	2,340	8.8	30.8
16	SE.	7.44	1.14	0.21	0.49	0.05	38.25	22.43	30.39	494.6	460.0	1.86	13.38

Max: Maximum values, **Min:** Minimum values, **Av:** Average values, **SE.** Standard Error, **CS:** Compressive strength, **UV:** Ultrasonic velocity, P1S1, P2S1, P3S1..., refer to profile 1 sample 1, profile 2 sample 2, etc.

Table 4. Uniaxial compressive strength of wet and dry samples (MPa) perpendicular (90°) and parallel (0°) to bedding planes and softness coefficient calculation

No.	Samples	CS _{Wet} (MPa)		CS _{Dry} (MPa)		Sc	
		90°	0°	90°	0°	90°	0°
1	P1S1	15.1	14.4	25.47	24.56	0.59	0.59
2	P2S1	33.6	28.9	111.87	97.32	0.30	0.30
3	P3S1	14.8	12.2	53.66	47.29	0.28	0.26
4	P4S1	26.5	22.6	83.67	50.02	0.32	0.45
5	P5S1	7.6	5.1	13.64	28.19	0.56	0.18
6	P6S4	21.0	24.3	58.21	49.11	0.36	0.49
7	Maximum	33.6	28.9	111.87	97.32	0.59	0.59
8	Minimum	7.6	5.1	13.64	28.19	0.28	0.18
9	Average	20.6	17.0	62.76	62.76	0.44	0.39
10	St. Error	8.53	8.14	33.56	27.19	0.13	0.14

$$E = UPV^2 \rho / g \quad (5)$$

Where: UPV = ultrasonic pulse velocity, ρ = density, and g = gravity.

When we subject sandstone samples to the uniaxial compressive strength test, different types of failures occur, samples exhibit brittle tensile failures. The direction of bedding planes to the applied load plays a crucial role in the behavior of rock failure.

Different types of rock failure occurred when examining the uniaxial compressive strength, including multiple fracturing, double fractures, shear fractures along bedding planes at 0°, and axial splitting fractures or extension failures at 90° similar to rock failures in the field (Fig. 9).

5. DISCUSSION

Field observations of the WHOI formation highlight different primary structures influencing geomechanical parameters, including bedding planes (planar, crossbedding, and trough crossbedding), weathering-induced features (caves and honeycomb), and vertical and horizontal joints. Profiles 1, 3, 4 and 5 exhibit slight to moderate weathering, showing no significant loss of strength or discoloration, while Profile 2 displays increased rock joints and falling due to higher weathering.

Bedding inclination measurements indicate mostly sub-horizontal layers (0–5°), with some gently inclined layers exceeding (5°). All profiles feature thick beds or layers

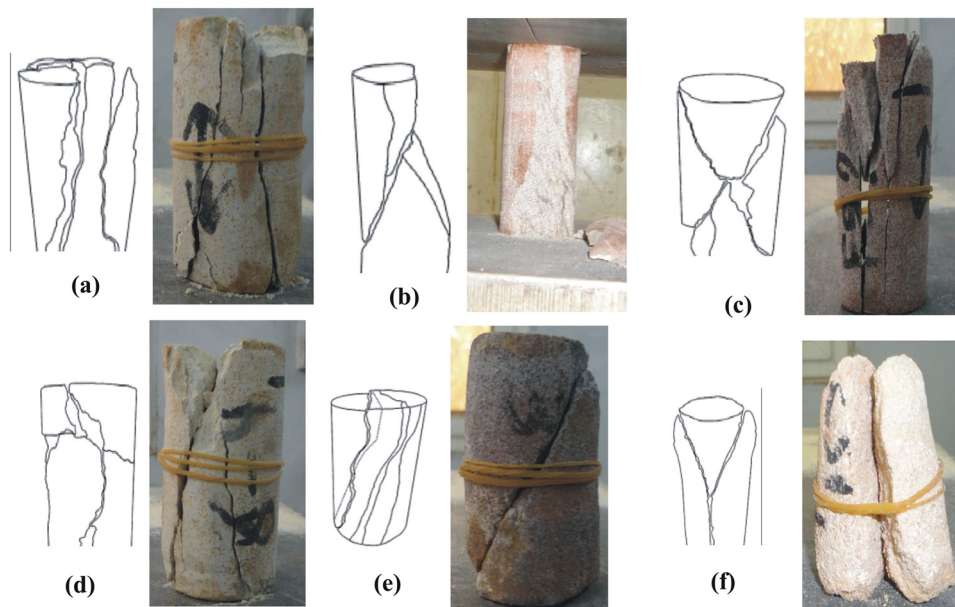


Fig. 9. Schematic shows different types of failure under uniaxial compressive strength recorded in most of studied samples, (a) axial splitting failure at 90°; (b) shearing along bedding planes at 0°; (c) double shearing; (d) multiple fracturing; (e) failure along bedding planes at 45°; and (f) Y shaped failure corresponding to toppling failure

exceeding 2.0 m in thickness. Geomechanical properties of rock samples are influenced by factors such as grain sizes and distribution, grain shapes and contacts, types, and amounts of cementing materials, and pore sizes.

