

Direct and Indirect Engineering Geology Methods for Estimating Limestone's UCS in Mostufi Mountain, Arak

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Abstract: Uniaxial Compressive Strength (UCS) is a fundamental parameter in engineering geology, particularly for evaluating the mechanical behavior of rock materials in construction and mining projects. This study aims to estimate the UCS of limestone formations in Mostufi Mountain, Arak, using both direct laboratory testing and indirect empirical methods. A total of 75 limestone specimens were collected from various locations within the study area and subjected to laboratory uniaxial compression tests to determine their UCS values. In addition, 75 specimens were tested using the point load index test, and 150 rebound measurements were obtained using the Schmidt hammer in order to develop empirical correlations for indirect UCS estimation. The results were analyzed to assess the reliability and accuracy of the indirect methods in predicting UCS. Statistical correlations were developed between the UCS values obtained from direct tests and the results of the point load and Schmidt hammer tests. These correlations provide a practical approach for UCS estimation in field conditions where direct testing is not feasible due to time and cost constraints. The findings of this study contribute to improving geotechnical site characterization and can be beneficial for engineering applications such as slope stability analysis and urban development projects in limestone-dominated regions.

Keywords: Uniaxial Compressive strength, Engineering geology, Limestone, Schmidt hammer test, Point load test.

I. INTRODUCTION

Limestone is one of the most widespread sedimentary rocks on Earth, primarily composed of calcium carbonate (CaCO_3) in the form of calcite or aragonite. It forms in marine environments through the accumulation of biological materials such as coral, shells, and microfossils (Tucker, 2003). Over millions of years, these materials lithify to create extensive limestone formations (Folk, 1959). Due to its abundance and ease of extraction, limestone has been a crucial resource for construction, industry, and engineering applications (James &

Jones, 2015). Limestone deposits are widely distributed across all continents, with major reserves located in North America, Europe, Asia, and the Middle East (James & Jones, 2015). In Iran, extensive limestone formations occur within the Zagros, Alborz, and Central Iranian geological units (Saein & Riahi, 2019), where they play a significant role in infrastructure development and cement production (Ghorbani, 2013).

From an engineering geology perspective, limestone exhibits a range of mechanical properties depending on its mineral composition, porosity, and diagenetic history (Tsiambaos & Sabatakakis, 2004). Some limestones are highly durable and resistant to weathering, while others are susceptible to karstification (Iqbal, 2018), leading to the formation of caves, sinkholes, and underground drainage systems (Wright, 1992). This variability necessitates thorough geological and geotechnical assessments before limestone formations are utilized in construction projects (Attewell & Farmer, 2012). One of the critical challenges associated with limestone is its jointed and fractured nature (Tucker, 2003). Fractures and bedding planes significantly influence the strength and stability of limestone rock masses (Bell, 2007). In Iran, many limestone-dominated mountain ranges exhibit high degrees of jointing, which can lead to instability in slopes and excavation sites (Pourhashemi et al., 2021). Understanding the jointing patterns and their influence on rock mass behavior is essential for designing stable engineering structures (Fookes & Knill, 1969).

The stability of rock slopes in limestone terrain is a significant concern for infrastructure development (Azarafza et al., 2017). In mountainous areas, slope failures due to rockfalls, toppling, and planar or wedge failures are common, especially in jointed limestone formations (Bell, 2007). Engineering geologists must carefully assess slope conditions to prevent catastrophic failures that can endanger human lives and damage property (Cemiloglu et al., 2023). Limestone formations are also crucial in the context of urban expansion. Many cities, including those in Iran, are expanding toward mountainous regions where limestone formations dominate (James & Jones, 2015). The development of roads, buildings, and tunnels in these areas requires careful consideration of rock stability, water infiltration, and the

potential for karst-related subsidence (Pourhashemi et al., 2021). Another important aspect of engineering geology is the assessment of limestone's response to weathering and environmental conditions (Mohammadian et al., 2021). Limestone is particularly sensitive to chemical weathering, especially in humid regions where acidic rainwater can dissolve calcium carbonate, leading to increased porosity and reduced strength (Folk, 1959; White et al., 1986). This phenomenon, known as karstification, can create underground cavities that pose risks to infrastructure (Bell, 2007).

