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Study of physico-mechanical Characteristic of Jurassic Rock Unit from the Serki and Sehkaniyan Formations for a Dimension Stone, Sulaimaniyah City, NE-Iraq

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Abstract

Natural stones are widely used for paving, crushing, building, and dimensioning purposes worldwide. There are plenty of natural stone resources in the Sulaimaniyah governorate of north-eastern Iraq that can be used for a range of architectural and ornamental purposes. The aim of this study is to evaluate the suitability of dolomitic limestone from the Serki and Sehkaniyan formations for use as dimension stone based on their physical and mechanical properties. In this study, 21 samples of the Serki and Sehkaniyan dolomitic limestone rock were collected in outcropped rock units within the quarry sites. The physical testing of rocks includes assessments of total porosity, water absorption, saturation coefficient, apparent specific gravity, and bulk density. Based on Iraqi standard specification 1989, 1387 and American standards 2004, C568, all tested characteristics were classified as having very high density, and the rock units were frost-resistant. The uniaxial compressive strength (UCS) of the rock samples indicated a strength range of 60 to 80 MPa, these values are higher than the strength in the parallel orientation tested samples which are 43 to 56 MPa. Based on different classifications and standards, the majority of the tested samples were rated as strong to very strong, while only a few were considered moderately strong. Notably, there are significant relation between the UCS values and the physical parameters of the rock units, also strong relation with the point load index were observed in both perpendicular and parallel testing modes, yielding R^2 values of 0.85 and 0.76, respectively. Excavatability assessment shows most samples need hard ripping or blasting due to high strength and wide fractures. Standard excavation tools may not be effective for these rocks. The results reveal that the Serki and Sehkaniyan formations examined are of high quality and suitable for use as dimension stone for both exterior and interior applications, as well as for paving and construction materials.

1. Introduction:

Dimension stones are natural rocks that are cut and shaped for use in construction and decoration, playing a vital role in the building industry. Their appeal lies not only in their aesthetic qualities but also in their strength and durability. For a rock to be considered a suitable dimension stone, it must be free from defects such as cracks, seams, or pits, which could compromise its performance over time [1]. Among the various types of rocks used, carbonate rocks, especially limestone and dolomitic limestone, are among the most valued due to their strength, resistance to weathering, and widespread availability [2].

Dolomitic limestone is widely recognized for its excellent compressive strength, resistance to chemical weathering and acids, and its durability under both mechanical and environmental stress [3], [4]. Despite these advantages, the dolomitic limestone found in northeastern Iraq, particularly within the Serki and Sehkaniyan formations, has received limited scientific attention. These formations, dating back to the Early Jurassic period, are present in several regions, including Said Sadiq and Penjween, which form the main focus of this study. They are also prominently exposed in areas such as Dukan, Surdash, and Ranya. While some quarrying activity exists in the studied locations, much of it has developed in response to market needs rather than through detailed geological or engineering evaluation [1].

What makes these formations particularly promising is the presence of thick, massive carbonate beds that can be extracted in large blocks suitable for use as dimension stone. Additionally, their proximity to transportation routes provides easy access to nearby cities such as Sulaimaniyah. However, past research in the region has primarily focused on the more familiar Pila Spi Formation, which has been studied extensively for cement and building stone applications [5], [6], [7], [8], [9], [10], [11]. In contrast, the Serki and Sehkaniyan formations remain relatively understudied despite their apparent physical and mechanical advantages.

Previous studies have shown that factors such as porosity, texture, and compressive strength are key to evaluating the quality and durability of dimension stones [12], [13], [3]. It has also been noted that carbonate rocks composed predominantly of calcite, and lacking dolomite or iron oxides as cementing materials, tend to be more vulnerable to mechanical failure [4].

This study aims to address this research gap by examining dolomitic limestone from the Pali Hero area near Said Sadiq. Through a combination of petrographic analysis and physico-mechanical laboratory testing, the research evaluates the potential of these rock units as dimension stone, offering new insights into the untapped carbonate resources of the Kurdistan Region.

2. Geological Setting:

The study area is located near Pali Hero, southeast of Said Sadiq in northeastern Iraq. Geologically, this region lies along the former passive margin of the Neo-Tethys Ocean, close to the present-day boundary between the Arabian and Eurasian plates. These rock formations, particularly prominent in the Halabja to Said Sadiq area, were first described in locations such as Sazan and Kolus villages [14] see Figure 1.

Tectonically, the area falls within the Zagros Fold and Thrust Belt and is specifically influenced by the Zagros Main Reverse Fault. It has been significantly shaped by the collision between the Arabian Plate and the Eurasian margin, resulting in intense folding, faulting, and uplift. These dynamic forces have played a major role in the exposure and current structural condition of the rocks.

Field observations show that both formations are composed mainly of well-bedded, massive dolomitic limestone with a range of textures and colors. The rocks are generally dense and crystalline, with a sugary appearance, and range in color from light to very dark grey. Some layers are bituminous, and bed thickness typically falls between 0.6 and 1.2 meters. Fossils are sparse, though Posidonia shell fragments can occasionally be found in the Serki Formation.

Petrographic analysis of thin sections reveals that the rocks are primarily dolomitic limestones. When cut and polished, they take on attractive greyish to black hues (Figure 2 and Figure 3). The microstructure often includes recrystallized grains, intercrystalline porosity, and microfractures, especially visible under crossed polarized light (Figure 2 B, D, F, H). These features likely developed due to tectonic stress and diagenetic processes such as compaction and recrystallization. Despite the microfractures, the rocks remain very hard and compact, suggesting a high resistance to both mechanical and environmental stress.

More specifically, thin section analysis shows that Units 1 and 4 consist of fine-grained, partially recrystallized packstone, while Units 2 and 3 exhibit more medium-grained, compressed and recrystallized textures, with few visible fossils beyond Posidonia fragments. These features point to a complex geological history and underscore the formations potential for use as dimension stones, given their structural integrity and visual appeal.

Climatic conditions in the area add another layer of relevance. The region experiences a hot, dry summer and a cold, rainy winter, under the influence of the Mediterranean climate system. Temperatures range from 3.3^{o}C in winter to 43.4^{o}C in summer, and the average annual rainfall is about 622.6 mm, based on records from 2001 to 2021 [15]. Recent studies also suggest that this area may face increasing climate variability in the coming decades [16]. These climatic factors, especially freeze-thaw cycles and rainfall, can impact the weathering resistance of exposed rocks, making it essential to assess their long-term durability when used in construction.