Our results reveal that coarse-grained sandstone samples generally exhibit lower compressive strength compared to medium- and fine-grained samples. The angularity of quartz

grains also affects compressive strength, with samples P1S2, P2S1, and P2S2 showing high strength attributed to their iron oxide cement content, while P1S1 and P5S1 exhibit lower strength due to weathering, high porosity, and weak cementing material (carbonates).

The petrographic and geomechanical study results are depicted in scattered plots to illustrate the relationships

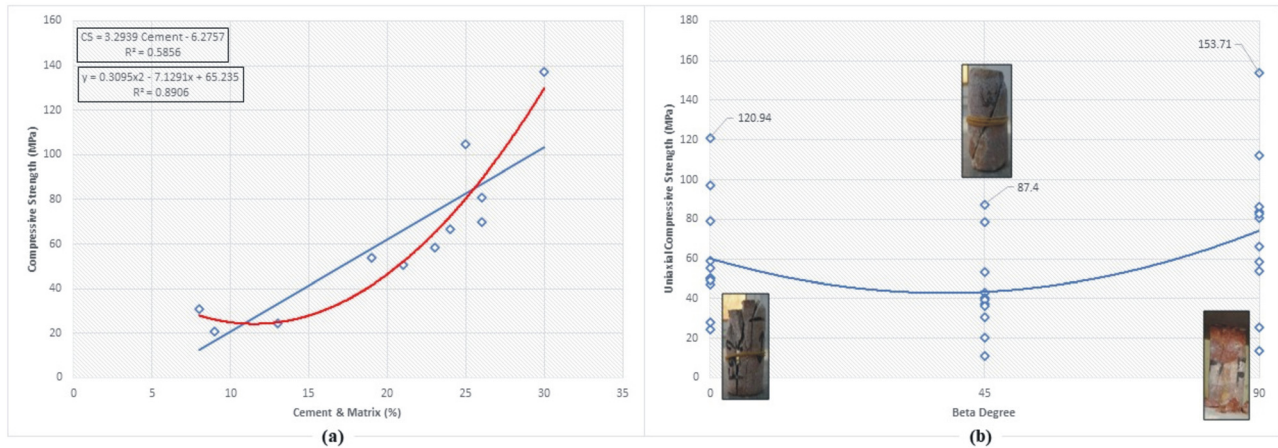


Fig. 10. Scatter plot showing (a) the relationship between compressive strength and cementing materials and matrix of studied sandstone samples (red and blue curves refers to polynomial and linear relations respectively); (b) the variation between the values of compressive strength depending on the direction of loading relative to the direction of bedding planes anisotropy angle ($\beta = 0^\circ, 45^\circ$, and 90°) showing U-shape curve of anisotropy