The durability of limestone as a construction material also depends on its mineralogical composition and the presence of impurities such as clay, silica, and iron oxides (Tucker, 2003). Some limestone varieties, when exposed to fluctuating moisture conditions, can experience deterioration due to swelling and shrinkage. These factors must be considered in selecting suitable limestone for engineering applications. Another challenge in limestone engineering geology is the potential for groundwater interactions (Hussain et al., 2022). Limestone formations often act as aquifers, storing and transmitting groundwater (Yan et al., 2021). The presence of water within rock joints and fractures can significantly reduce rock strength and contribute to slope failures (Zhao et al., 2022). Engineers must consider hydrogeological factors when designing foundations and excavations in limestone terrain (Yuhang et al., 2021). Seismic activity is another factor influencing the stability of limestone formations (Almajed et al., 2021). In seismically active regions like Iran, earthquake-induced shaking can trigger landslides and rockfalls in limestone slopes. The presence of pre-existing fractures can exacerbate the effects of seismic loading, making it crucial to incorporate seismic risk assessments in limestone-related engineering projects (Daraei et al., 2024).

Despite these challenges, limestone remains one of the most versatile and widely used rock types in engineering (Bell, 2007). It serves as a key material in cement and concrete production, road construction, and structural foundations (Pourhashemi et al., 2021). Engineering geologists play a crucial role in characterizing limestone formations to ensure safe and sustainable development. Modern geotechnical and geophysical methods, such as point load tests, Schmidt hammer tests, and uniaxial compressive strength (UCS) estimation, are essential for evaluating the mechanical properties of limestone (Garrido et al., 2022; Cemiloglu et al., 2023). These methods help engineers and geologists develop accurate models for predicting rock behavior under various loading conditions (Contreras et al., 2021). Given the extensive use of limestone in engineering applications (Azimian, 2017), continued research in limestone engineering geology is necessary (Heidari et al., 2018). By improving our understanding of limestone's geomechanical properties, we can optimize its use in construction while minimizing risks associated with slope instability, karstification, and groundwater interactions (Marker, 2009; Nazir et al., 2013).

The primary objective of this study is to assess the UCS of limestone in Mostufi Mountain, Arak, using both direct and indirect engineering geology methods where this research aims to establish reliable correlations for UCS estimation. These correlations provide a practical approach for geotechnical assessments, particularly in situations where direct UCS testing is not feasible due to time and cost constraints. The study

contributes to a better understanding of the mechanical properties of limestone in the region, which is crucial for infrastructure development, slope stability, and urban expansion projects. So, the key objective of this research lies in its systematic integration of different testing methods to develop empirical relationships for UCS estimation. The findings offer a valuable reference for geologists and engineers working on limestone terrains, particularly in Iran, where limestone formations are prevalent. The study's outcomes have significant implications for sustainable urban development, as they aid in the design of safer foundations, tunnels, and slopes. By improving geotechnical site characterization, this research enhances risk mitigation strategies, ultimately supporting the long-term stability and safety of engineering projects in limestone-dominated regions.

II. GEOTECHNICAL PROPERTIES OF LIMESTONE

The geotechnical behavior of limestone is primarily governed by its mineralogical composition, texture, degree of cementation, porosity, and discontinuity patterns. Laboratory investigations reported in the literature indicate that the dry unit weight of limestone typically ranges between 22 to 27 kN/m³, while porosity values generally vary from 1% in dense crystalline varieties to more than 20% in highly weathered or bioclastic types. Water absorption commonly falls within the range of 0.2% to 5%, depending on pore connectivity and microfracture density. The UCS of intact limestone exhibits significant variability, typically ranging from 20 MPa for weak, porous limestone to over 150 MPa for dense, well-cemented formations. In engineering classification systems, these values correspond to weak to very strong rock categories. The tensile strength, often estimated as 5–15% of UCS, generally ranges between 2 and 15 MPa. Elastic modulus values reported for limestone commonly vary between 10 and 70 GPa, with higher values associated with low-porosity, crystalline textures. Table 1 summarizes the typical geotechnical properties of limestone reported in the literature. The presented ranges highlight the significant variability of limestone behavior, which is primarily controlled by mineralogical composition, porosity, and structural discontinuities. The wide range of UCS values (20–150 MPa) reflects differences in cementation degree and weathering intensity, while variations in elastic modulus (10–70 GPa) indicate substantial differences in stiffness among limestone types.