3. Materials and methods:

This study evaluated the suitability of dolomitic limestone from the Serki and Sehkaniyan formations for use as dimen-

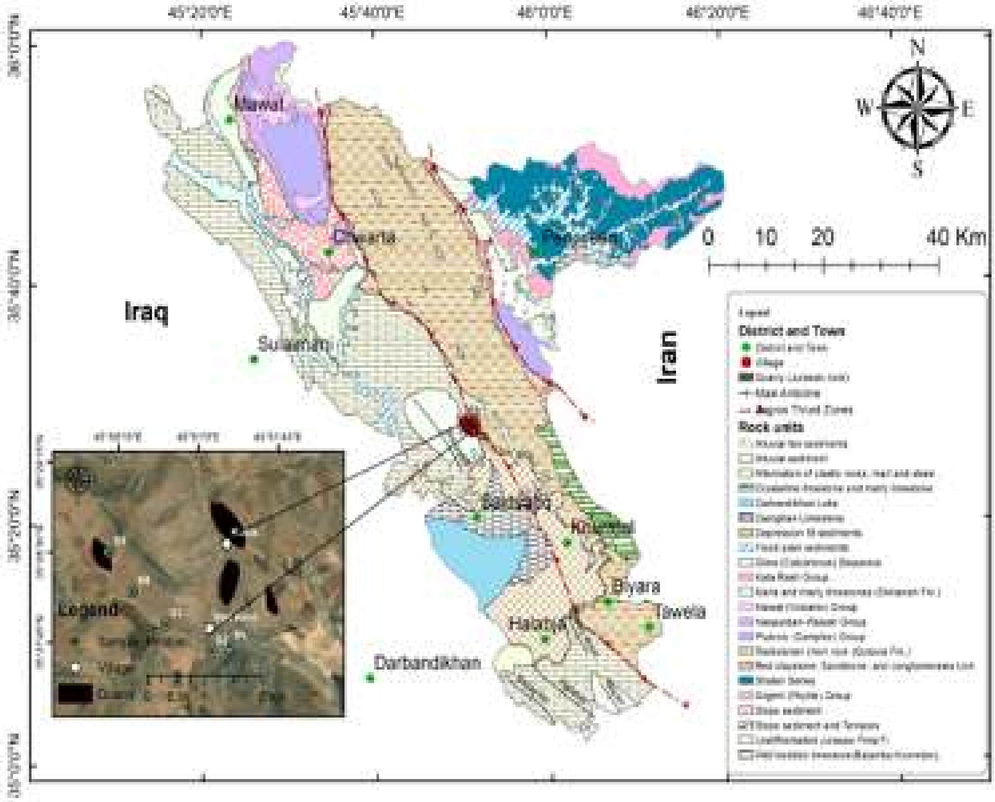

Figure 1. Geological map of the studied area showing quarry sample locations (modified from [17], [18]).

sion stone. A total of 21 rock block samples were collected from four distinct lithological units exposed in an active quarry within the imbricated zone near Said Sadiq, northeastern Iraq. The samples were selected to reflect the natural variation in texture and composition observed across the site. The details of the rock unit's properties are shown in Table 1.

3.1 Sample Collection and Preparation:

The rock blocks were selected to reflect variations in texture and appearance across the formations. Each block was carefully cut into cube-shaped specimens with dimensions of (5 × 5 × 5 cm), using a precision diamond saw cutting machine following ASTM C170/C170M [19].

To study the influence of rock fabric orientation, the specimens were divided into two groups: one set was cut parallel to the bedding planes, while the other was cut perpendicular to them. Figure 3 showing large dolomitic limestone blocks from the active quarry site in the Serki and Sehkaniyan formations near Said Sadiq, highlighting their massive, jointed structure and the displays 21 prepared standardized cube specimens, ready for physical and mechanical testing.

3.2 Physical Testing:

Prior testing, all samples were oven-dried at 105°C for 24 hours to remove any moisture. Their dry weights were measured using high-precision electronic balance (±0.001 g) accuracy, and their volumes were recorded to calculate dry and saturated unit weights, following the procedure described in C97/C97M-18 [20].

This provided insight into the density and porosity of the rocks, which are key indicators of quality in dimension stone. Dry and saturated unit weights were calculated by dividing the sample weight by its volume, with results expressed in grams per cubic centimeter (g/cm^{-3}). Tables 2 and 3.

3.3 Mechanical Strength Testing:

Mechanical testing began with Point Load Index (Is_{50}) was measured using a Wille Geotechnik Digital Point Load Tester. This test followed the ASTM D5731-16 [21], and it helped to estimate the uniaxial compressive strength (UCS). The results are detailed in Table 4.

3.4 Petrographic Analysis:

After completing the physical and mechanical tests, thin sections were prepared to better understand the internal structure and mineral composition of the rocks. A total of eight thin sections were produced, with two representative samples taken from each of the four lithological units. These samples were carefully cut, trimmed, and polished before being examined under an Olympus BX51 polarizing microscope at 40× magnification.

Observations were made using both plane-polarized and cross-polarized light, allowing for detailed analysis of the mineral textures, grain boundaries, signs of recrystallization, bituminous material, and microfractures and microstructural features. Representative petrographic images are shown in Figure 2.

4. Results and Discussion:

4.1 Physical integrity, mechanical strength, and petrographic features:

This study aimed to evaluate the dolomitic limestone from the Serki and Sehkaniyan formations to determine its suitability as a dimension stone. Based on both field observations and laboratory analyses, the results provide a detailed understanding of the rocks' physical characteristics, internal structure, and mechanical performance, which are essential when assessing their potential for construction and decorative use. The evaluation of the physical and mechanical properties adhered to the international ASTM C97/C97M-18, ASTM C568M-04 [20], [22].

The physical testing results, summarized in Tables 2 and 3, show that most samples display consistent values for bulk density (average > 2.6 g cm^{-3}), low porosity ($< 5\%$), and minimal water absorption ($< 2\%$). These characteristics are typical of durable and compact limestones. However, some variability is evident across different lithological units. Samples from Units 1 and 4, including S_1, S_2 S_3, S_{16}, S_{20} and S_{21}, show slightly higher porosity and water absorption.

These results may be attributed to differences in mineral content, microfracture density, or lower degrees of dolomitization, possibly resulting from localized tectonic stress or diagenetic alteration. In contrast, samples from Units 2 and 3 exhibit lower porosity and higher density, which suggests tighter crystal packing and more extensive recrystallization.

The type and distribution of porosity also play a critical role in the durability of the studied rocks. In most of the samples, the pores are narrow and well connected, which helps limit how easily water can seep in. This makes the rocks more resistant to weathering over time. According to established classifications for frost resistance, all of the tested samples are considered frost resistant.

This quality is especially important when the stone is used outdoors, for example in cladding or paving, where it may be exposed to cycles of freezing and thawing [23]. In such environments, having a material that can withstand these conditions without cracking or deteriorating is a major advantage. Regarding their suitability for polishing and cutting, the rocks exhibit a fine-grained, compact crystalline structure with minimal visible defects such as fractures or large voids. These features enhance the rocks' ability to take on a smooth, glossy finish during polishing, making them aesthetically appealing for architectural and decorative applications [24].

Statistical correlation analysis (Figure 4, 5, 6) further reveals strong relationships among physical properties. For instance, total porosity (ϕ %) shows an inverse correlation with bulk density (R^2 = 0.7503), apparent specific gravity (R^2 = 0.7096), and saturation coefficient (R^2 = 0.7089).

Water absorption also correlates strongly with porosity (R^2 = 0.9998), underscoring the influence of pore structure on fluid ingress and durability. Understanding these correlations is essential for predicting how the stone will behave under environmental and mechanical stress, particularly in applications where dimensional stability and weather resistance are critical. These insights also support more informed selection and processing of stone for use in construction. See Table 8.

The mechanical properties, assessed through uniaxial compressive strength (UCS) and point load index (Is_{50}), demonstrate considerable consistency with the physical characteristics. Average UCS values range from 60 to 80 MPa, classifying most samples as "strong" per ISRM and ASTM criteria (Tables 5, 6, 7).

Samples S_3, S_4, S_7, and S_{20}, which showed relatively higher porosity, fall into the "moderately strong" category. The point load strength index (Is_{50}) values range from 1.42 to 4.71 MPa. This alignment between porosity and mechanical strength confirms that microstructural density plays a crucial role in load-bearing capacity. Additionally, point load test results are in good agreement with UCS values, providing a useful rapid screening method.