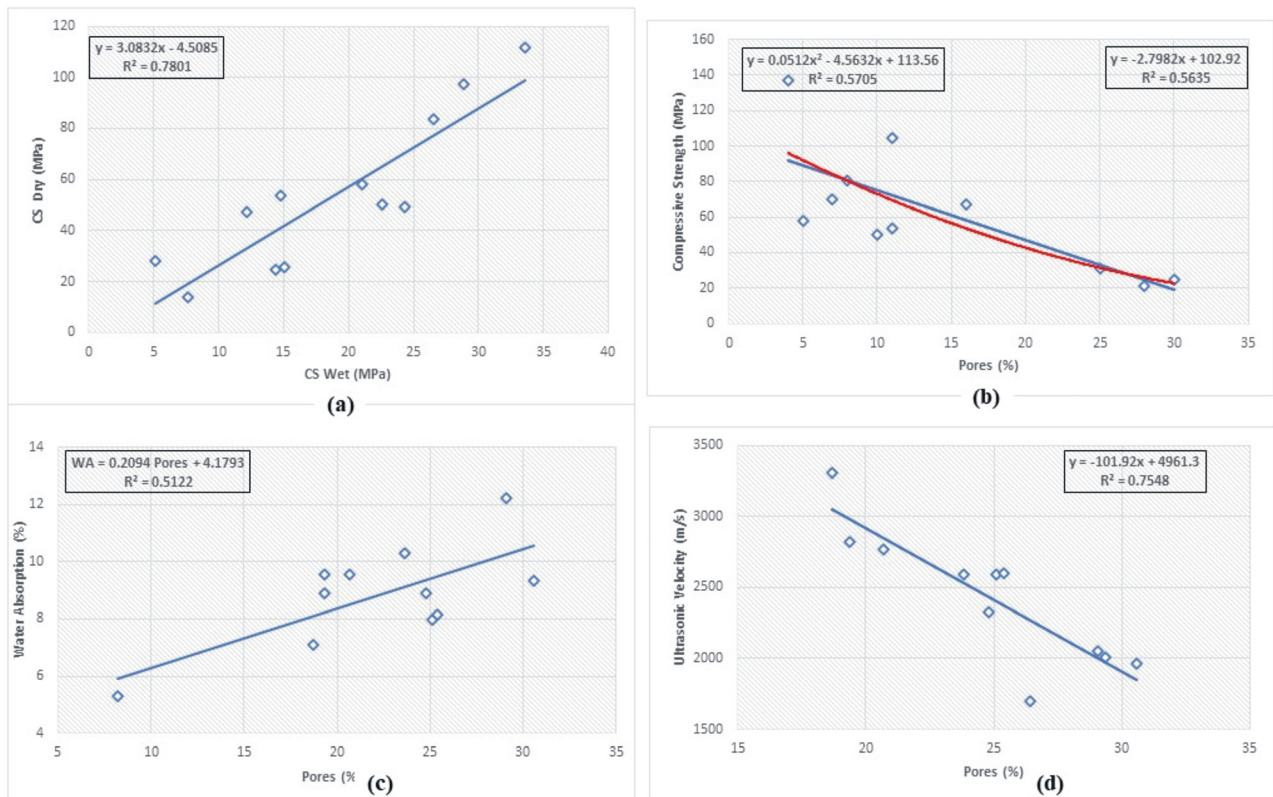


Fig. 11. Scatter plot showing (a) the relationship between compressive strength of dry and wet samples; (b) compressive strength vs pores of studied samples (red curve polynomial relation); (c) water absorption versus porosity of the studied samples excluding oolitic sample; (d) porosity versus ultrasonic pulse velocity

between geotechnical and petrographic parameters. Both linear and polynomial analysis between compressive strength and cementing materials of sandstone suggests that an increase in cementing materials and matrix corresponds to an increase in the strength of the sandstone (Fig. 10a).

Bedding planes in sedimentary rocks, being planes of weakness, influence compressive strength variations based on the angles between loading directions and bedding planes. Results in (Table 3, Fig. 10b) indicate higher compressive strength when the load direction is perpendicular ($\beta = 90^\circ$) or parallel ($\beta = 0^\circ$) to bedding planes, and lower values when inclined ($\beta = 45^\circ$), dependent on sandstone anisotropy.

The average compressive strength of wet samples in applying load to bedding plane direction indicates a moderately strong to weak classification (20.6 and 17.0 MPa, respectively). The coefficient of softness varies from 0.28 to 0.59, averaging 0.44 when the load is perpendicular to bedding planes, and ranges from 0.18 to 0.59, averaging 0.39 when the load is parallel to bedding planes as dedicated in Table 4. Observations suggest that the uniaxial compressive strength is more affected by wetting when the direction of loading is parallel to bedding planes (0°), compared to the

case of perpendicular or vertical direction of load to bedding planes. A good linear relationship ($R^2 = 0.7801$) is evident between the compressive strength of dry and wet samples (UCS_{dry} and UCS_{wet}) (Fig. 11a).

The relationship between compressive strength and porosity obtained from point counting in petrographic studies indicates that an increase in pore volume results in a decrease in compressive strength as illustrated in (Fig. 11b) in both simple and complex relationship as porosity increases, the strength of the sandstone samples decreases with ($R^2 = 0.6$) indicating a moderate in linear and polynomial relationship. Additionally, good linear relationships are observed between water absorption and porosity (Fig. 11c) and between ultrasonic pulse velocity and porosity (Fig. 11d).

Moisture content is inversely related to ultrasonic velocity, compressive strength, cement, pores, and unit weight. Direct relationships are identified between cement and uniaxial compressive strength, as well as between cement and ultrasonic pulse velocity. Similarly, there are direct relationships between uniaxial compressive strength and ultrasonic pulse velocity, porosity and cement, specific gravity and compressive strength, cement, and porosity.

		UPV	UCS	Cement & Matrix	Pores	n	GS	Unit Weight	e
UCS	r	0.425							
	p	0.193							
Cement & Matrix	r	0.219	0.849*						
	p	0.518	0.001*						
Pores	r	-0.171	-0.724*	-0.595					
	p	0.616	0.012*	0.054					
n (Porosity)	r	-0.333	-0.115	0.134	-0.379				
	p	0.318	0.735	0.693	0.251				
Specific Gravity	r	-0.015	0.274	0.378	-0.404	0.456			
	p	0.965	0.415	0.252	0.218	0.159			
Unit Weight	r	0.170	0.018	-0.139	0.319	-0.793*	-0.347		
	p	0.618	0.958	0.684	0.340	0.004*	0.296		
e (Void Ratio)	r	-0.337	-0.150	0.138	-0.268	0.671*	0.452	-0.187	
	p	0.311	0.659	0.685	0.426	0.024*	0.163	0.582	
Moisture Content	r	-0.378	-0.094	-0.068	-0.363	0.515	0.245	-0.029	0.800*
	p	0.251	0.784	0.843	0.272	0.105	0.468	0.933	0.003*

r: Pearson coefficient

*: Statistically significant at $p = 0.05$

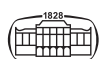
Fig. 12. Correlation matrix between different studied petrographical and geomechanical parameters

Table 5. Geomechanical rock mass classification (RMR and GSI) of all profiles

Profiles	R1	R2	R3	R4	R5	RMR*	GSI	Classification	Cohesion (C) MPa	Friction Angle (ϕ^0)
1	7	13	20	28	15	83	58	Very good	0.95	58.2
2	12	13	10	21	15	71	41	Good	0.84	59.2
3	7	20	20	30	15	92	61	Very good	0.95	57.8
4	7	17	20	25	15	84	50	Very good	0.65	55.4
5	7	17	15	25	15	79	57	Good	1.1	59.2
6	4	8	8	23	15	58	33	Fair	0.40	49.6

R1 UCS rating in (MPa); R2 RQD rating in (%); R3 discontinuity spacing; R4 condition of discontinuities which include degree of weathering, persistency, aperture, roughness, and infilling materials; R5 ground water condition.

