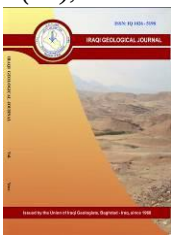
Iraqi Geological Journal

Journal homepage: https://www.igj-iraq.org



Geotechnical Characterization of Euphrates Formation Limestone near Haditha City in Western Iraq for Engineering Design Purposes

Mohanad E. Khudher[1], Maha S. Badowi[1], Ahmed J. Hussein[1], Laith I. Salah[1], and Marwa T. Mohammed[2]

1 Department of Geological Applied, College of Sciences, University of Tikrit, Tikrit, Iraq
2 Independent Researcher
* **Correspondence:** mohanad_droesh@tu.edu.iq

Received:
21 January 2026
Accepted:
31 March 2026
Published:
31 May 2026

Abstract

The main aim of the study is to characterize the geotechnical properties of the Euphrates rocks at selected site in western Iraq based on rock core data from 28 boreholes, with depths ranging from 16 m (minimum) to 22 m (maximum) and a total of 112 rock samples collected. Rock mass quality was assessed using the Rock Quality Designation, total core recovery and solid core recovery indices alongside the physical properties including dry and saturated density, water absorption, specific gravity and porosity were determined. Mechanical properties were assessed through the unconfined compressive strength and point load index (IS_{50}) tests in accordance with ASTM standards. The results show significant variability in rock mass quality with the investigated depths, with Rock Quality Designation values ranging from 0 to 100% which reflecting the influence of fracturing and secondary porosity within the carbonate rocks. Corrected uniaxial compressive strength values ranged between 3.15 and 23.57 MPa, indicating weak to moderately strong rock behavior, whereas IS_{50} values varied from 0.081 to 1.368.The RMR values for the models, after accounting for the underlying parameters, ranged between 50 to 68.The importance of depth-dependent geotechnical characterization was highlighted for engineering design and demonstrate that the point load test can be used as supplementary classification tool after appropriate local calibration.

Keywords: Euphrates Formation; Rock mass quality; RQD; UCS; TCR

1. Introduction

Investigations of geotechnical properties for foundation zone rocks are critical for infrastructure and heavy construction projects, foundation stability and design safety depend on the geological and mechanical properties of the rock mass. Factors such as lithology, fracture intensity and porosity highly influence rock mass quality and bearing capacity. Previous studies in northern Iraq have shown that groundwater chemistry is strongly influenced by lithology and dissolution processes within geological formations, which leads to spatial variations in hydrochemical characteristics (Khudher et al., 2025).

In western Iraq the Early Miocene Euphrates Formation represents a major carbonate bedrock unit in engineering works. The formation consists mainly of limestone and dolomite and exhibits variable degrees of dolomitization, recrystallization and secondary porosity, resulting from shallow marine depositional conditions and subsequent diagenetic processes (Al Ghreri et al., 2014). This variability leads to heterogeneity in physical and mechanical properties, even within the same stratigraphic interval.

Rock Quality Designation (RQD) is widely used as a preliminary indicator of rock mass quality and fracture degree; however, its reliability can be affected by drilling conditions and core recovery in fractured or weathered carbonate rocks, highlighting the need for complementary indices and strength-based tests (Deere and Deere 1989; Zhang 2016). Uniaxial compressive strength (UCS) tests in accordance with ASTM- D7012, 2023 and point load index tests (IS_{50}) following ASTM D5731 are commonly applied to evaluate intact rock strength and its relationship to rock mass quality. The integrating of RQD with total and solid core recovery (TCR and SCR) and strength parameters provides a more reliable geotechnical characterization of carbonate formations (Hoek and Brown 2019). Al-Dabbas et al. (2013) evaluates the mineralogical and geochemical characteristics of the Lower Miocene Euphrates Formation in the Bahr AlNajaf area and confirms that its limestone with stable chemical composition is suitable for Portland cement production with an estimated reserve of about 63 million tons. (Al-Taha and Al-Haj, 2024) studied the carbonate formations in western Iraq, emphasized that integrating rock mass quality indices with physical and mechanical properties is essential for reliable geotechnical characterization and engineering assessment.

This study aims to assess the geotechnical characteristics of the Euphrates Formation by integrating rock mass quality indices (RQD, TCR, and SCR), Calculating RMR values based on the physical properties, and mechanical properties derived from UCS and point load index tests, providing practical insight for foundation design near Haditha City in western Iraq.

2. Materials and Methods

The study area is located in western Iraq within the distribution of the Euphrates Formation, and is geographically bounded by coordinates (255800–256200 E) and (3772800–3773200 N) according to the WGS 1984 / UTM Zone 38N coordinate system (Fig. 1 and Table 1). Geological map of Haditha City, shown in Fig. 2 (Sissakian and Fouad, 2015).

The exploratory drilling program that conducted at the study site was to comprising 28 wells with depths ranging from 20 to 22 meters to assess the geotechnical properties of the Euphrates Formation rocks at these depths. Continuous core samples were obtained from all boreholes whenever possible with the depths of the samples documented and core recovery rates and quality recorded during drilling with including fragmentation instances or core loss. The lithostratigraphic succession of the study area is illustrated in Fig. 3. This vertical succession reflects the stratigraphic variability within the Euphrates Formation which contributes to the heterogeneity in assessed properties.

2.1. Core Recovery

The core recovery defined as the summed length of all pieces of recovered core expressed as a percentage of the length drilled, it should be measured and recorded to the nearest 2 percent if possible. When the core is highly fragmented, the length of such portions is estimated by assembling the fragments and estimating the length of core that the fragments appear to represent (IS 11315-11, 1985). The core recovery parameters are:

2.1.1. Rock quality designation (RQD)

The Rock Quality Designation (RQD) denotes the percentage of intact rock retrieved from a borehole (Eq. 1). All pieces of intact rock core equal to or greater than 100 mm (4 in.) long are summed and divided by the total length of the core run. Engineering judgment may be necessary to determine whether a piece of core qualifies as intact (ASTM D 6032 – 96):

$$\mathrm{RQD} = \frac{\sum Li \;\; length\; of\; core\; pieces\; that\; are \;>\; 100\, mm}{Lt\; Total\; length\; of\; core\; run} * 100\%, \qquad (1)$$