An important consideration in the evaluation is the effect of loading direction relative to bedding planes. As shown in Table 4, samples loaded perpendicular to bedding exhibit higher UCS values than those loaded parallel, reflecting anisotropy typical of bedded sedimentary rocks. This behavior, also reported by [25], is attributed to the mechanical discontinuities along bedding planes that act as planes of weakness under parallel stress. Moreover, the average values of uniaxial compressive strength (UCS) show strong correlations with all the physico-mechanical properties evaluated in this study, including the point load index, as shown in Figure 7.

In addition, all rock units from the Serki and Sehkaniyan formations meet the UCS requirements outlined by ASTM C568 (2004) and the Iraqi Standard Specification No. 1387

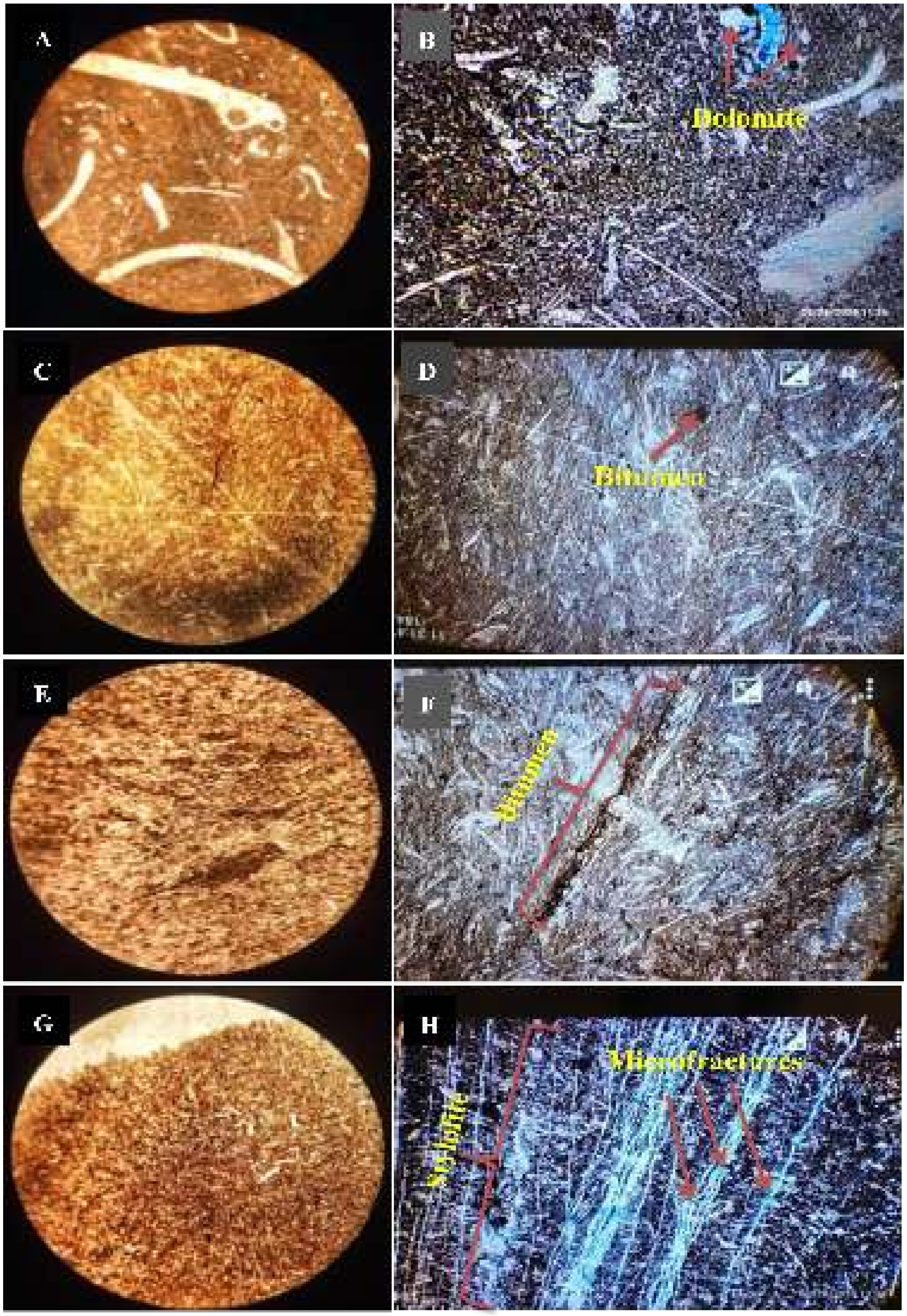

Figure 2. (A, B): Fine-grained limestone packstone, partially recrystallized, containing shell fragments of Posidonia; (C, D, E, F): Medium-grained dolomitic limestone, compacted and recrystallized, exhibiting a crystalline packstone texture; (G, H): Partially recrystallized calcitic limestone, showing moderate crystalline development.

Figure 3. Rock sample collection, cutting, dry and wet weighting and point load testing.