* Total rating refers to values of RMR <21 very poor rock; 21–40 poor rock; 41–60 fair rock; 61–80 good rock; 81–100 very good rock [35].



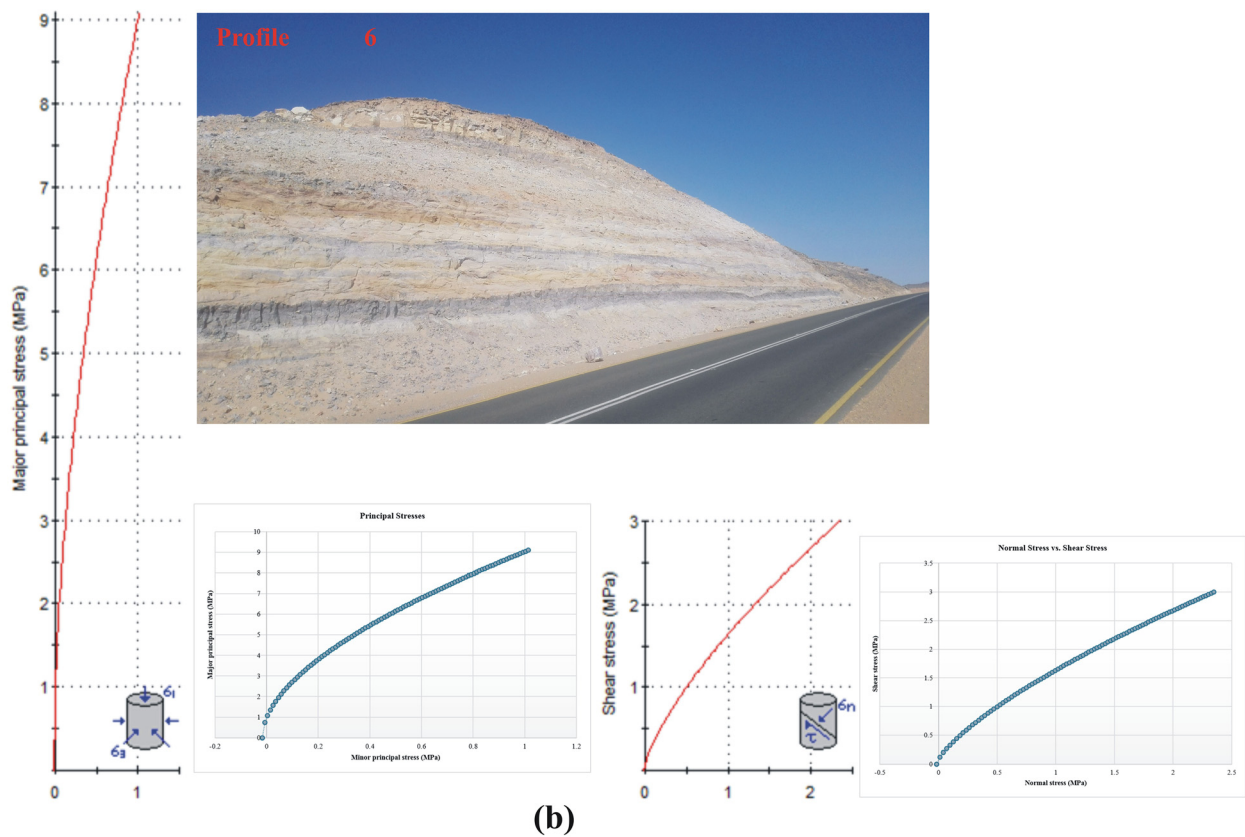
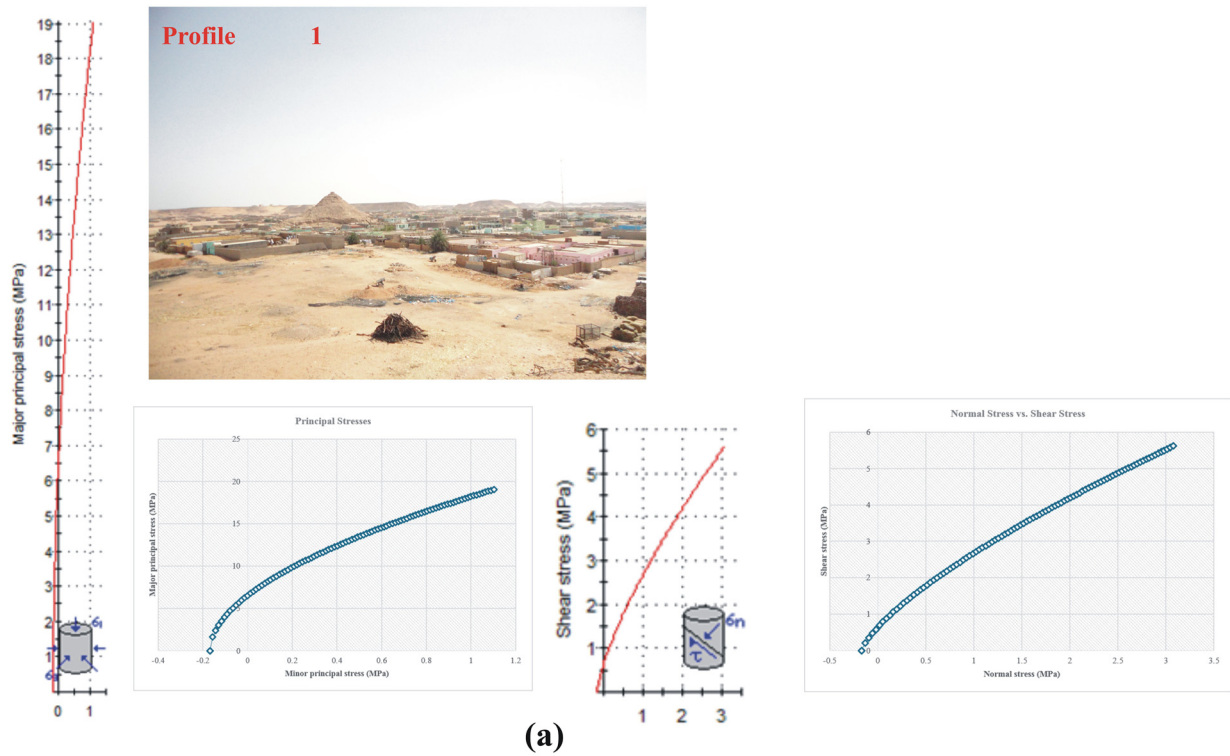