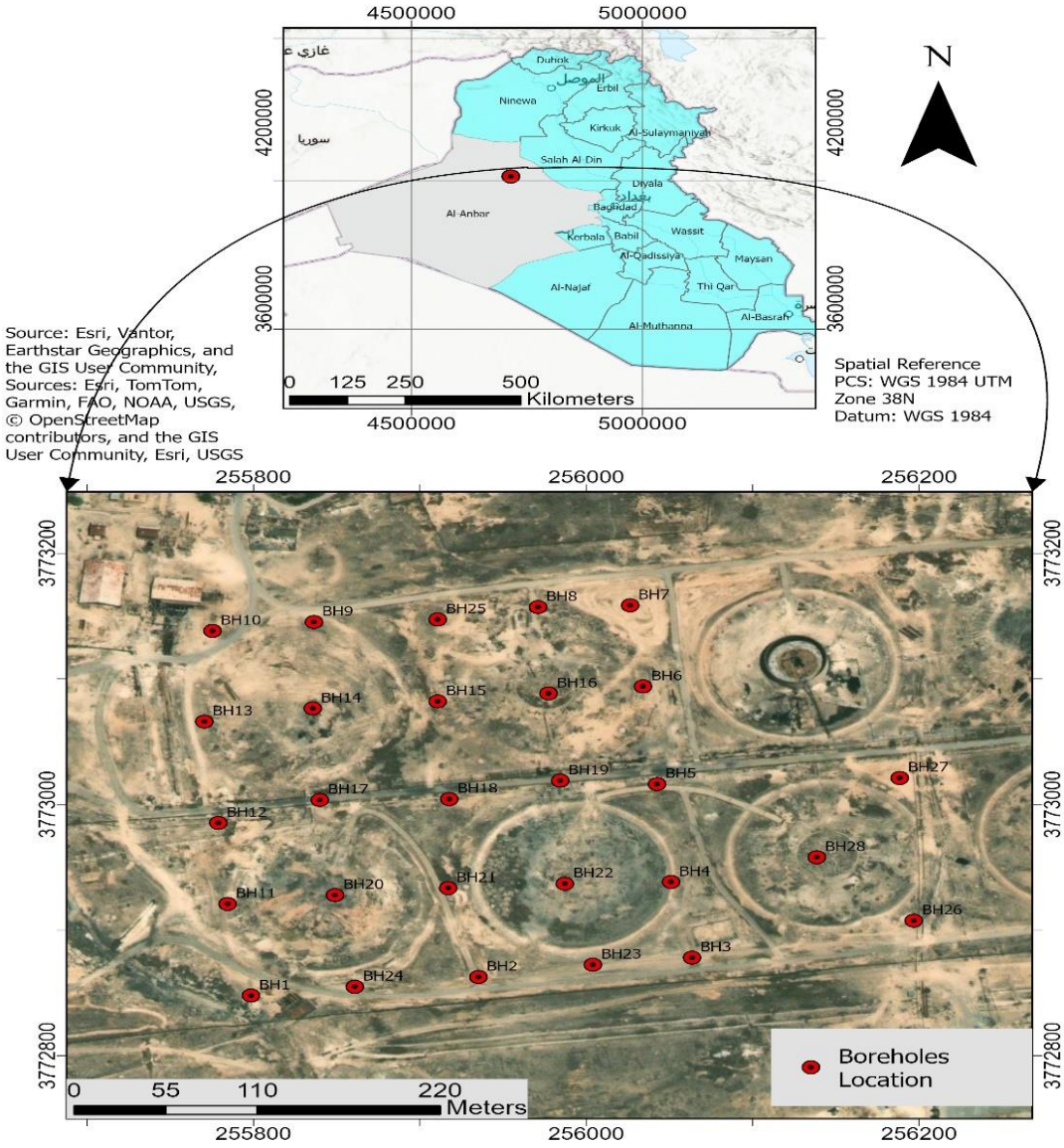


Fig. 1. Location map of the study area showing borehole distribution

2.1.2. Total core recovery TCR

Total core recovery (TCR) is a measure of the total length of the recovered intact rock core compared to the total length of the drilled interval (Eq. 2). It is expressed as a percentage and provides information about the efficiency of core recovery during drilling (ASTM D6032/D6032M-17).

$$TCR = \frac{Total\ length\ of\ core\ recovered}{Drilled\ length} * 100\%, \quad (2)$$

2.1.3. Solid core recovery (SCR)

Solid Core Recovery (SCR) is the ratio of solid core recovered to length of core run, provides a more accurate representation of the intact rock quality by considering the actual length of intact core recovered (Eq. 3) (Valentine and Norbury, 2011).

$$SCR = \frac{Total\ length\ of\ core\ in\ pieces\ >\ core\ diameter}{Drilled\ length} * 100\%, \quad (3)$$

Table 1. Approximate UTM coordinates of borehole locations in the study area

Borehole	Easting (m)	Northing (m)
BH1	255830	3772830
BH2	255950	3772850
BH3	256020	3772870
BH4	256060	3772950
BH5	256020	3773000
BH6	255990	3773100
BH7	256010	3773180
BH8	255980	3773180
BH9	255900	3773170
BH10	255820	3773150
BH11	255850	3772900
BH12	255830	3773000
BH13	255820	3773070
BH14	255880	3773080
BH15	255920	3773070
BH16	255960	3773080
BH17	255880	3773000
BH18	255930	3773000
BH19	255960	3773020
BH20	255900	3772920
BH21	255940	3772920
BH22	255980	3772920
BH23	256000	3772880
BH24	255880	3772850
BH25	255940	3773180
BH26	256180	3772850
BH27	256180	3773000
BH28	256120	3772950

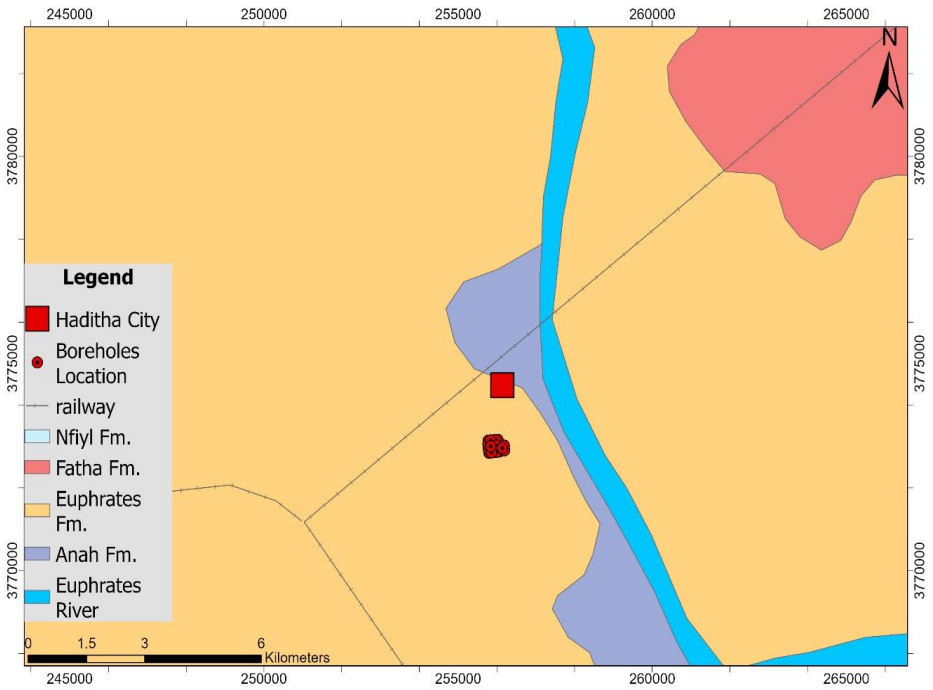


Fig. 2. Geological map of Haditha City, (modified from Sissakian and Fouad, 2015)