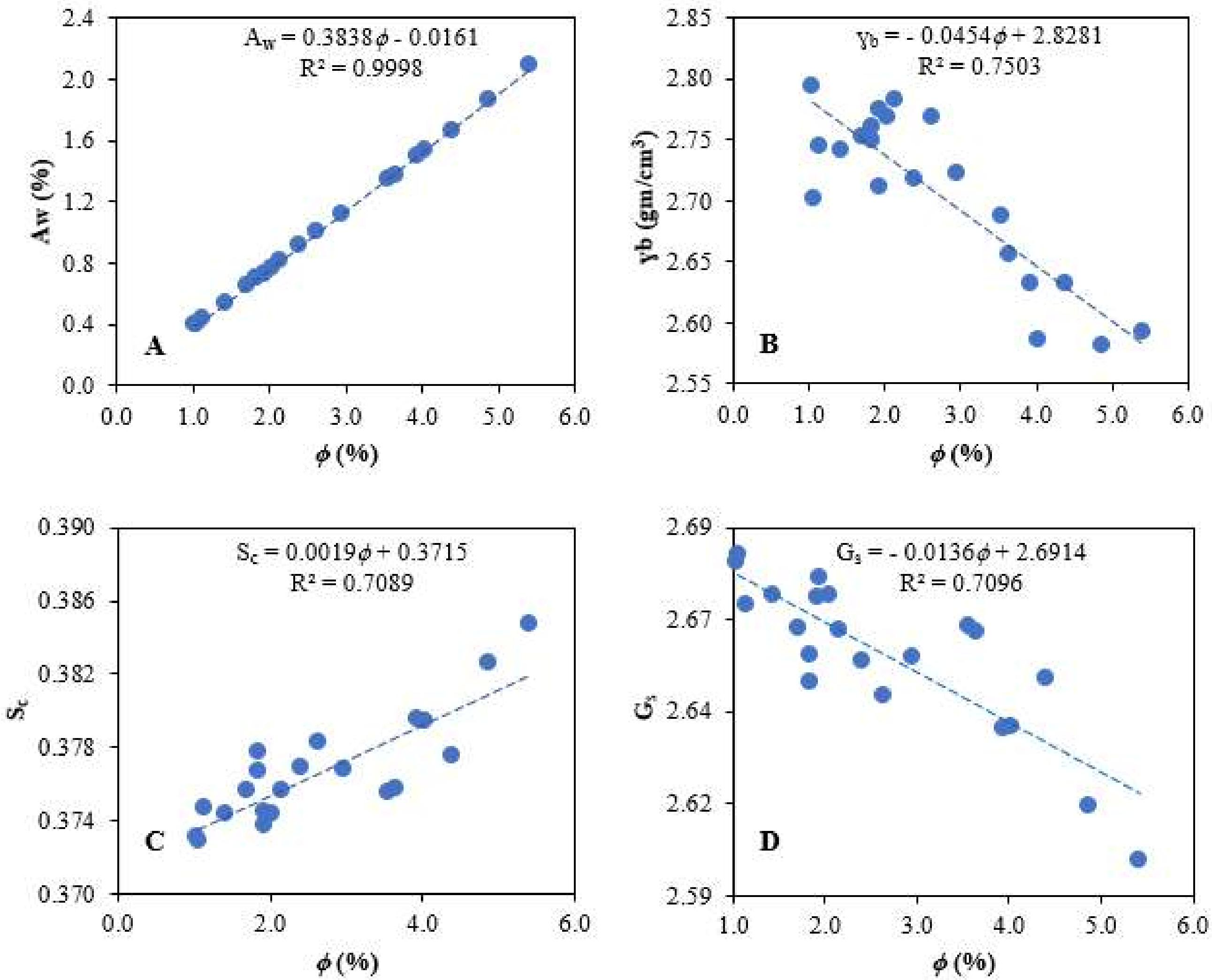

Figure 4. The total porosity versus A) water absorption, B) bulk density, C) saturation coefficient, D) apparent specific gravity.

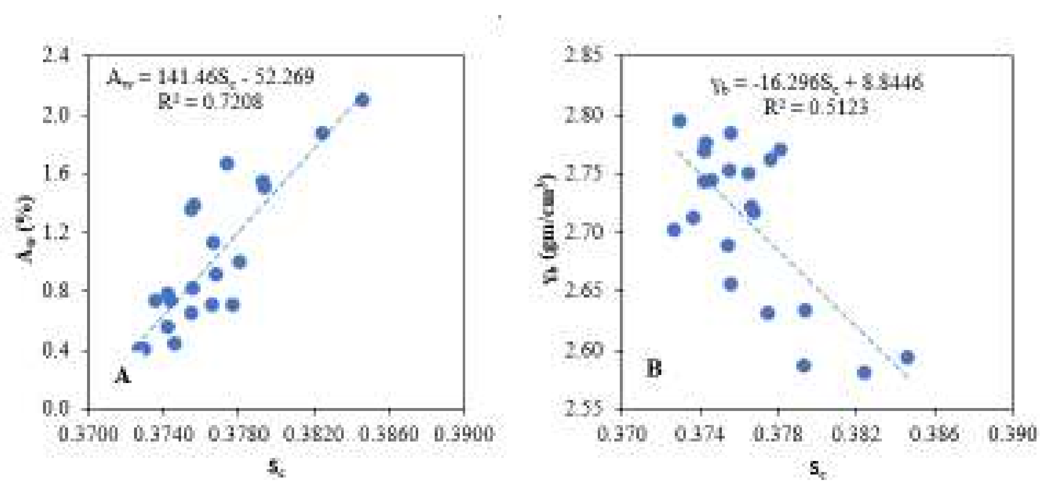

Figure 5. The saturation coefficient versus A) water absorption, B) bulk density.

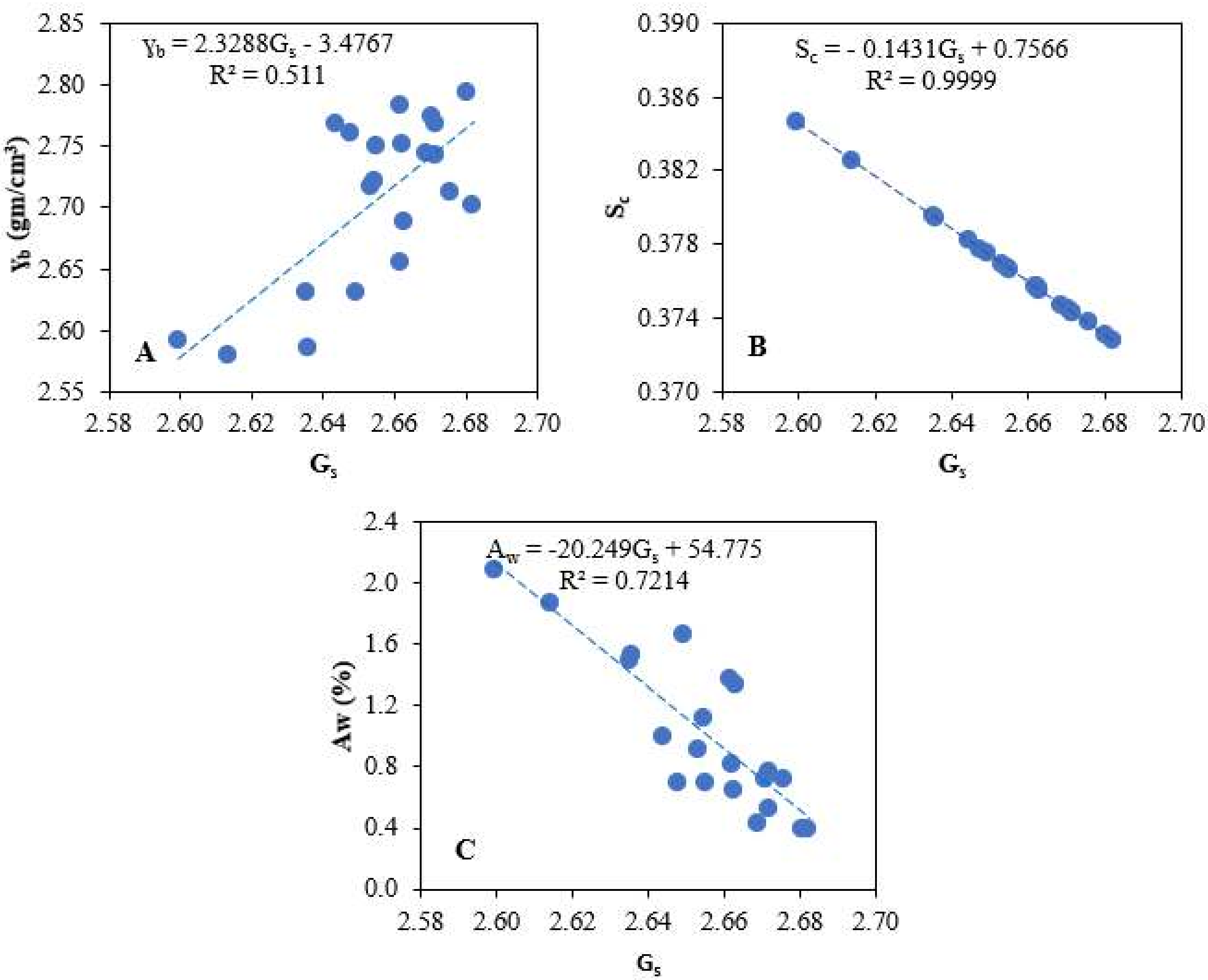

Figure 6. The apparent specific gravity versus A) bulk density, B) saturation coefficient, C) water absorption.

Table 1. Rock properties of the study area.