Fig. 13. Hoek-Brown Criterion and classification of selected profiles (a) Profile 1; and (b) Profile 6 around Wadi Halfa

Furthermore, a direct relationship is observed between unit weight and ultrasonic velocity, compressive strength, and pores. Void ratio is directly related to cement, while porosity is directly related to specific gravity. Moisture content exhibits a direct relationship with porosity and specific gravity, and an inverse relationship with void ratio as illustrated in Fig. 12.

Inverse relationships are identified between pores and ultrasonic velocity, compressive strength, and cement. Porosity shows an inverse relationship with ultrasonic velocity, compressive strength, and pores. Specific gravity is inversely related to ultrasonic velocity and pores. Void ratio exhibits inverse relationships with ultrasonic velocity, compressive strength, porosity, and unit weight. Finally, pores are inversely related to specific gravity, moisture

content, void ratio, porosity, compressive strength, ultrasonic velocity, and cement.

The combination of field observations and the laboratory tests can be used for geomechanical classification of the vertical lithofacies associations of the Wadi Halfa which can help for several future engineering projects such as allowable bearing pressure for foundations, analyze the stability of rock slopes, assessment of rock mass strength parameters (cohesion, friction angle, deformation, etc.), and cut slope angle along hill for roads and rail lines.

In applying rock mass classification system such as Rock Mass Rating (RMR) and Geological Strength Index (GSI) followed by Hoek-Brown Criterion [34] in studied six vertical lithofacies of Wadi Halfa; the rock masses divided into a number of geomechanical units according to [20, 35] which is the most recent version of the RMR system of all six parameters. On the basis of RMR values for a given engineering structure, the rock mass is sorted into five classes: very good (100–81), good (80–61), fair (60–41), poor (40–21), and very poor (<20) [35].

For example, selection of Profile 1 and Profile 6 because they were found near the construction builds and roads; for profile 1 the average values of uniaxial compressive strength are 68.22 MPa, the Rock Quality Designation (RQD) 60%, the spacing of discontinuities found to be extremely closed spacing of less than 20 mm, the condition of discontinuities slightly rough surface separation of less than 1 mm and the degree of weathering slightly to unweathered as shown in Table 5 and Fig. 13a.

Table 6. Analysis of rock mass parameters using Hoek Brown classification and MOHR-coulomb fit

Profiles	Uniaxial Compressive Strength (MPa)	Tensile Strength (MPa)	Global Strength (MPa)	Modulus of Deformation (MPa)
1	6.949	−0.169	18.090	13069.36
2	5.276	−0.103	27.909	5956.62
3	6.455	−0.177	16.169	14221.24
4	3.312	−0.075	13.376	7416.20
5	7.667	−0.195	22.139	13794.61
6	0.971	−0.017	7.140	2549.05