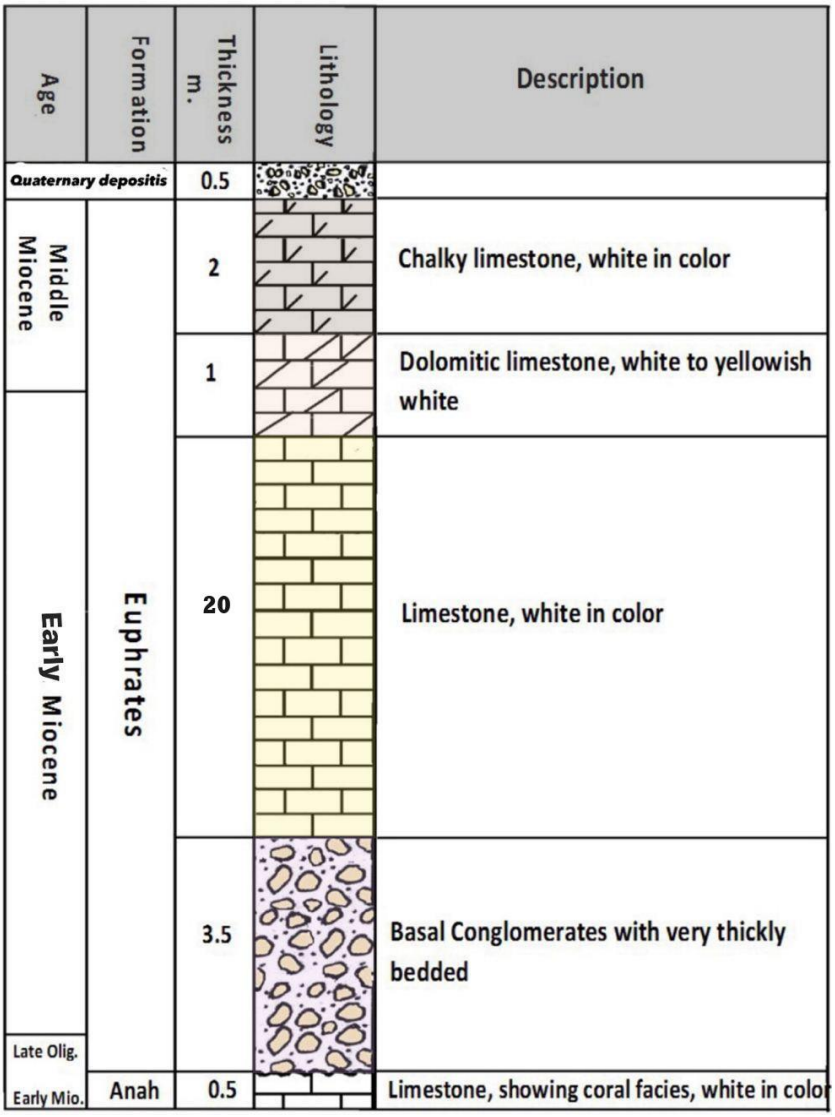


Fig. 3. Lithostratigraphic column of the Euphrates Formation at the study area

2.2. Physical Property Tests

Physical property tests were conducted on 112 rock samples taken from varying depths and at regular intervals. The tests, performed using three weighting methods according to ASTM C-97, 2010, included determining dry and saturated density, true specific gravity, absorption ratio, and porosity (ASTM C-127, 2004), all in accordance with established standards. Samples were selected to be representative of the prevailing rock texture, excluding damaged or incomplete samples.

Calculate the bulk specific gravity (SSD), apparent specific gravity, and absorption (Eqs. 4, 5, 6, and 7), for each specimen, and their values were obtained in Table 2, at ambient laboratory temperature as follows:

$$bulk\ specific\ gravity = \frac{A}{(B-C)}, \quad (4)$$

$$bulk\ specific\ gravity\ (SSD) = \frac{B}{(B-C)\ldots(5)}, \quad (5)$$

$$apparent\ specific\ gravity = \frac{A}{(A-C)}, \quad (6)$$

$$absorption\ \% = [\frac{(B-A)}{A] \times 100}], \quad (7)$$

where:
A = mass of oven-dry test specimen in air, g,
B = mass of saturated-surface dry test specimen in air, g, and
C = buoyant mass of submerged test specimen in water, g.

2.3. Mechanical Properties

2.3.1. Unconfined compressive strength (UCS)

Execute the unconfined compressive strength test (UCS) following the guidelines specified in the ASTM D7012-14e1 standard. Apply an axial load gradually to the rock core specimen until failure occurs, monitoring the load and corresponding deformation during the test. The peak load at failure was measured, the unconfined compressive strength by Eq (8), the corrected unconfined compressive strength by Eq (9), and Poisson's ratio by Eq (10):

$$\sigma_c = \frac{P}{A}, \tag{8}$$

$$\sigma_{corrected} = \frac{\sigma_{calculated}}{0.778 + 0.222\frac{D}{L}}, \tag{9}$$

$$poissons\ ratio\ (\upsilon) = \frac{Lateral\ StrainE}{Longitudinal\ Strain}, \tag{10}$$

2.3.2. The Unconfined compressive strength (UCS) by Point load index

The determination of the point load index for the axial samples was performed following the ASTM D5731-16 standard. The measured IS_{50} as in Table (5) and the unconfined compressive strength were indirectly determined by Eqs. 11,12,13,14, and 15:

$$IS = \frac{F}{{D_e}^2}, \tag{11}$$

$$D_e = \sqrt{\frac{4A}{\pi}}, \tag{12}$$

$$IS_{50} = f\left(\frac{F}{De^2}\right), \tag{13}$$

$$f = (\frac{De}{50)}^{0.45}, \tag{14}$$

$$UCS = 21 \times IS_{50}, \tag{15}$$

2.3.3. Poisson's ratio

Quantifying the intact rock's Poisson's ratio in a laboratory setting using indirect or dynamic approaches is relatively straightforward, or directly via static (uniaxial compressive) tests (ASTM D3148-96). The laboratory phase is illustrated in Fig. 4.

The failure patterns variations showed the influence of internal discontinuities and porosity on the mechanical behavior of the tested carbonate rocks.



Fig. 4. a) Measuring the dimensions of the rock core; b) Rock core box after retrieval; c) Preparing core samples for laboratory tests; d) Sample after failure; e) Core sample exposed to weathering; f) Failure pattern in the unconfined compressive strength (UCS) test; g) Point load test (IS_{50}); h) Arrangement of the rock core inside storage boxes

3. Results and Discussion

3.1. Rock Core Recovery RQD, TCR and SCR

Rock core recovery indicators are essential tools in characterizing rock masses for geotechnical purposes. The RQD index is widely used to represent the degree of fracturing and rock quality based on the lengths of intact core pieces. The TCR index is used to represent the total core recovery ratio, while the SCR index represents a corrected version of RQD that takes into account the actual length of intact recovered rock, providing a more realistic characterization of rock quality, particularly in fractured or weathered zones (Deere and Deere, 1989; Zhang, 2016) (Table 2). Similar depth-dependent variability in the geotechnical behavior of the Euphrates Formation rocks has been reported in previous engineering. The Rock Mass Rating (RMR) values were determined using the Bieniawski (1989) classification system based on core data from the 28 boreholes. The assessment incorporated UCS, RQD, discontinuity spacing and condition derived from core logging, as well as groundwater conditions. Each parameter is rated according to standard RMR guidelines and RMR values were obtained by the individual ratings summing.