Location No.	Rock unit	Lithology	Bed Thickness (m)	Dip/Strike	Joints spacing	Colour	Grain size	Weathering state
1	Unit 1	Dolomitic Limestone	0.75	Close to horizontal	2 set unequal	Light grey	Fine	Slightly weathered
2	Unit 2	Compact Dolomitic Limestone	0.95	Close to horizontal	2 set unequal	Dark grey to black	Medium	Fresh to very slightly weathered
3	Unit 3	Compact Dolomitic Limestone	1.2	Close to horizontal	2 set unequal	Dark grey to black	Medium	Fresh to very slightly weathered
4	Unit 4	Dolomitic Limestone	0.85	Close to horizontal	2 set unequal	Dark grey	Fine	Fresh to slightly weathered

from 1989, as presented in Table 5. The classifications of UCS for intact rocks are summarized in Tables 6 and 7, based on the criteria from references [26], [27] and [28].

According to the results of the UCS and point load tests, and when compared with the referenced standards and classification systems, samples S_3, S_4, S_7, and S_{20} are categorized as moderately strong. The rest of the samples, specifically S_1, S_2, S_5 through S_6, and S_8 through S_{19} along with S_{21}, are classified as strong.

These findings suggest that the dolomitic limestones of the Serki and Sehkaniyan formations possess excellent mechanical strength, making them highly suitable for use as dimension stones in both indoor and outdoor architectural applications.

4.2 Excavatability assessment using the Pettifer and Fookes chart:

To understand what excavation methods would work best at the quarry site, the study used the excavatability chart developed by Pettifer and Fookes (1994) [29]. This chart helps assess how difficult it is to excavate rock by comparing two main factors: the spacing between natural fractures (discontinuities) and the point load strength index (Is_{50}).

By plotting the data for each rock sample on this chart (see Figure 8), the type of excavation needed for the Serki and Sehkaniyan dolomitic limestone was identified. The results show that most of the rock units fall into the categories that require either extra hard ripping or controlled blasting. This means that standard excavation tools, like basic rippers or excavators, would likely not be effective.

The high strength of the rock and the relatively wide spacing between fractures make the formations tougher to break apart. These insights are valuable for quarry operations, helping to choose the right equipment, manage costs, and plan for efficient block extraction. [30].

5. Statistical Analysis:

A comprehensive statistical evaluation of 21 dolomitic limestone samples was conducted to assess their physical integrity and mechanical strength, as presented in the Table 8 The analysis reveals important variability patterns, consistency measures, and implications for engineering applications, especially as dimension stones.

5.1 Water Absorption (Aw) and Porosity (ϕ):

Water absorption ranged from 0.39% to 2.08% with a mean of 1.008% and a high coefficient of variation (CV = 49.54%), suggesting moderate heterogeneity in the pore structure. Porosity followed a similar trend (mean = 2.67%, CV = 48.75%), which is typical for variably dolomitized limestones.

These two parameters are strongly correlated and significantly influence durability and frost resistance. Samples with higher porosity tend to exhibit greater water absorption, which may negatively impact long-term performance in freeze–thaw environments.

5.2 Saturation Coefficient (Sc):

Sc values were narrowly distributed (mean = 0.374, range = 0.370–0.380, CV = 1.36%), indicating high internal consistency across all samples. The narrow range is particularly significant in evaluating frost durability, as values below 0.75

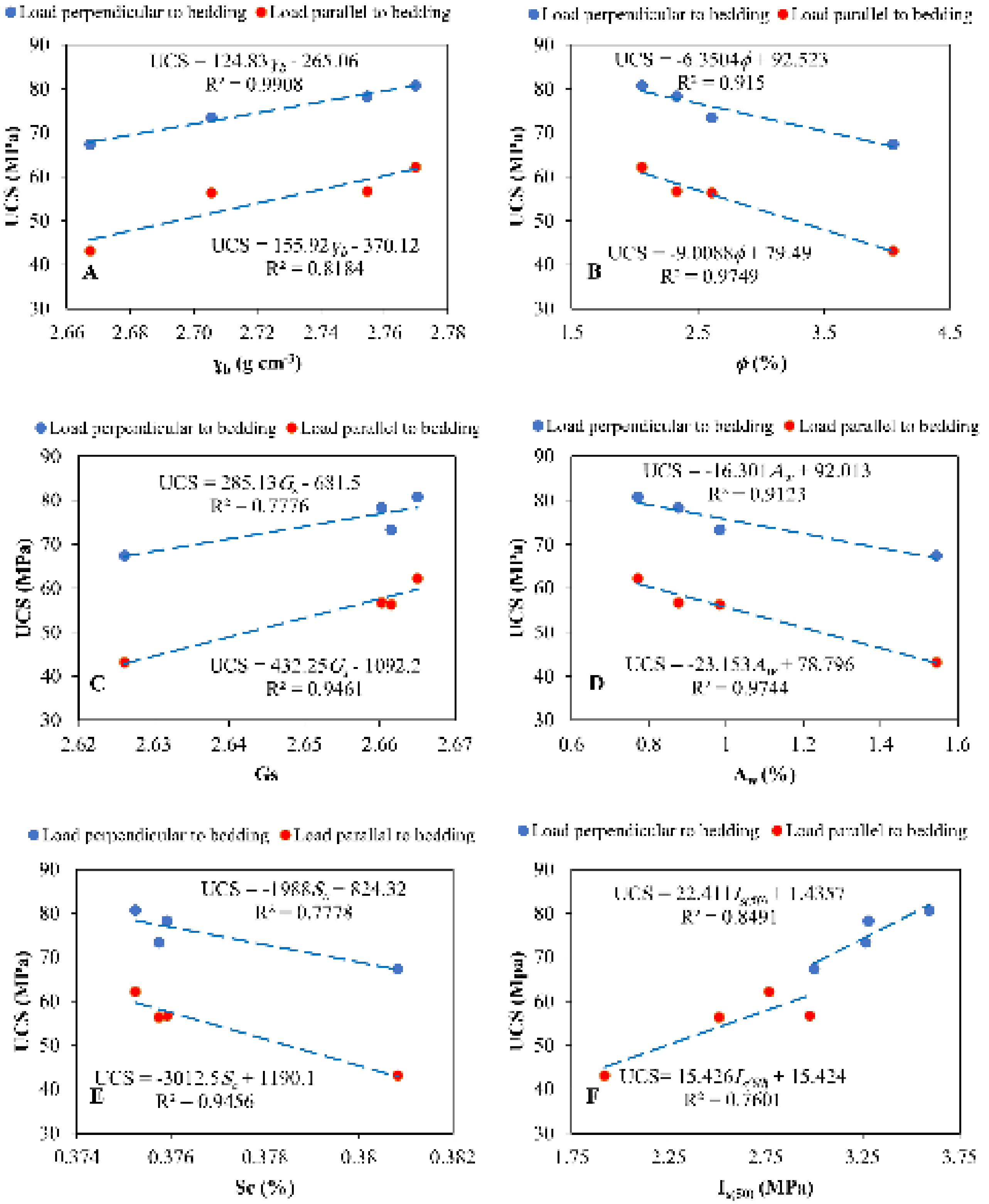

Figure 7. The Uniaxial compressive strength versus A) bulk density, B) porosity, C) apparent specific gravity, D) water absorption, E) saturation coefficient, F) diametral point load.