Table 1 Typical geotechnical properties of limestone

Parameter	Unit	Typical Range
Unit weight	kN/m ³	22 – 27
Porosity	%	1 – 20
UCS	MPa	20 – 150
Tensile strength	MPa	2 – 15
Elastic modulus	GPa	10 – 70
Cohesion	MPa	2 – 25
Friction angle	degrees	30 – 45
RMR	-	40 – 80
Permeability (intact)	m/s	10 ⁻⁹ – 10 ⁻¹²

Similarly, the broad permeability spectrum demonstrates the strong influence of fracturing and karst development on hydraulic behavior. These variations emphasize the necessity of site-specific testing and careful geotechnical characterization when limestone formations are involved in engineering projects.

Shear strength parameters derived from triaxial compression tests indicate cohesion values between 2 and 25 MPa and internal friction angles ranging from 30° to 45°, depending on structural integrity and confinement conditions. However, in rock mass conditions, these parameters are significantly reduced due to jointing and fracturing. Rock Mass Rating (RMR) values for limestone formations typically range from 40 to 80, reflecting fair to good rock quality in moderately fractured terrains. The Geological Strength Index (GSI) for jointed limestone commonly falls between 45 and 75. Permeability characteristics of limestone are highly variable and strongly influenced by secondary porosity and karst development. Intact limestone generally exhibits low permeability (10^{-9} to 10^{-12} m/s), whereas fractured or karstified limestone may display permeability values several orders of magnitude higher. Such hydrogeological behavior directly affects slope stability and foundation performance, particularly under saturated conditions.

Given this variability, indirect index tests such as the point load index (I_{s50}) and Schmidt hammer rebound number (RN) are frequently used to estimate strength parameters in the field. Empirical correlations reported in previous studies suggest that UCS values are commonly 20–25 times the point load index for limestone formations, while linear relationships between UCS and Schmidt rebound number often yield determination coefficients (R^2) greater than 0.70 in well-characterized formations. These quantitative relationships form the basis for practical geotechnical assessment when direct laboratory testing is limited.

The empirical relationship between UCS, I_{s50} , and RN has been extensively investigated in rock mechanics research. Numerous studies have demonstrated that UCS can be reliably estimated from index tests through regression-based correlations. For limestone formations, UCS is commonly found to be proportional to the point load index, with multiplication factors typically ranging between 20 and 25. Similarly, linear or power-law relationships have been proposed between UCS and Schmidt rebound number, often yielding strong correlation coefficients ($R^2 > 0.70$) under controlled laboratory conditions. These empirical relationships provide practical tools for preliminary site investigations and rapid field assessments. Table 2 presents selected empirical correlations between UCS, I_{s50} , and RN as reported in widely cited rock mechanics studies. These equations are frequently used in engineering practice for preliminary strength estimation. As shown in Table 2, the UCS– I_{s50} relationship is generally expressed as a linear proportionality, with conversion factors typically between 20 and 25 for sedimentary and carbonate rocks. In contrast, correlations between UCS and RN may follow either linear or nonlinear trends depending on lithological uniformity and surface conditions. The variability among equations reflects differences in sample preparation, testing standards, weathering degree, and statistical treatment. So, although these empirical models provide useful preliminary estimates, calibration using site-specific data is strongly recommended to improve prediction accuracy.