Table 2 shows notable variation in rock mass quality in drilling cores with RQD values ranging from 0% to 100%, this variation reflect the heterogeneity of the rock and differences in fracturing between sections. In some sections, low RQD values were recorded with high SCR values, that indicate low RQD is often due to loss or breakage of the core during drilling rather than to weakness of the intact rock.

Table 2. The RQD, RMR, TCR and SCR values of the borehole

Borehole NO.	Core Depth	RQD %	TCR %	SCR%	RMR	Borehole NO.	Core Depth	RQD%	TCR %	SCR%	RMR
BH1	5-6.5	0	50	70	51	BH14	3-4.5	0	50	80	50
	8.5-9.75	0	0	80			6.5-8	0	36	40	
	11.5-13	0	8	20			10-11.5	0	0	50	
	15-16.5	12	30	50			17-18.5	0	50	50	
BH2	2.5-18	100	100	100	65	BH15	20.5-22	0	30	40	58
	2.5-18	41	50	55			4.5-6	70	85	90	
	2.5-18	0	10	20			8-9.5	10	40	75	
	16-18	0	10	20			15-16.5	10	25	65	
BH3	6.5-4.7	70	90	90	55	BH16	18-20	0	15	95	60
	8.5-10	0	50	90			2.5-4	0	20	85	
	12-14-5	60	100	100			6-7.5	20	20	50	
BH4	2.5-4	0	10	50	50		9.5-11	36	36	75	
	6.0-8	32	60	85			18.5-20	50	75	75	
	10-11.5	0	20	60			17-18.5	0	20	80	
	13.5-15	0	0	50			2.5-4	0	20	85	
BH5	15-17	26	30	30	59	BH17	7-8.5	0	32	95	60
	17-18.5	39	65	80			10.5-12	0	28	35	
	5.5-7.5	60	90	100			14.5-16	48	60	80	
	13.5-15	0	40	70			18.5-20	50	80	95	
	16.5-18	85	90	100			3-4.5	0	10	70	
BH6	19-20	45	65	85	53	BH18	6.5-8	28	50	70	61
	4.5-6	0	0	0			10-11.5	34	65	80	
	8-11.5	0	0	0			13.5-15	72	85	95	
	17-18.5	36	41	75			4-5.5	51	65	80	
BH7	18.5-20	0	0	0	58	BH19	7.5-9.5	0	0	50	58
	15.5-18	60	70	25			15-16.5	62	80	90	
	12-13.5	0	25	75			18.5-20	13	30	70	
	06-Oct	60	80	95			3-4.5	46	65	75	
BH8	2.5-4	50	55	90	58	BH20	6.5-8	0	50	80	56
	0.7-2	0	20	90			10.0-11	14	50	70	
	4-5.5	30	35	95			17-18.5	0	0	0	
	7.5-9	40	55	96			14.5-16	0	30	70	
	11-12.5	0	12	80		BH21	10-Dec	17	22	22	50
	14.5-16	0	12	50			6.5-8	0	17	55	
	18.5-20	65	71	95			5-6.5	36	46	85	
BH9	2-3.5	0	10	50	52	BH22	11-12.5	95	95	95	68
	5.5-7	0	20	65			18.5-20	52	85	95	
	9.5-10						4-5.5	20	20	85	
	12.5-14.5						7.5-9	40	40	65	
	17-18.5	0	15	65		BH23	11-12.5	63	95	98	67
BH10	Feb-35	80	80	95	54		18.5-20	100	100	100	
	5.5-7	0	0	80			14.5-16	35	65	90	
	9-10.5	0	10	90			6-7.5	16	40	75	
	12.5-14.5	60	60	90		BH24	9.5-11	85	95	95	64
	17-18.5	78	78	90			17.5-18.5	70	80	95	
BH11	18.5-20	12	50	85	61	BH25	11-12.5	12	35	60	51
	02-Apr	12	16	25			14.5-16	0	50	70	
	6-7.5	61	90	100			18.5-20	0	50	75	
	9.5-12	0	28	25			3.5-5	60	80	95	
	16.5-18.5	24	50	90			7-8.5	76	80	80	
BH12	18.5-20	30	90	100	62	BH26	10.5-12	22	22	50	61
	3.25-4.5	18	90	30			14-15.5	76	80	80	
	4.5-6	24	65	95			17-18.5	48	80	95	
	9-10.5	84	84	90		BH27	14.5-16	30	35	35	54
	10.5-11.5	0	50	70			18.5-20	55	85	95	
BH13	4-5.5	54	80	90	58	BH28	8.5-10	20	20	50	58
	7.5-9	0	30	60			12-13.5	20	60	75	
	11-12.5	20	80	90			15.5-18	10	50	55	
	14.5-16	26	85	95			18.5-20	51	70	80	
							19-20	51	70	80	

Also a notable variation in TCR especially in fractured or weathered sections where recovery ratios clearly decreased. The comparison between RQD, TCR and SCR show the importance of not depending on only a single indicator. The moderate RMR values (50–68) from an engineering perspective indicate fair rock mass quality suitable for shallow foundations. However, the presence of highly fractured intervals suggests that localized stability variations should be considered in design.

The SCR provides accurate characterization of rock quality in the Euphrates Formation, thereby strengthening geotechnical design parameters.

3.2. Physical Properties

The physical properties of rocks are considered fundamental indicators in geotechnical studies. They reflect the nature of the rock texture, the degree of cohesion and porosity, and directly affect the mechanical behavior of rocks. In carbonate rocks of the Euphrates Formation, these properties are influenced by dissolution processes and secondary fracturing, leading to significant variations in density, absorption, and porosity (Hoek and Brown, 2019) (Table 3).