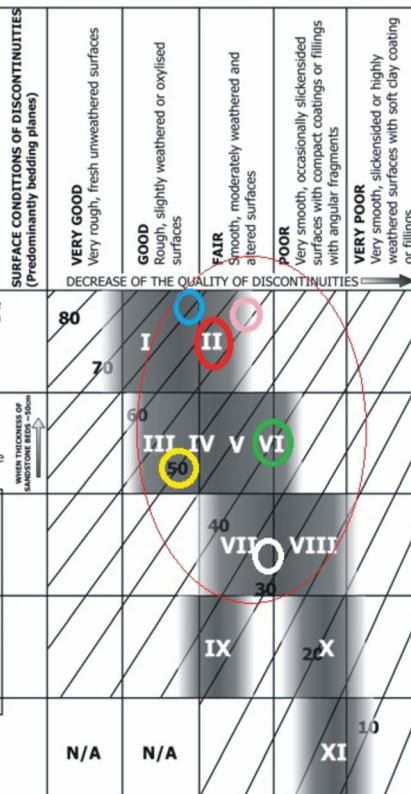
GEOLOGICAL STRENGTH INDEX (GSI) FOR HETEROGENEOUS ROCK MASSES

Heterogeneous rockmasses are meant those with alternating layers of clearly different lithology types with significant differences in their strength properties. For flysch, a typical formation with heterogeneous rock masses, these alternations are consisting of sandstones and siltstones. Clay shales may be present. From a description of the lithology, structure and surface conditions of discontinuities (particularly of the bedding planes), choose a box in the chart. The selection of the structure should be based on the tectonic disturbance (undisturbed, slightly disturbed, strongly disturbed - folded, desintegrated, sheared), the proportion of siltstones against sandstones and the expressed or not stratification inside the siltstone layers. In the type IV and V when the thickness of sandstone beds exceed 50cm an increase of the GSI value by 5 is suggested. From type IV and the following types, the stratification planes are perceptible inside the siltstone mass. Locate the position in the box that corresponds to the conditions and estimate the average value GSI from the contours. The determination of the structure and the condition of discontinuities may range between two adjacent fields. Note that the Hoek - Brown criterion does not apply to structurally controlled failures. Where unfavourably oriented continuous weak planar discontinuities are present, these will dominate the behaviour of the rock mass. The strength of some rock masses is reduced by the presence of groundwater and this can be allowed for by a slight shift to the right in the columns for fair, poor and very poor conditions. Water pressure does not change the value of GSI and it is dealt with by using effective stress analysis.

STRUCTURE AND COMPOSITION

TYPE I. Undisturbed, with thick to medium thickness sandstone beds with sporadic thin films of siltstone. In shallow tunnels or slopes where confinement is poor the mode of the failure has a kinematic character controlled by the bedding planes and GSI is meaningless	TYPE II. Undisturbed massive siltstone (stratification planes are imperceptible) with sporadic thin interlayers of sandstones
TYPE III. Moderately disturbed sandstones with thin films of interlayers of siltstone	TYPE IV. Moderately disturbed rockmass with sandstone and siltstone similar amounts
TYPE VII. Strongly disturbed, folded rockmass that retains its structure, with sandstone and siltstone in similar extend	TYPE VIII. Strongly disturbed, folded rockmass, with siltstones and sandstone interlayers. The structure is retained and deformation - shearing is not strong
TYPE IX. Desintegrated rockmass that can be found in wide zones of faults or/and of high weathering. In this type mainly brittle material is present with some disturbed siltstones between rock pieces	TYPE X. Tectonically deformed intensively folded/ faulted siltstone or clay shale with broken and deformed sandstone layers forming an almost chaotic structure
TYPE XI. Tectonically strongly sheared siltstone or clayey shale forming a chaotic structure with pockets of clay. Thin layers of sandstone are transformed into small rock pieces. Ultimately the ground behavior is that of a soil	

→ Means deformation after tectonic disturbance



- Profile 1
- Profile 2
- Profile 3
- Profile 4
- Profile 5
- Profile 6

Fig. 14. Ranges of GSI for Wadi Halfa sandstone, original chart from [20, 34]

Profile 6 of the average UCS 65.93 MPa, 45.7% RQD, the spacing of discontinuities found to be close to very close spacing (20–200 mm), slightly rough surface separation of less than 1 mm and slightly weathered.

The combination of RMR and GSI using Hoek-Brown Criterion and Classification has yielded favorable results for the estimation of the overall rock mass strength of the selected profiles (Fig. 13b).

Useful parameters, such as global strength, cohesion, friction angle, and major deformation of rock masses, have been obtained through a comprehensive analysis of rock strength using Hoek-Brown criteria and Mohr-Colom strength parameters, as detailed in Table 6. These parameters are critical for a wide range of engineering projects, providing essential insights for applications across various fields. Their applicability spans from geotechnical and structural engineering to mining and tunneling, making them invaluable tools for ensuring the stability and safety of constructions in different geological settings specially in sedimentary rocks. Our study provides a valuable framework for assessing the quality of the sandstone rock mass by considering the typical GSI Hoek's classification ranges (33–61) which are impacted mainly by petrographical factors such as grains, cement, matrix and pores (Fig. 14).

6. CONCLUSION

The following conclusions have been drawn based on the results obtained from the detailed field observations and laboratory analyses:

1. Petrographic assessments display different sandstone facies with different types of cementing materials, grain size and shape, that influence the geomechanical properties.
2. Anisotropy played an important role, with a U-shaped curve in uniaxial compressive strength. Samples highly cemented by iron oxides exhibited higher strength, while weathered and porous samples with carbonate cementation showed lower strength. The softness coefficient highlighted the role of porosity in strength reduction due to wetting.
3. The post-test specimen of sandstone showed multiple fracturing, double fractures, shear fractures along bedding planes at 0°, and axial splitting fractures or extension failures at 90°, similar to real-field rock failures.
4. The combination of field and laboratory analyses provides a robust framework for the geomechanical classification (RMR and GSI) of the vertical lithofacies associations in Wadi Halfa. This classification is essential for future engineering projects such as determining allowable bearing pressure for foundations, analyzing rock slope stability, assessing shear strength parameters, and designing cut slope angles for roads and railways.
5. Deep examination of petrographic effects on the geomechanical and engineering properties by comprehensive field observations and laboratory analyses of the

sandstone can be widely used for different construction engineering projects in the region of Wadi Halfa and other similar regions.