III. ENGINEERING GEOLOGY OF STUDIED LOCATION

Arak, the capital city of Markazi Province in central Iran, is strategically located on the Iranian plateau, where diverse geological formations intersect with significant tectonic activities (Mahmoodi et al., 2018). Its urban landscape is deeply influenced by the underlying geology, making the region a focal point for both geological and engineering studies (Khani et al., 2016). The geological map of the studied region has been provided in Figure 1. Mostufi Mountain, located west of Arak, represents a prominent geological structure that provides valuable insights into the structural framework of the region. Its topography reflects the combined effects of tectonic deformation and long-term sedimentary evolution in central Iran (Babaadam et al., 2023). The climatic conditions in Arak and its surrounding areas are typically continental. The climate is characterized by hot, dry summers and cold winters with occasional snowfall (Asakere et al., 2016). These climatic variations significantly influence the weathering processes of the exposed rock formations, particularly affecting sedimentary rocks such as limestone through thermal expansion and contraction as well as chemical weathering (Karampoor et al., 2023). Geologically, the region boasts a complex history characterized by multiple phases of sedimentation, tectonic uplift, and erosion (Raeisizadeh et al., 2021). The stratigraphy of the area includes a variety of sedimentary rocks that record the evolution of ancient marine environments followed by subsequent tectonic events associated with the collision of the Arabian and Eurasian plates (Javidfakhr & Ahmadian, 2018). Engineering geology in the Arak region is of paramount importance due to the inherent challenges posed by its geological setting (Rad et al., 2014). The area's rock masses are often highly jointed and fractured, which can lead to issues in construction and slope stability. This necessitates thorough geotechnical investigations before the development of infrastructure such as roads, buildings, and tunnels, to ensure safety and durability (Raeisizadeh et al., 2020). The main geological formations in and around Arak include extensive sedimentary layers that have been uplifted and deformed over time (Javidfakhr & Ahmadian, 2018). Among these, limestone formations are particularly significant. They have been deposited in ancient shallow marine environments and later subjected to tectonic forces, resulting in the complex structures observed today (Rad et al., 2014). Limestone in the Mostufi Mountain area is widely distributed and exhibits considerable variability in texture, cementation, and porosity, ranging from highly crystalline and well-cemented units to more porous and weathered varieties. This heterogeneity significantly influences its mechanical behavior and suitability for construction applications (Babaadam et al., 2023). The engineering properties of the local limestone are closely examined through various geotechnical tests, as its strength and durability are critical for the stability of natural slopes and man-made structures (Pourhashemi et al., 2021). Issues such as jointing, fissuring, and karstification in the limestone can lead to challenges in foundation design and slope reinforcement, making it essential to understand these factors in detail (Contreras et al., 2021). From a geological perspective, limestone formations also offer a window into the paleoenvironmental conditions that prevailed during their deposition (Rad et al., 2014). Figure 2 illustrates the elevation variations within the study area.

Table 2 The several fuzzy rules in RI modeling

Author(s)/Year	Rock Type	Empirical Relationship	R ²	Limitations
Broch & Franklin (1972)	Various rocks	UCS = 24 × I _{s50}	-	Generalized, site-specific calibration required
Bieniawski (1975)	Sedimentary rocks	UCS ≈ (20–25) × I _{s50}	-	Provides a range factor rather than regression equation
Kahraman (2001)	Carbonate rocks	UCS = 9.95 RN – 114	0.79	Sensitive to surface condition and hammer orientation
Sharma & Singh (2008)	Quartzite	UCS = 5.12 Is(50) + 12.6	0.90	Valid for intact quartzite
Yagiz (2009)	Limestone	UCS = 6.67 RN – 93	0.74	Valid mainly for intact limestone samples
Diamantis et al. (2009)	Carbonate rocks	UCS = 2.21 RN ^{1.7}	0.83	Nonlinear model; low accuracy for weathered samples
Mishra & Basu (2013)	Sandstone	UCS = 1.61 RN – 36.2	0.88	Weathering affects RN
Tandon & Gupta (2014)	Granitoid rocks	UCS = 5.602 I _{s50} + 4.380	0.92	Requires I _s standardization
Kallu & Roghanchi (2015)	Limestone	UCS = 2.08 RN – 23.4	0.84	Small dataset
Shahri et al. (2016)	Marlstone	UCS = 56.939 ln(I _{s50}) + 1.655	0.59	Valid for Iranian marlstone dataset
Azarafza et al. (2021)	Marlstone	UCS = 14.847 I _{s50} + 19.887	0.57	Valid for Iranian marlstone dataset Schmidt hammer condition sensitive
		UCS = 0.93 RN ^{1.51}	0.78	
		UCS = 2.37 RN – 45.6	0.88	