Table 3. The values of each of the Water content, Dry Density, Saturated Density, Absorption, True specific gravity and Porosity

Borehole NO.	Sample NO.	Depth (m)	Water content %	Dry Density (gm/cm^3)	Saturated Density (gm/cm^3)	ABS %	T. GS	n%
	1	5-6.5	0.67	1.85	2.01	8.63	2.20	15.96
BH1	2	11.5-13	0.52	2.22	2.35	6.00	2.56	13.30
	3	15-16.5	0.54	1.95	2.17	11.41	2.50	22.20
	4	18.5-19.5	1.32	1.85	2.05	10.92	2.32	20.21
	1	2.5-4						
BH2	2	7-8.5	0.20	2.11	2.31	9.41	2.63	19.86
	3	11.5-13	0.22	2.07	2.25	8.77	2.53	18.16
	4	16-18	0.51	2.33	2.44	4.51	2.60	10.52
	1	4-6	0.23	2.10	2.26	7.61	2.50	15.96
BH3	2	8.5-10	0.53	2.20	2.37	7.65	2.64	16.82
	3	12-14.5	0.50	2.29	2.40	4.85	2.57	11.09
	4	16.5-18	0.24	2.40	2.50	4.01	2.65	9.62
	1	2.5-4	0.29	2.15	2.33	8.03	2.60	17.28
BH4	2	10-11.5	0.24	2.20	2.40	9.20	2.76	20.24
	3	13.5-15	0.30	2.06	2.19	6.17	2.36	12.71
	4	17-18.5	0.28	2.01	2.22	10.42	2.54	20.91
	1	1.5-3.5	0.19	2.06	2.23	8.66	2.50	17.80
BH5	2	5.5-7.5	0.37	2.22	2.31	4.10	2.44	9.11
	3	13.5-15	0.28	1.98	2.20	11.30	2.55	22.37
	4	16.5-18	0.25	2.13	2.28	7.16	2.51	15.24
	1	0.7-2.5	1.14	2.10	2.22	5.81	2.39	12.18
BH6	2	4.5-6	0.84	2.08	2.25	8.37	2.52	17.40
	3	13.5-15	0.69	1.86	2.14	15.17	2.59	28.17
	4	18-20	2.90	2.34	2.46	5.30	2.67	12.40
	1	2.5-4	3.12	2.31	2.43	5.23	2.62	12.05
BH7	2	6-10	0.32	2.05	2.26	10.43	2.60	21.35
	3	12.-13.5	0.21	2.12	2.29	7.83	2.55	16.62
	4	15.5-18	0.31	2.37	2.49	4.71	2.67	11.19
	1	0.7-2	0.71	1.81	2.13	17.09	2.63	31.01
BH8	2	7.5-9	1.15	2.48	2.55	2.86	2.67	7.09
	3	11-12.5	0.35	2.19	2.34	6.79	2.58	14.89
	4	18.5-20	0.32	1.77	2.11	19.21	2.68	34.02
	1	2-3.5	0.58	2.41	2.50	3.99	2.66	9.61
BH9	2	9-10						
	3	17-18.5	0.27	1.96	2.20	11.92	2.56	23.40
	4	0						
	1	2-3.5	3.31	2.14	2.31	8.17	2.59	17.49
BH10	2	5.5-7	0.24	1.93	2.14	10.60	2.43	20.51
	3	12.5-14	0.18	1.95	2.19	12.79	2.59	24.88
	4	18.5-20	0.39	2.08	2.29	10.21	2.63	21.19
	1	2-4	0.83	2.21	2.37	6.97	2.61	15.42
BH11	2	6-7.5	0.46	2.32	2.45	5.65	2.67	13.10
	3	9.5-12	0.25	2.23	2.37	6.53	2.60	14.55
	4	18.5-20	0.36	2.09	2.32	10.78	2.70	22.57
	1	3.25-4.5	1.05	2.05	2.26	10.11	2.59	20.73
BH12	2	6-7.5	0.74	2.05	2.25	9.71	2.56	19.89
	3	9-10.5	0.41	2.18	2.31	6.09	2.51	13.27
	4	10.5-11.5	0.29	1.92	2.16	12.22	2.51	23.46
	1	11.5-13	0.77	2.25	2.38	5.72	2.58	12.85
BH12	2	14.5-16	0.71	1.83	2.13	15.92	2.59	29.21
	3	16-17.5	0.28	1.92	2.17	12.73	2.55	24.49
	4	19-20	0.39	2.62	2.74	4.91	3.00	12.84
BH13	1	4-5.5	0.32	1.81	1.96	8.50	2.13	15.35

	2	7.5-9	0.13	1.60	1.80	12.88	2.01	20.58
	3	11-12.5	0.07	1.71	1.93	13.40	2.21	22.86
	4	18.5-20	0.39	1.93	2.06	6.89	2.22	13.26
	1	3-4.5	0.26	1.77	2.01	13.56	2.33	24.03
BH14	2	6.5-8	0.15	2.37	2.46	3.86	2.61	9.15
	3	10-11.5	0.33	2.05	2.24	9.02	2.52	18.53
	4	20.5-22	0.16	2.20	2.29	4.12	2.42	9.05
	1	4.5-6	0.99	2.12	2.22	4.93	2.36	10.43
BH15	2	8-9.5	0.15	1.80	1.97	9.26	2.16	16.67
	3	15-16.5	0.23	1.79	2.03	13.57	2.36	24.24
	4	18.5-20	0.16	1.56	1.63	4.58	1.68	7.15
	1	2.5-4						
BH16	2	9.5-11	0.28	2.11	2.27	7.85	2.53	16.55
	3	17-18.5	0.26	2.01	2.26	12.59	2.69	25.28
	4	18.5-20						
	1	7-8.5	0.30	1.96	2.22	13.50	2.66	26.40
BH17	2	10.5-12	0.31	1.85	2.09	12.98	2.44	24.06
	3	14.5-16	0.26	1.92	2.17	13.16	2.57	25.23
	4	18.5-20	0.89	2.41	2.52	4.82	2.72	11.60
	1	3-4.5	0.09	2.10	2.27	8.26	2.54	17.34
BH18	2	10-11.5	0.17	1.76	2.05	16.15	2.47	28.49
	3	13.5-15	0.22	2.02	2.24	10.81	2.59	21.88
	4	15-17	0.09	2.14	2.32	8.32	2.61	17.83
	1	1-1.5	0.10	2.35	2.44	3.92	2.59	9.23
BH19	2	7.5-9	0.28	1.93	2.15	11.27	2.47	21.80
	3	15-16.5	0.09	2.18	2.34	7.16	2.59	15.65
	4	Failed						
	1	3-4.5						
BH20	2	6.5-8	1.67	1.96	2.21	12.52	2.60	24.55
	3	17-18.5	0.14	2.40	2.45	2.30	2.54	5.51
	4	NO SAMPLE						
	1	0						
BH21	2	6.5-8	0.48	2.36	2.47	4.42	2.64	10.46
	3	10-12	0.23	1.94	2.20	13.52	2.63	26.24
	4	14.5-16	0.25	2.26	2.43	7.71	2.73	17.41
	1	1.5-3	0.23	1.93	2.13	10.65	2.42	20.51
BH22	2	5-6.5	0.24	2.08	2.23	7.22	2.45	15.04
	3	8.5-9.5	0.21	2.16	2.31	6.88	2.54	14.86
	4	18.5-20	0.94	2.09	2.21	5.36	2.36	11.21
	1	4-5.5	0.74	2.00	2.18	8.98	2.44	17.96
BH23	2	11-12.5	0.85	1.78	2.04	14.75	2.41	26.27
	3	14.5-16						
	4	18.5-20	0.20	1.21	1.33	9.66	1.37	11.72
	1	6-7.5	0.17	1.80	2.05	13.78	2.40	24.84
BH24	2	9.5-11	0.12	1.80	2.06	14.70	2.45	26.46
	3	13-14.5	0.31	1.97	2.18	10.74	2.50	21.15
	4	17-18.5	0.07	1.91	2.02	5.62	2.14	10.74
	1	0.5-2	0.24	1.87	2.12	12.85	2.47	24.08
BH25	2	7.5-9	0.22	1.93	2.14	11.00	2.45	21.24
	3	11-12.5	0.18	1.69	1.99	17.63	2.41	29.83
	4	18.5-20	0.18	2.09	2.25	7.54	2.49	15.79
	1	3.5-5	0.58	2.18	2.34	7.29	2.59	15.91
BH26	2	7-8.5	0.56	2.03	2.28	12.02	2.69	24.41
	3	10.5-12	0.40	2.05	2.20	7.08	2.40	14.53
	4	17-18.5	0.40	2.24	2.37	5.96	2.59	13.35
	1	7.5-9	0.27	1.94	2.19	12.79	2.58	24.84
BH27	2	14.5-16	0.40	1.90	2.17	14.26	2.60	27.06
	3	18.5-20	0.72	1.91	2.14	12.20	2.48	23.25
	4	NO SAMPLE						
	1	5-6.5	0.37	1.92	2.13	10.86	2.42	20.82
BH28	2	8.5-10	0.33	1.86	2.09	12.74	2.43	23.66
	3	12-13.5	4.60	1.90	2.10	10.57	2.38	20.11
	4	19-20	0.07	1.89	2.01	6.41	2.15	12.14