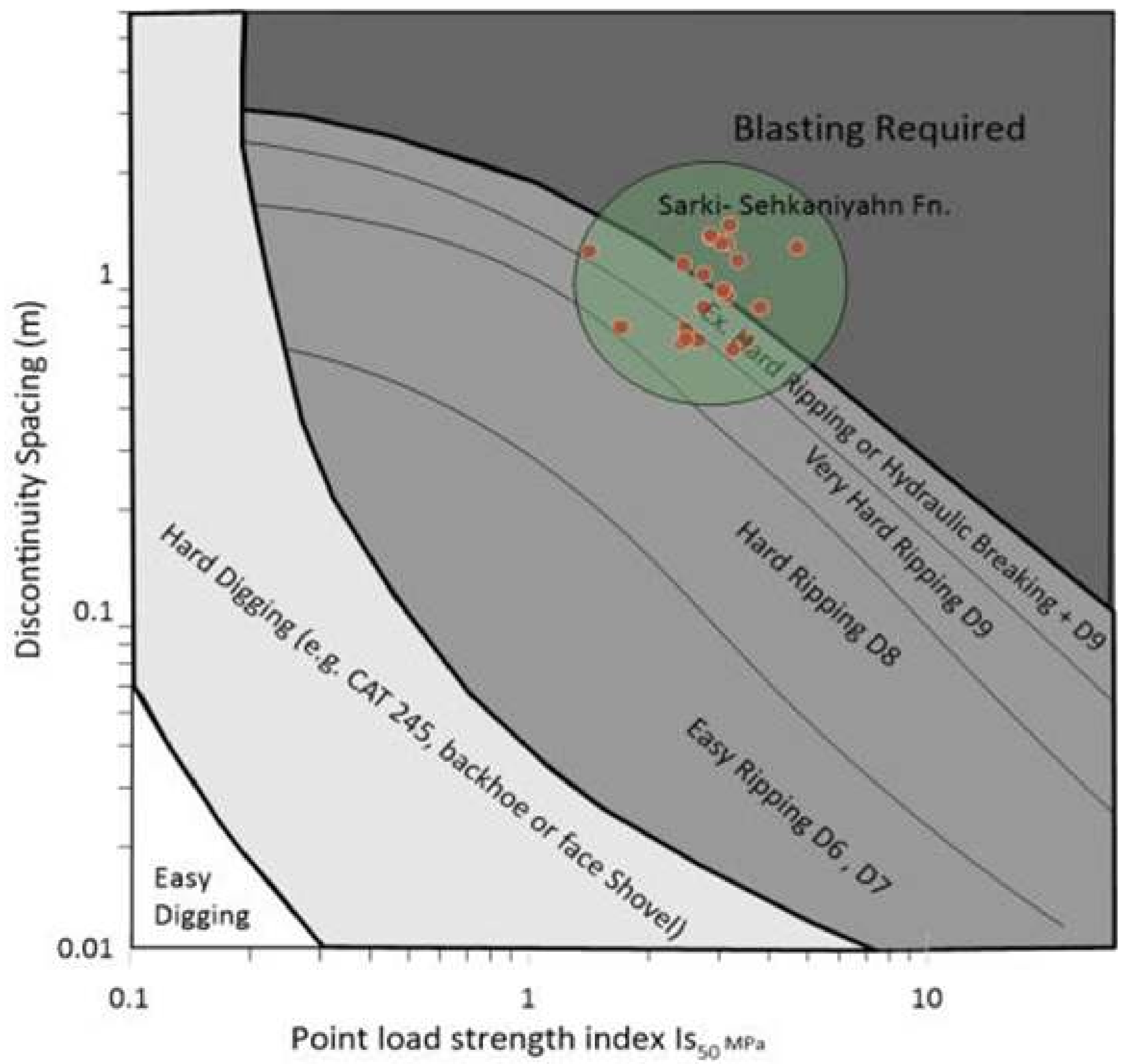

Figure 8. Evaluation the rock's excavatability at the quarry site for this study (Pettifer and Fookes 1994) [29] chart was used.

Table 2. Results of natural wet weight, dry weight and natural water content (W %).

Location No.	Rock unit	Dimensions (cm)	Mode of Cutting	Samples No.	Natural Wet weight (g)	Dry weight (g)	Natural Water Content (W %)
1	Unit 1	Cube 5×5×5	Perpendicular	S_1	339.48	333.05	1.93
				S_2	333.26	327.56	1.74
			Parallel	S_3	327.05	324.03	0.93
				S_4	344.83	342.93	0.55
				S_5	344.26	341.72	0.74
				S_6	348.97	345.32	1.05
2	Unit 2	Cube 5×5×5	Perpendicular	S_7	339.93	337.71	0.65
				S_8	347.15	342.81	1.26
			Parallel	S_9	344.48	341.73	0.80
				S_{10}	345.51	344.18	0.39
				S_{11}	342.31	340.15	0.64
3	Unit 3	Cube 5×5×5	Perpendicular	S_{12}	342.55	340.11	0.71
				S_{13}	341.11	338.55	0.76
			Parallel	S_{14}	344.59	341.41	0.93
				S_{15}	342.34	339.98	0.70
				S_{16}	331.14	326.85	1.31
4	Unit 4	Cube 5×5×5	Perpendicular	S_{17}	339.18	337.51	0.50
				S_{18}	332.14	331.01	0.3
			Parallel	S_{19}	324.98	323.72	0.39
				S_{20}	329.93	325.47	1.37
				S_{21}	336.83	331.37	1.65

are generally considered safe for exterior use in cold climates. Thus, the Serki and Sehkaniyan dolomitic limestones demonstrate excellent resistance to weathering and freeze–thaw cycles, making them ideal for architectural applications.

5.3 Specific Gravity (Gs) and Bulk Density (γb):

The specific gravity values (mean = 2.654, CV = 0.80%) and bulk density (mean = 2.705 g cm^{-3}, CV = 2.54%) show very low variability, indicating mineralogical uniformity and high degree of compaction. These properties are critical in determining the mass-volume relationships and give confidence in consistent behavior during cutting, transport, and installation.

5.4 Point Load Strength Index (Is) and $Is_{(50)}$:

The raw and corrected point load strength values Is and $Is_{(50)}$ range from 1.23–4.10 MPa and 1.42–4.71 MPa, respectively. Exhibit moderate variability (CV $\approx$ 24%), reflecting differences in local fabric, orientation, and jointing. Despite this variability, the majority of samples fall within ISRM strength classifications of moderately strong to strong, which supports their use in structural and load-bearing applications.

5.5 Uniaxial Compressive Strength (UCS):

Estimated UCS values (derived from $Is_{(50)}$ range from 31.90 MPa to 106.10 MPa with a mean of 65.84 MPa and CV = 23.75%. Measured UCS values (available for 8 samples) align closely, with a mean of 64.07 MPa and lower variability (CV = 16.94%).

This strong agreement between measured and estimated UCS confirms the reliability of empirical UCS–$Is_{(50)}$ relationships (UCS $\approx$ 22.5 × $Is_{(50)}$ for these formations.

Samples with UCS $>$ 70 MPa generally correspond with lower Aw and ϕ, reinforcing the inverse correlation between porosity-related properties and compressive strength. The interquartile range (IQR) for UCS_est (16.4 MPa) and UCS_avg (6.85 MPa) also suggests more consistency in lab-tested values compared to those derived from field data, possibly due to controlled test conditions.

Table 3. Results of water absorption, porosity, saturation coefficient, apparent specific gravity and bulk density of rock samples with correlation coefficients.