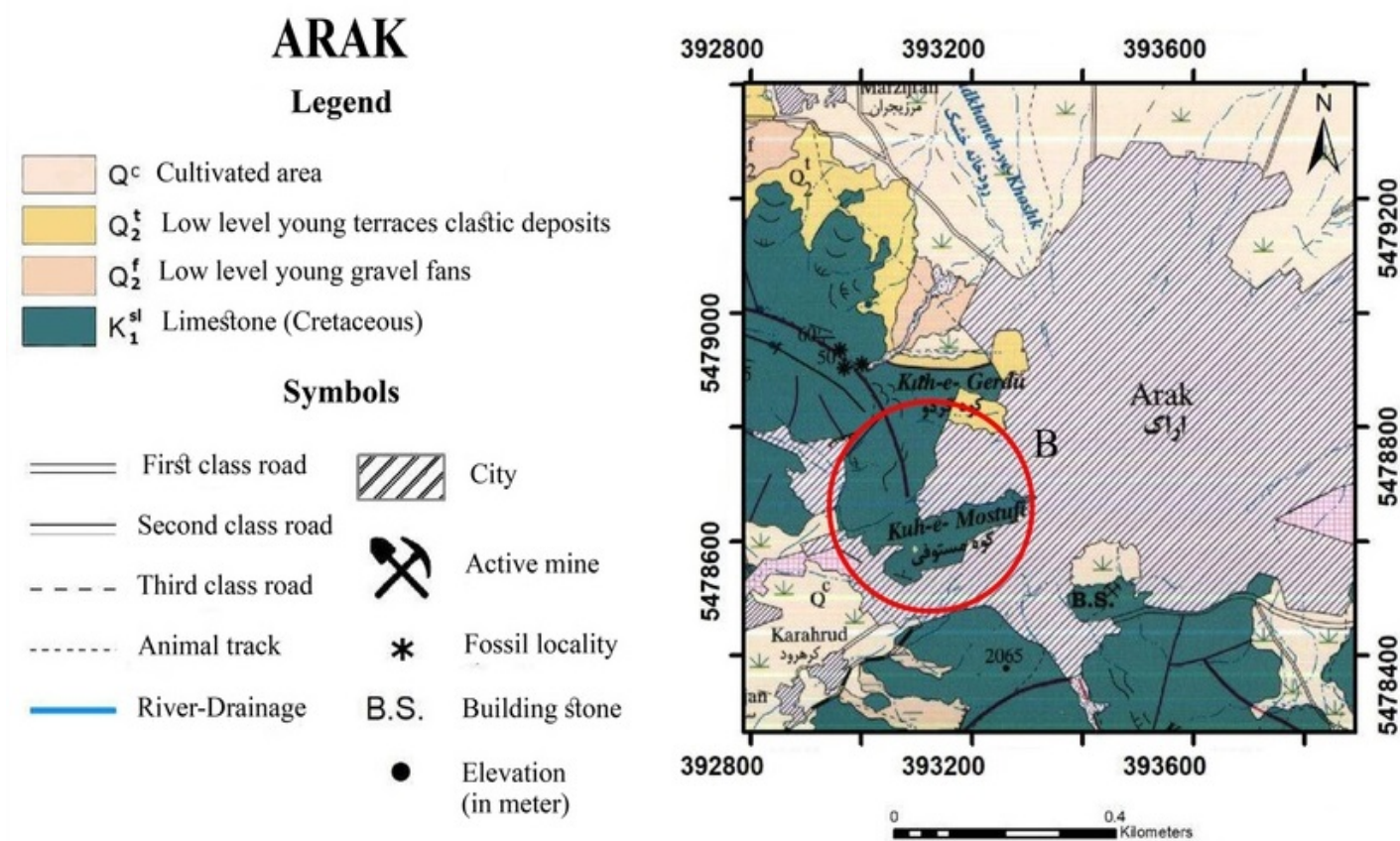


Fig. 1 Geological map of studied area (Babaadam et al., 2023)