Table 3 shows clear variation in the physical properties of the Euphrates Formation samples. The dry density ranging approximately between 1.56 and 2.62 g/cm³, absorption rates ranging between 2.30% and 19.21% and porosity ranging from about 5.51% to 34.02%. This variation reflects the heterogeneity of the rock and differences in the degree of secondary porosity resulting from dissolution and weathering.

High values of porosity and absorption in some sections indicate a relative weakness in the structural cohesion of the rocks and may lead to decreases their mechanical strength, while low values

indicate more cohesive and stable sections. These results emphasize the necessity of conducting in depth characterization and avoiding the use of a single representative value in geotechnical design. Similar variability in limestone properties has been reported by Ahmed et al. (2022), who documented comparable physical heterogeneity in carbonate rocks from the Nfayil Formation in Iraq. This variability indicates that secondary porosity and dissolution processes play a dominant role in controlling the engineering performance of the Euphrates limestone, particularly in terms of durability and strength reduction.

3.3. Mechanical Tests

3.3.1. Unconfined compressive strength (UCS)

Unconfined Compressive Strength (UCS) is one of the most important mechanical properties used in geotechnical rock characterization. UCS represents the rock's ability to withstand axial loads and is widely used in rock classification and in the input of design parameters, especially in fractured carbonate rocks (Hoek and Brown, 2019) (Table 4).

Table 4. The values of each unconfined compressive strength and Poisson's ratio

Borehole No.	Depth of sample	Diameter	Length	Corrected UCS	UCS classification	lateral strain (mm)	axial strain (mm)	Poisson's ratio
BH1	18.5-20	70	147	8.77	Moderately weak	0.01	0.04	0.25
BH2	7-8.5	53	118	23.57	Moderately strong	0.02	0.06	0.33
	11.5-13	53	112	10.58	Moderately strong	0.02	0.08	0.25
BH3	6-7.5	53	105	7.08	Moderately weak	0.01	0.04	0.25
BH4	4-5.5	70	115	11.17	Moderately weak	0.03	0.07	0.42
	17-18.5	70	160	12.89	Moderately strong	0.01	0.04	0.25
BH5	5.5-7.5	53	120	12.56	Moderately strong	0.02	0.06	0.33
	16.5-18	53	127	19.90	Moderately strong	0.01	0.08	0.12
BH6	4.5-6	53	117	19.95	Moderately strong	0.01	0.04	0.25
	17-18.5	53	117	16.98	Moderately strong	0.01	0.04	0.25
BH7	6-10	70	152	10.09	Moderately weak	0.01	0.04	0.25
	6-10	53	124	11.27	Moderately weak	0.02	0.04	0.50
BH8	0.7-2	53	117	5.12	Moderately weak	0.01	0.04	0.25
	7.5-9	53	116	14.87	Moderately strong	0.01	0.09	0.11
BH10	17-18	53	126	11.42	Moderately weak	0.02	0.08	0.25
BH11	6-7.5	53	127	6.66	Moderately weak	0.02	0.06	0.33
BH12	14.5-16	70	163	4.48	Weak	0.01	0.06	0.16
	16-17.5	70	154	7.88	Moderately weak	0.01	0.04	0.25
BH13	7.5-9	70	150	13.91	Moderately strong	0.01	0.04	0.25
	14.5-16	70	98	4.16	Weak	0.01	0.03	0.33
BH14	20.5-22	53	104	12.02	Moderately weak	0.02	0.06	0.33
BH15	1-2.5	70	161	14.98	Moderately strong	0.01	0.04	0.25
	11.5-13	70	115	19.71	Moderately strong	0.02	0.06	0.33
BH16	17-18.5	53	130	4.38	Weak	0.03	0.11	0.27
BH17	14.5-16	53	120	15.97	Moderately strong	0.02	0.06	0.33
	14.5-16	53	113	11.86	Moderately weak	0.01	0.04	0.25
BH18	10-11.5	70	172	13.57	Moderately strong	0.01	0.06	0.16
BH19	4-5.5	70	140	7.80	Moderately weak	0.01	0.04	0.25
	15-16.5	70	129	15.55	Moderately strong	0.02	0.04	0.50
BH20	6.5-8	70	104	5.32	Moderately weak	0.01	0.04	0.25
	10-11.5	70	108	3.15	Weak	0.01	0.04	0.25
BH21	10-12	53	114	6.24	Moderately weak	0.02	0.08	0.25
BH22	5.5-6	53	125	18.39	Moderately strong	0.02	0.06	0.33
BH23	14.5-16	70	152	12.69	Moderately strong	0.01	0.04	0.25
BH24	9.5-11	70	140	10.08	Moderately weak	0.01	0.06	0.16
BH25	18.5-20	53	98	4.23	Weak	0.01	0.04	0.25
BH26	7-8.5	70	157	12.70	Moderately strong	0.01	0.03	0.33
	14-15.5	70	140	19.12	Moderately strong	0.01	0.04	0.25
BH27	14.5-16	70	130	4.01	Weak	0.02	0.05	0.40
BH28	5-6.5	53	99	5.02	Moderately weak	0.02	0.06	0.33

Table 4 shows the corrected UCS values ranging from weak to moderately strong for the Euphrates Formation rocks as classified based on Anon (1977) classification. This variation points to the differences in cracking and porosity among the different sections. Poisson's ratio also ranged between 0.09 and 0.43 indicating variability in the deformation behavior of the rocks. These results show the necessity of adopting a detailed characterization and not using uniform values in geotechnical design. The moderate UCS range suggests that the Euphrates limestone behaves as weak to moderately strong carbonate rock, this should considered when selecting conservative design parameters for foundation applications.