Samples No.	Water Absorption A_w (%)	Porosity ϕ (%)	Saturation Coefficient S_c	Apparent Specific gravity G_s	Bulk Density γ_b (g cm^{-3})	Correlation coefficient of physical properties
S_1	2.08	5.417	0.38	2.60	2.59	
S_2	1.87	4.876	0.38	2.61	2.58	
S_3	1.53	4.034	0.38	2.64	2.58	
S_4	0.70	1.850	0.37	2.65	2.75	$A_w = 0.3838\ \phi - 0.016$
S_5	0.80	2.150	0.37	2.66	2.78	$R^2 = 0.9998$
S_6	0.39	1.044	0.37	2.68	2.79	$\gamma_b = -0.1185\ \phi + 2.82$
S_7	1.12	2.967	0.38	2.65	2.72	$R^2 = 0.7503$
S_8	0.70	1.850	0.38	2.65	2.76	$S_c = 0.0019\ \phi + 0.37$
S_9	1.34	3.558	0.37	2.66	2.69	$R^2 = 0.7089$
S_{10}	0.90	2.407	0.38	2.65	2.71	$G_s = -0.0136\ \phi + 2.69$
S_{11}	0.64	1.714	0.37	2.66	2.75	$R^2 = 0.7096$
S_{12}	0.73	1.943	0.37	2.68	2.71	$A_w = 141.46\ S_c - 52.26$
S_{13}	0.76	2.044	0.37	2.67	2.77	$R^2 = 0.7208$
S_{14}	0.99	2.633	0.38	2.64	2.77	$\gamma_b = -16.296\ S_c + 8.84$
S_{15}	0.72	1.932	0.37	2.67	2.77	$R^2 = 0.5123$
S_{16}	1.49	3.943	0.38	2.63	2.63	$\gamma_b = 2.3288\ G_s - 3.47$
S_{17}	0.54	1.433	0.37	2.67	2.74	$R^2 = 0.511$
S_{18}	0.43	1.145	0.37	2.67	2.74	$Sc = -0.1431\ G_s + 0.75$
S_{19}	0.40	1.069	0.37	2.68	2.70	$R^2 = 0.9999$
S_{20}	1.37	3.656	0.37	2.66	2.65	$A_w = -20.249\ G_s +$
S_{21}	1.66	4.405	0.38	2.65	2.63	54.77
Mean	1.00	2.67	0.38	2.65	2.70	$R^2 = 0.7214$
St. dev.	0.50	1.30	0.01	0.02	0.07	

6. Conclusions:

Based on the study of Early Jurassic Serki and Sehkaniyan formations for use as dimension stones the following main conclusions can be drawn:

1. This study highlights the potential of the Early Jurassic Serki and Sehkaniyan formations as promising sources of dimension stone. The rocks are largely uniform in appearance, displaying a consistent gray to grayish-black tone, occasionally accented by lighter bands that enhance their visual appeal. Petrographic analysis revealed that the formations are primarily composed of fine- to medium-grained limestone and dolomitic limestone, with extensive recrystallization. As a result, fossils are seldom visible, apart from the occasional Posidonia shell.

2. Laboratory testing showed that these rocks possess desirable physical properties for building materials: high bulk density, low porosity, and low water absorption. These characteristics meet both international (ASTM C568-2004) and national (Iraqi Standard 1387-1989) specifications, confirming their suitability for both indoor and outdoor use.

3. The tested samples also demonstrated a strong resistance to frost action. This makes them especially well-suited for external architectural uses in regions subject to freeze–thaw cycles, extending their applicability beyond aesthetic appeal to structural reliability in harsh climates.

4. Mechanically, most of the rocks showed uniaxial compressive strength values between 60 and 80 MPa, while some of them ranged between 43 and 56 MPa with strong correlations to physical properties and point load test results. The orientation of loading relative to the bedding planes also played a role in strength variation. Samples loaded perpendicular to bedding planes consistently showed higher strength than those tested parallel, indicating anisotropy in mechanical behavior and importance of considering geological structure in practical applications.

5. The formations offer excellent material quality, exca-

Table 4. Results of the point load and uniaxial compressive strength of the tested rock sample.

Samples No.	Mode of tested samples	Is (MPa)	Is(50) (MPa)	UCS = 22.5 × Is(50) (MPa)	Av. UCS (MPa)	Grade	Correlation coefficient (Perpendicular & Parallel)
S_1	Perpendicular	2.53	2.85	64.1	67.46	Strong	UCS = 124.83 ɣb - 265.06
S_2		2.80	3.15	70.8			R^2 = 0.9908
S_3	Parallel	2.14	2.42	54.5	43.19	Medium	UCS = 155.92 ɣb - 370.12
S_4		1.23	1.42	31.9		Strong	R^2 = 0.8184
S_5		2.78	3.14	70.7			UCS = -6.3504 ϕ + 92.52
S_6	Perpendicular	3.07	3.50	78.7	68.13		R^2 = 0.915
S_7		2.12	2.44	54.9		Strong	UCS = -9.0088 ϕ + 79.49
S_8		2.34	2.65	59.7			R^2 = 0.9749
S_9	Parallel	3.36	3.80	85.6	66.95		UCS = -16.301 A_w +92.01
S_{10}		2.15	2.47	55.6			R^2 = 0.9123
S_{11}	Perpendicular	2.75	3.20	72.1	80.77		UCS = -23.153 A_w +78.79
S_{12}		2.50	2.85	64.2			R^2 = 0.9744
S_{13}		4.10	4.71	106.1		Strong	UCS = -1988Sc + 824.32
S_{14}	Parallel	2.13	2.48	55.7	62.24		R^2 = 0.7778
S_{15}		2.68	3.05	68.7			UCS = -3012.5Sc + 1190.1
S_{16}		2.80	3.19	71.8			R^2 = 0.9456
S_{17}	Perpendicular	2.88	3.25	73.0	67.44		UCS = 22.411Is(50)+1.43
S_{18}		2.96	3.35	75.4		Strong	R^2 = 0.8491
S_{19}		2.41	2.75	61.9			UCS = 15.42 Is(50) +15.42
S_{20}	Parallel	1.49	1.70	38.2	56.40		R^2 = 0.7601
S_{21}		2.69	3.07	69.1			

vation may require advanced methods such as blasting or hard ripping due to their high strength. Nonetheless, their abundance and mechanical reliability make them a valuable resource for use in dimension stone, paving, and decorative architectural applications provided that quarrying is carefully planned and executed.

6. Low variability in Sc, Gs, and γb reflects strong structural consistency across the formations. Although porosity and water absorption show moderate variation, all values remain within acceptable limits for dimension stone. Most samples fall into strong or moderately strong categories, making them suitable for decorative and structural use. The tight UCS range and strong correlation with Is(50) support its use as a reliable proxy in early-stage testing. Overall, the Serki and Sehkaniyan formations meet technical and economic criteria for high-quality dimension stone, aligning with local and international standards for durability, workability and strength.

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Table 5. Standard specification of physical and mechanical properties of limestone for construction materials [22], [26].

Type	Class	Density (g cm^{-3})	Absorption %	Compressive strength (MPa)	Grade	Studied samples for dimension stone
I	A	1.76-2.16	12	12-28	Low	-
II	B	2.16-2056	7.5	28-55	Moderate	S_3, S_4, S_7, S_{20}
III	C	$\geq$ 2.564	3	>55	High	S_1, S_2, S_5, S_6, S_7, S_9, S_{10}, S_{11}, S_{12} S_{13}, S_{14}, S_{15}, S_{16}, S_{17}, S_{18}, S_{19}, S_{21}

Table 6. Grade of the uniaxial compressive strength of intact rock pieces after (Brown, 1981) [31].