REFERENCES

- [1] S. Guo, Q. Wei, S. Qi, L. Xue, B. Zheng, H. Wang, J. Li, S. Song, N. Liang, and Y. Zou, "Research progress on the geomechanical properties of block-in-matrix rocks," *Materials*, vol. 17, no. 5. Multidisciplinary Digital Publishing Institute (MDPI), Mar. 01, 2024. <https://doi.org/10.3390/ma17051167>.
- [2] R. Khajevand, "Estimating geotechnical properties of sedimentary rocks based on physical parameters and ultrasonic P-wave velocity using statistical methods and soft computing approaches," *Iranian J. Sci. Technol. Trans. Civil Eng.*, vol. 47, no. 6, pp. 3785–809, Dec. 2023. <https://doi.org/10.1007/s40996-023-01148-0>.
- [3] A. H. E. Bailey, L. Wang, D. N. Dewhurst, J. R. Anderson, L. K. Carr, and P. A. Henson, "Geomechanical rock properties of the officer basin," *APPEA J.*, vol. 62, no. 2, pp. S385–91, May 2022. <https://doi.org/10.1071/aj21083>.
- [4] P. A. Kamenev, L. M. Bogomolov, O. M. Usoltseva, P. A. Tsoi, and V. N. Semenov, "Geomechanical parameters of sedimentary rocks of Southern Sakhalin," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Dec. 2021. <https://doi.org/10.1088/1755-1315/946/1/012013>.
- [5] A. K. Tomor, J. M. Nichols, and Z. Orbán, "Evaluation of the loss of uniaxial compressive strength of sandstones due to moisture," *Int. J. Architectural Heritage*, 2023. <https://doi.org/10.1080/15583058.2023.2188313>.
- [6] M. C. Villeneuve, M. J. Heap, A. R. L. Kushnir, Q. Tao, B. Patrick, Z. Guanglei, and X. Tao, "Estimating in situ rock mass strength and elastic modulus of granite from the Soultz-sous-Forêts geothermal reservoir (France)," *Geothermal Energy*, vol. 6, no. 1, Dec. 2018. Available: <https://doi.org/10.1186/s40517-018-0096-1>.
- [7] B. Yan, P. Wang, F. Ren, Q. Guo, and M. Cai, "A review of mechanical properties and constitutive theory of rock mass anisotropy," *Arabian J. Geosciences*, vol. 13, no. 487, Jun. 2020. <https://doi.org/10.1007/s12517-020-05536-y/Published>.
- [8] L. Tian, Z. Feng, Z. Wu, B. Liu, J. Zhang, and J. Pan, "Mechanical properties of rock specimens containing pre-existing cracks with different dip angles based on energy theory and cohesive element method," *Appl. Sci.*, vol. 14, no. 4, p. 1484, Feb. 2024. <https://doi.org/10.3390/app14041484>.
- [9] M. Awad, A. Henaish, and A. El Shinawi, "Geotechnical investigation and characterization of intact rocks using destructive and non-destructive techniques: a case study at Gebel El Ramliya-Akheider, Cairo-Suez District, Egypt," *Bull. Fac. Sci. Zagazig Univ.*, vol. 2023, no. 4, pp. 129–43, Jan. 2024. <https://doi.org/10.21608/bfszu.2023.205407.1267>.
- [10] N. Barton and E. Quadros, "Anisotropy is everywhere, to see, to measure, and to model," *Rock Mech. Rock Eng.*, vol. 48, no. 4, pp. 1323–39, Jul. 2015. <https://doi.org/10.1007/s00603-014-0632-7>.
- [11] Q. Su and J. Tu, "Dynamic failure behavior of sandstone with various weak-filling joints using the Brazilian disc method," *Geotechnical Res.*, pp. 1–11, May 2024. <https://doi.org/10.1680/jgere.23.00041>.