3.3.2. Point load (PL)

The Strength point load test is considered a quick and widely used test for classifying rock strength, when performing unconfined compressive strength tests is difficult due to the lack of samples length which is not suitable to direct UCS. This test is characterized by its ease of execution and minimal sample preparation requirements, with the possibility of applying it to rock core samples or irregular blocks, according to ASTM D5731 (ASTM, 2016; Broch and Franklin, 1972) (Table 5).

Table 5. Shows the values of IS_{50}

Borehole NO.	Depth of sample	Is_{50}	F (kN)	Borehole NO.	Depth of sample	Is_{50}	F (kN)
BH1	11.5-13	0.766	6.87	BH15	8-9.5	0.8	1.48
	18.5-19	0.705	5.4		18.5-20	1.053	16.33
BH2	7-8.5	1.323	13.55	BH16	18.5-20	0.45	26.14
	16-18	0.761	3.96	BH17	10.5-12	0.867	6.9
BH3	8.5-10	0.568	7.02	BH18	10-11.5	0.858	18.15
	16.5-18	0.604	18.02		13.5-15	0.217	1.09
BH4	06-Aug	0.45	2.26	BH19	15-16.5	0.881	2.2
BH5	5.5-7.5	0.501	3.45	BH20	10-11.5	0.404	2.62
	16.5-18	0.886	0.76		6.5-8	1.208	9.3
BH6	13.5-15	0.385	1.97	BH21	14.5-16	0.327	0.65
	18.5-20	1.077	8.72		6.5-8	0.749	5.98
BH7	06-Oct	0.798	12.13	BH22	11-12.5	1.057	5.31
	18.5-20	0.868	5.46		18.5-20	0.482	2.31
BH8	7.5-9	0.381	1.9	BH23	7.5-9	0.742	6.79
	18-20	0.219	0.05		14.5-1`6	0.974	4.56
BH9	5.5-7	0.081	0.42	BH24	6-7.5	0.766	3.76
	18.5-20	0.563	2.35		17-18.5	0.153	0.6
BH10	2-3.5	0.886	5.08	BH25	11-12.5	1.368	6.56
	18-20	0.866	9.08		18.5-20	0.261	1.28
BH11	18-20	0.289	0.3	BH26	7-8.5	0.798	7.94
	9.5-11	0.735	3.8		14-15.5	0.785	5.36
BH12	16-17.5	0.269	1.29	BH27	18.5-20	0.312	0.54
BH13	11-12.5	0.127	0.22		14.5-16	0.298	1.55
	4.5.5	0.73	4.18	BH28	1-1.5	0.709	3.36
BH14	6.5-8	1.208	10.38		15.5-17	0.323	1.55
	20.5-22	0.847	7.04				

Table 5 shows that the IS_{50} values for the Euphrates Formation rocks ranged between 0.081 and 1.368 MPa, indicating a clear variation in rock strength between different cores and depths. Low values indicate fractured or highly porous rocks, the higher values reflect relatively more cohesive sections.

A general agreement is observed between the Is_{50} results and the laboratory measured UCS values, supporting the potential use of the point load index as a preliminary classificatory tool for estimating rock strength and provided it is done after local calibration and the values are not used directly for design purposes. This agreement supports the use of the point load test as a rapid and practical field tool for preliminary strength estimation in similar carbonate formations.

Combined correlation analysis in order to further investigate the relationships between physical and mechanical properties presented in Fig. 5.

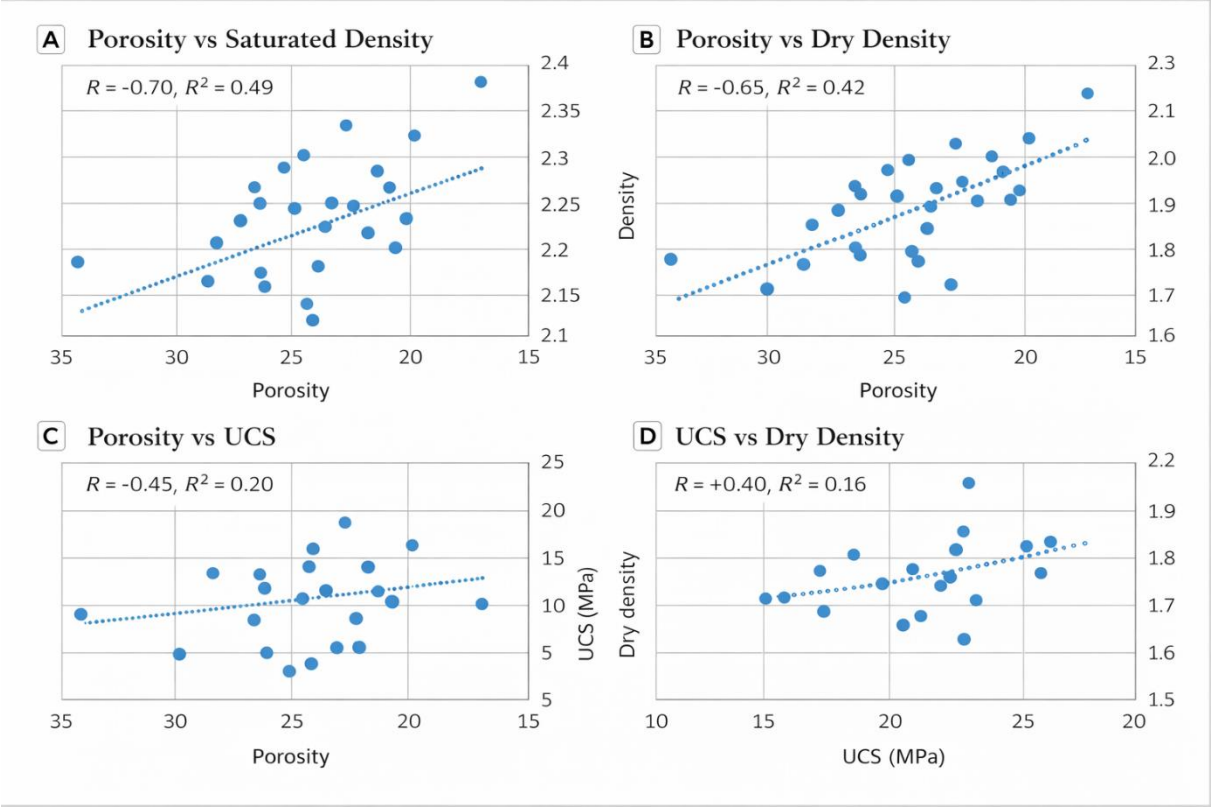


Fig. 5. Multi-panel correlation plots between physical and mechanical properties of the Euphrates Formation

The correlation analysis reveals moderate inverse relationships between porosity and density parameters and indicating that pore reduction linked with compaction plays key role in increasing rock density. The correlations involving UCS are relatively weaker that suggest rock strength is influenced by additional factors such as microfracturing and cementation. These findings highlight the complex mechanical behavior of the Euphrates Formation and emphasize the importance of multiple parameter evaluation in geotechnical design.