Grade	Term	UCS (MPa)	Point load index (MPa)	Field estimate of strength	Studied samples for dimension stone
R6	Extremely strong	>250	>10	The specimen can only be chipped with geological hammer.	-
R5	Very Strength	100-250	4-10	Specimen requires many blows of a geological hammer to fracture it.	-
R4	Strong	50-100	2-4	Specimen requires more than one blow of a geological hammer to fracture it.	S_1, S_2, S_3, S_5, S_6, S_7, S_8, S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{17}, S_{18}, S_{19}, S_{21}
R3	Medium strong	25-50	1-2	It can't be scraped or peeled with a pocketknife; the specimen can be fractured with a single blow from a geological hammer.	S_4, S_{20}
R2	Weak	5-25	-	It can be peeled with a pocketknife with the difficulty, shallow indentation made by the firm blow with the point of a geological hammer.	-
R1	Very weak	1-5	-	Crumbles under a firm blow with the point of a geological hammer, which a pocketknife can peel.	-
R0	Extremely weak	0.25-1	-	Indented by thumbnail.	-

Table 7. Uniaxial compressive strength classification according to [27], [28].

ISRM 1981 (MPa)	Description of UCS classes	Studied samples for dimension stone	Franklin and Dusseault, 1989 (MPa)	Description of UCS classes	Studied samples for dimension stone
< 6	Very low	-	$2 > UCS$	Extremely weak	-
6 – 20	Low	-	$6 \geq UCS \geq 2$	Weak	-
20 – 60	Moderate	S_3,S_4,S_7,S_{20}	$20 \geq UCS \geq 6$	Moderately weak	-
60 – 200	High	S_1, S_2, S_5, S_6, S_8, S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{17}, S_{18}, S_{19}, S_{21}	$60 \geq UCS \geq 20$	Moderately strong	S_3,S_4,S_7,S_{20}
>200	Very high	-	$200 \geq UCS \geq 60$	Strong	S_1, S_2, S_5, S_6, S_8, S_9, S_{10}, S_{11}, S_{12}, S_{13}, S_{14}, S_{15}, S_{16}, S_{17}, S_{18}, S_{19}, S_{21}
			$UCS > 200$	Extremely strong	-

Table 8. Descriptive statistics of physical and mechanical properties of dolomitic limestone samples from the Serki and Sehkaniyan formations.

Property	Mean	Std Dev.	Min	Max	Median (50%)	Q1 (25%)	Q3 (75%)	Range	CV (%)
Water Absorption (Aw, %)	1.008	0.499	0.390	2.080	0.800	0.700	1.370	1.690	49.54
Porosity (ϕ, %)	2.670	1.302	1.044	5.417	2.150	1.850	3.656	4.373	48.75
Saturation Coefficient (Sc)	0.374	0.005	0.370	0.380	70.370	0.370	0.380	70.010	1.36
Specific Gravity (Gs)	2.654	0.021	2.600	2.680	2.660	2.650	2.670	0.080	0.80
Bulk Density (γb, g cm^{-3})	2.705	0.069	2.580	2.790	2.720	2.650	2.760	0.210	2.54
Point Load Strength (Is, MPa)	2.567	0.611	1.230	4.100	2.680	2.150	2.800	2.870	23.82
Corrected Is(50) (MPa)	2.926	0.694	1.420	4.710	3.050	2.480	3.200	3.290	23.71
Estimated UCS (MPa)	65.84	15.64	31.90	106.1	68.70	55.70	72.10	74.20	23.75
Measured UCS (MPa) (n=8)	64.07	10.85	43.19	80.77	67.20	60.78	67.63	37.58	16.94

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Conflict of interest: The authors declare that they have no conflict of interest.

Ethical approval: This study did not involve human participants or animals; therefore, ethical approval was not required.

Author Contributions: Rozhgar A. Hasan led all aspects of the research, including field data acquisition, data analysis, and interpretation of results. He was solely responsible for drafting the manuscript and ensuring the accuracy and clarity of the final version through comprehensive proofreading.

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دراسة الخصائص الفيزيائية والميكانيكية لوحدة صخرية جوراسية من تكويني سركي وسيهكانيان لحجر البعد، مدينة السليمانية، شمال شرق العراق

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الخلاصة

تُستخدم الأحجار الطبيعية على نطاق واسع في أعمال الرصف، والتكسية، والبناء، وتحديد الأبعاد في مختلف أنحاء العالم. وتزخر محافظة السليمانية، شمال شرق العراق، بموارد وفيرة من الأحجار الطبيعية التي يمكن توظيفها في العديد من الاستخدامات المعمارية والزخرفية. في هذه الدراسة، تم جمع 21 عينة من صخور الحجر الجيري الدولوميتي العائد لتكويني سركي وسيهكانيان من وحدات صخرية بارزة ضمن مواقع محجرية. شملت الاختبارات الفيزيائية تقييم كلٍّ من: المسامية الكلية، وامتصاص الماء، ومعامل التشبع، والثقل النوعي الظاهري، والكثافة الظاهرية. استنادًا إلى المواصفة القياسية العراقية رقم 1387 لعام 1989 ، والمعيار الأمريكي *ASTM C*568 لعام 2004 ، صُنّفت جميع الخصائص الفيزيائية ضمن فئة الكثافة العالية جدًا، وأظهرت الصخور مقاومة جيدة للصقيع. أظهرت اختبارات قوة الضغط أحادية المحور (*UCS*) للعينة قيمًا تراوحت بين 60 و 80 ميغاباسكال، وهي أعلى من تلك المسجلة في العينات ذات الاتجاه الموازي، والتي تراوحت بين 43 و 56 ميغاباسكال. وفقًا للتصنيفات والمعايير المعتمدة، تم تصنيف غالبية العينات على أنها قوية إلى قوية جدًا، في حين صُنّفت نسبة قليلة منها على أنها متوسطة القوة. كما لوحظ وجود علاقة ارتباط واضحة بين قيم *UCS* والخصائص الفيزيائية للصخور، إضافة إلى علاقة قوية مع مؤشر الحمل النقطي في كل من الاتجاه العمودي والتوازي، حيث بلغت قيم معامل التحديد R^2 نحو 0.85 و 0.76 على التوالي. تُظهر النتائج أن تكويني سركي وسيهكانيان يتمتعان بخصائص جيولوجية وميكانيكية تؤهلهما للاستخدام كأحجار بُعد عالية الجودة في التطبيقات المعمارية الخارجية والداخلية، وكذلك في أعمال الرصف والبناء.

الكلمات الدالة : حجر البُعد؛ تكويني سركي وسيهكانيان؛ الحجر الجيري الدولوميتي؛ العلاقات الفيزيائية – الميكانيكية؛ الصخور الجوراسية.

التمويل: لايوجد.

بيان توفر البيانات: جميع البيانات الداعمة لنتائج الدراسة المقدمة يمكن طلبها من المؤلف المسؤول.

اقرارات:

تضارب المصالح: يقر المؤلفون أنه ليس لديهم تضارب في المصالح.

الموافقة الأخلاقية: لم يشمل هذا البحث أي تجارب على البشر أو الحيوانات، ولذلك لم تكن هناك حاجة للحصول على موافقة أخلاقية.

مساهمات المؤلفين: تولى رۆژگار عبدالله حسن جميع جوانب البحث، بما في ذلك جمع البيانات الميدانية، وتحليل البيانات، وتفسير النتائج. وكان مسؤولًا بشكل كامل عن إعداد مسودة البحث وضمان دقة ووضوح النسخة النهائية من خلال المراجعة الشاملة والتدقيق اللغوي.