- [12] Z. Ijaz, C. Zhao, N. Ijaz, Z. ur Rehman, and A. Ijaz, "Advanced geospatial modeling and statistical evaluation of heterogenous geotechnical facets at multiple depths using the improved formulation of modified Shepard IDW algorithm," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1337, no. 1, May 2024, Art no. 012053. <https://doi.org/10.1088/1755-1315/1337/1/012053>.
- [13] H. Jia, S. Ding, F. Zi, G. Li, and Y. Yao, "Development of anisotropy in sandstone subjected to repeated frost action," *Rock Mech. Rock Eng.*, vol. 54, no. 4, pp. 1863–74, Apr. 2021. <https://doi.org/10.1007/s00603-020-02343-5>.
- [14] A. M. A. Abazar, M. A. Rashed, A. M. Elsharief, N. S. Kadry, and A. M. Elamein, "The geotechnical properties of the oolitic ironstone formation, Wadi Halfa, North Sudan," *J. Geology. Mining Res.*, vol. 12, no. 1, pp. 25–34, Feb. 2020. <https://doi.org/10.5897/jgmr2019.0326>.
- [15] M. A. A. Daoud, M. A. Rashed, K. N. Sediek, A. M. Elsharief, and A. M. Elamein, "Petrography, diagenesis and Paragenesis of Wadi Halfa oolitic Ironstone Formation, North Sudan," *Eur. J. Appl. Sci.*, vol. 9, no. 3, Jun. 2021. <https://doi.org/10.14738/aivp.93.10461>.
- [16] M. Nafi, A. El Amein, M. El Dawi, and K. Salih, "Wadi Halfa Oolitic Ironstone Formation, Wadi Halfa and Argein Areas, North Sudan," 2015. [Online]. Available: <https://www.researchgate.net/publication/284028965>.
- [17] R. J. Stern, A. Kröner, R. Bender, T. Reischmann, and A. S. Dawoud, "Precambrian basement around Wadi Halfa, Sudan: a new perspective on the evolution of the East Saharan Craton," *Geologische Rundschau*, vol. 83, no. 3, pp. 564–77, Oct. 1994. <https://doi.org/10.1007/bf01083228>.
- [18] A. M. A. Daoud, M. A. Rashed, K. N. Sediek, A. M. Elamein, and A. M. Elsharief, "Barite concretions in Wadi Halfa Oolitic Ironstone Formation, North Sudan," *J. Geogr. Environ. Earth Sci. Int.*, pp. 51–64, Jul. 2020. <https://doi.org/10.9734/jgeesi/2020/v24i530227>.
- [19] B. Vásárhelyi, G. Somodi, Krupa, and L. Kovács, "Determining the geological strength index (GSI) using different methods," in *Rock Mechanics and Rock Engineering: From the Past to the Future*, CRC Press/Balkema, 2016, pp. 1049–54. <https://doi.org/10.1201/9781315388502-183>.
- [20] V. Marinos, P. Marinos, and E. Hoek, "The geological strength index: applications and limitations," *Bull. Eng. Geology. Environ.*, vol. 64, no. 1, pp. 55–65, Apr. 2005. <https://doi.org/10.1007/s10064-004-0270-5>.
- [21] L. Zhang, "Determination and applications of rock quality designation (RQD)," *J. Rock Mech. Geotechnical Eng.*, vol. 8, no. 3, pp. 389–97, Jun. 2016. <https://doi.org/10.1016/j.jrmge.2015.11.008>.
- [22] A. Palmstrom, "Measurements of and correlations between block size and rock quality designation (RQD)," *Tunnelling Underground Space Technol.*, vol. 20, no. 4, pp. 362–77, Jul. 2005. <https://doi.org/10.1016/j.tust.2005.01.005>.
- [23] W. R. Dickinson, "Interpreting provenance relations from detrital modes of sandstones," in *Provenance of Arenites*, G. G. Zuffa, Ed., Dordrecht: Springer Netherlands, 1985, pp. 333–61. https://doi.org/10.1007/978-94-017-2809-6_15.
- [24] E. Garzanti, "Petrographic classification of sand and sandstone," *Earth-Science Rev.*, vol. 192, pp. 545–63, May 01, 2019. Elsevier B.V. <https://doi.org/10.1016/j.earscirev.2018.12.014>.
- [25] ASTM D6473-15, "Standard test Method for Specific Gravity and Absorption of Rock for Erosion Control 1," pp. 1–4, 2015. <https://doi.org/10.1520/D6473-15>.
- [26] ASTM D7012-23, "Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying states of Stress and temperatures 1," pp. 1–7, 2023. <https://doi.org/10.1520/D7012-23>.
- [27] ASTM D6473-15, "Specific Gravity and Absorption of Rock for erosion control 1," pp. 1–2, 2015. <https://doi.org/10.1520/D6473-15>.
- [28] ASTM C1721-21, "Standard Guide for Petrographic Examination of Dimension Stone 1," pp. 1–5, 2021. <https://doi.org/10.1520/C1721>.
- [29] ASTM D2845-05, "Standard Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock 1," 2017. [Online]. Available: www.astm.org.
- [30] ASTM C97, "Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone 1," 2008. [Online]. Available: www.astm.org.
- [31] G. Cui, C. Zhou, and Z. Liu, "Prediction method of water absorption of soft rock considering the influence of composition, porosity, and solute quantitatively," *Appl. Sci. (Switzerland)*, vol. 12, no. 12, Jun. 2022. <https://doi.org/10.3390/app12125938>.
- [32] İ. İnce, A. Bozdağ, M. Barstuğan, and M. Fener, "Evaluation of the relationship between the physical properties and capillary water absorption values of building stones by regression analysis and artificial neural networks," *J. Building Eng.*, vol. 42, Oct. 2021. <https://doi.org/10.1016/j.jobbe.2021.103055>.
- [33] M. Ünal and E. Altunok, "Determination of water absorption properties of natural building stones and their relation to porosity," *E-Journal New World Sci. Acad.*, vol. 14, no. 1, pp. 39–45, Jan. 2019. <https://doi.org/10.12739/nwsa.2019.14.1.1a0429>.
- [34] E. Hoek and E. T. Brown, "The Hoek–Brown failure criterion and GSI – 2018 edition," *J. Rock Mech. Geotechnical Eng.*, vol. 11, no. 3, pp. 445–63, Jun. 2019. <https://doi.org/10.1016/j.jrmge.2018.08.001>.
- [35] Z. T. Bieniawski, "Engineering rock mass classifications: a complete manual for engineers and geologists in mining, civil, and petroleum engineering," *John Wiley & Sons*, Aug. 1989. [Online]. Available: <https://www.rocsience.com/assets/resources/learning/hoek/Practical-Rock-Engineering-Chapter-3-Rock-Mass-Classification.pdf>.