4. Conclusions

The geotechnical evaluation of the Euphrates Formation rocks at the investigated site represents a notable variability according to depth in rock mass characteristics mainly related to variations in fracturing intensity and the development of secondary porosity within the carbonate lithology. The findings show the important side of integrating rock mass quality indices with physical and mechanical properties to obtain more reliable geotechnical characterization particularly in heterogeneous carbonate formations. The mechanical behavior of the Euphrates Formation limestone generally falls within the

weak to moderately strong range and the observed correspondence between the point load index and unconfined compressive strength suggests that the point load test may be used as a supportive classification tool following appropriate local calibration. The results provide a preliminary basis for foundation assessment at the study site. With increasing depth, there are several geotechnical properties that show clear trends in the Euphrates Formation. Properties related to density such as dry and saturated density generally increase with depth due to greater compaction and reduced weathering and this is accompanied by an overall increase in mechanical strength including UCS and PL. In contrast, porosity and water absorption typically decrease with depth as pore spaces become smaller and the rock becomes more consolidated. Some parameters such as RQD, RMR and Poisson's ratio may vary irregularly due to local fracturing and lithological heterogeneity within the carbonate formation. However detailed site investigations and careful consideration of depth- related variability are required before adopting the Euphrates Formation limestone for foundation design especially in zones affected by pronounced fracturing or elevated porosity. Correlation analysis indicates moderate relationships between porosity and density. Also strength parameters exhibit weaker dependence on physical properties which influenced by heterogeneity of the carbonate rocks.

Author Contributions (CRediT)

The article was developed and implemented collaboratively by all authors in accordance with the sequence of their names. All authors participated in designing the methodology and conducting the investigation and performing the analyses and validating the results. The manuscript was drafted and revised jointly and all authors approved the final version for publication.

Declaration of Competing Interest

The authors confirm that there are no financial, professional, or personal interests that could have affected the objectivity or integrity of the results presented in this study.

Acknowledgments

The authors gratefully acknowledge Professor Dr. Sabbar Abdullah Saleh and Professor Dr. Mohammed Rashid Aboud for their careful scientific review of the manuscript and for their valuable comments and professional insights, which significantly enhanced the scientific quality of this work.

Funding

This study was carried out with financial support provided by the authors' affiliated educational institution. The supporting institution had no involvement in the planning of the study, data acquisition, analysis, interpretation of the results, preparation of the manuscript, or the decision to submit it for publication.

Data Availability

The data supporting the findings of this study are fully presented and discussed in the article.

References

Ahmed, H.G., Issa, M.J., Ali, J.H., 2022. Study of limestones from the Nfayil Formation in Bahr Al-Najaf depression and suitability for thermal conductivity. Iraqi Journal of Science, 63(7), 2980–2986. https://doi.org/10.24996/ijs.2022.63.7.21

Al-Dabbas, M., Awadh, S.M., Zaid, A., 2013. Mineralogy, geochemistry, and reserve estimation of the Euphrates limestone for Portland cement industry at Al-Najaf area, south Iraq. Arabian Journal of Geosciences, 6(2), 491-503. https://doi.org/10.1007/s12517-011-0370-z

Al-Ghreri, M.F., Al-Jibouri, A.S., Al-Ahmed, A.A., 2014. Facies architecture and sequence development of the Euphrates Formation in western Iraq. Arabian Journal of Geosciences, 7, 2679–2687. https://doi.org/10.1007/s12517-013-0944-z

Al-Taha, S.A. Al-Haj, M.A., 2024. Depositional setting of the Euphrates Formation (Early Miocene) in selected wells, Hamrin oil field, northern Iraq. Iraqi National Journal of Earth Sciences, 24(1), 136–155. https://doi.org/10.33899/earth.2023.141083.1095

Anon, Q., 1977. The description of rock masses for engineering purposes. Quarterly Journal of Engineering Geology, 10, 355-388. https://doi.org/10.1144/GSL.QJEG.1977.010.04.01

ASTM International, 1998. ASTM D3148-96: Standard test method for elastic moduli of intact rock core specimens in uniaxial compression. In: Annual Book of ASTM Standards, 04.08 Soil and Rock, 306–310. West Conshohocken, PA: ASTM International. ASTM International | ASTM

ASTM International, 2004. ASTM C127-01: Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate. West Conshohocken, PA: ASTM International. ASTM International | ASTM

ASTM International, 2010. ASTM C97/C97M-09: Standard test methods for absorption and bulk specific gravity of dimension stone. West Conshohocken, PA: ASTM International. ASTM International | ASTM

ASTM International, 2016. ASTM D5731-16: Standard test method for determination of the point load strength index of rock. West Conshohocken, PA: ASTM International. ASTM International | ASTM

ASTM International, 2017. ASTM D6032/D6032M-17: Standard test method for determining rock quality designation (RQD) of rock core. West Conshohocken, PA: ASTM International | ASTM

ASTM International, 2023. ASTM D7012-14e1: Standard test methods for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures. West Conshohocken, PA: ASTM International.

Bieniawski, Z.T., 1989. Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering. New York: John Wiley and Sons.

Broch, E., Franklin, J.A., 1972. The point-load strength test. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 9(6), 669–676. https://doi.org/10.1016/0148-9062(72)90030-7

Deere, D.U., Deere, D.W., 1989. Rock quality designation (RQD) after twenty years. Contract Report GL-89-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hoek, E., Brown, E.T., 2019. The Hoek–Brown failure criterion and GSI – 2018 edition. Journal of Rock Mechanics and Geotechnical Engineering, 11(3), 445–463. https://doi.org/10.1016/j.jrmge.2018.08.001

IS 11315-11, 1985. Method for the quantitative description of discontinuities in rock masses, Part 11: Core recovery and rock quality designation [CED 48: Rock Mechanics]. Bureau of Indian Standards.

Khudher, M.E., Saleh, S.A., Ibrahim, O.S., 2025. Assessment of the hydrochemical characteristics of groundwater in the vicinity of Kirkuk irrigation project. Iraqi National Journal of Earth Sciences, 25(3), 44–57. DOI:10.33899/earth.2024.148833.1270

Sissakian, V.K., Fouad, S.F., 2015. Geological map of Iraq, scale 1: 1000 000, 2012. Iraqi Bulletin of Geology and Mining, 11(1), 9-16.

Valentine, S., Norbury, D., 2011. Measurement of total core recovery; dealing with core loss and gain. Quarterly Journal of Engineering Geology and Hydrogeology, 44(3), 397–403. https://doi.org/10.1144/1470-9236/10-009

Zhang, L., 2016. Determination and applications of rock quality designation (RQD). Journal of Rock Mechanics and Geotechnical Engineering, 8(3), 389–397. https://doi.org/10.1016/j.jrmge.2015.11.008