IV. MATERIALS AND METHODS

The comprehensive methodology integrates both direct and indirect testing methods to assess the mechanical properties of limestone in Mostofi Mountain. By combining the direct UCS tests in line with ASTM D7012 with indirect tests such as the point load test as per ISRM guidelines (Ulusay, 2015) and the Schmidt hammer test, the study aims to develop robust empirical correlations. The UCS test is one of the most widely used laboratory methods for determining the strength and deformation

characteristics of intact rock specimens (Barham et al., 2020). In this test, an axial compressive load is applied to a cylindrical specimen until failure, and the UCS is calculated by dividing the peak failure load by the specimen’s cross-sectional area (Sonmez et al., 2006). Prior to testing, rock specimens must be carefully prepared to meet standard dimensions, typically with a length-to-diameter ratio of 2:1. The end surfaces of the specimen are ground or cut to ensure parallelism, minimizing stress concentration effects (Ulusay, 2015). During testing, specimens were positioned between the loading platens of a uniaxial compression machine, and axial load was applied at a controlled

strain rate until failure occurred. The machine records applied stress and strain throughout the process, allowing for the calculation of elastic modulus and Poisson's ratio if strain gauges are used (Mogi, 2009). UCS tests are conducted in accordance with ASTM D7012, which defines the procedures for measuring compressive strength and elastic properties of intact rock core specimens.

The point load test is an indirect method for estimating the compressive strength of rock samples, widely used due to its simplicity, cost-effectiveness, and ability to be performed both in the field and in the laboratory (Li et al., 2021). The test involves applying a concentrated load through two conical plates until the rock sample fails (Kohno & Maeda, 2018). The resulting point load index is then correlated with UCS values, allowing engineers to estimate rock strength without conducting a full-scale UCS test. A schematic representation of the point load testing configuration used in this study is presented in Figure 3. In the laboratory, point load tests are performed on core, block, or irregular rock samples (Xie et al., 2021). The rock specimen is positioned between the plates, ensuring that the load is applied along a specific axis, either diametrically or axially (Ghosh & Srivastava, 1991). As the load increases, the rock eventually fractures along its weakest plane. The failure load is recorded, and the point load strength index is calculated using a standardized formula that accounts for the specimen's dimensions (Li & Wong, 2013). The point load test follows the ISRM suggested methods, which provide guidelines for specimen selection, test execution, and data interpretation (Ulusay, 2015). The results obtained from this test are particularly useful when UCS values are unavailable or when rapid assessments of rock strength are required (Basu et al., 2013). Due to its efficiency, the point load test is often used for preliminary site investigations, rock classification, and stability assessments in engineering geology projects (Basu & Kamran, 2010). The Schmidt hammer test was performed in accordance with ISRM recommendations, and rebound numbers were recorded from freshly exposed, smooth rock surfaces to minimize measurement bias. Multiple readings were taken at each test location, and the average rebound value was used for subsequent correlation analysis. This method provides a rapid and non-destructive means of estimating rock strength, particularly suitable for field-based investigations (Nazir et al., 2013).

The Schmidt hammer operates using a spring-loaded mass that delivers a standardized impact to the rock surface, and the resulting RN reflects surface hardness and resistance to deformation (Karaman & Kesimal, 2015; Ulusay, 2015). Owing to its rapid and non-destructive nature, the test is widely applied in in-situ rock strength assessments (Aydin & Basu, 2005). Prior to testing, rock surfaces were cleaned to remove loose particles and weathered material in order to ensure representative measurements (Jamshidi et al., 2018; Azarafza et al., 2021). During the test, the Schmidt hammer is held perpendicular to the rock surface, and a series of impacts are administered to obtain multiple rebound values. This repeated impact procedure helps in averaging out local heterogeneities in the rock, thereby yielding a reliable index of surface hardness (Buyuksagis & Goktan, 2005).

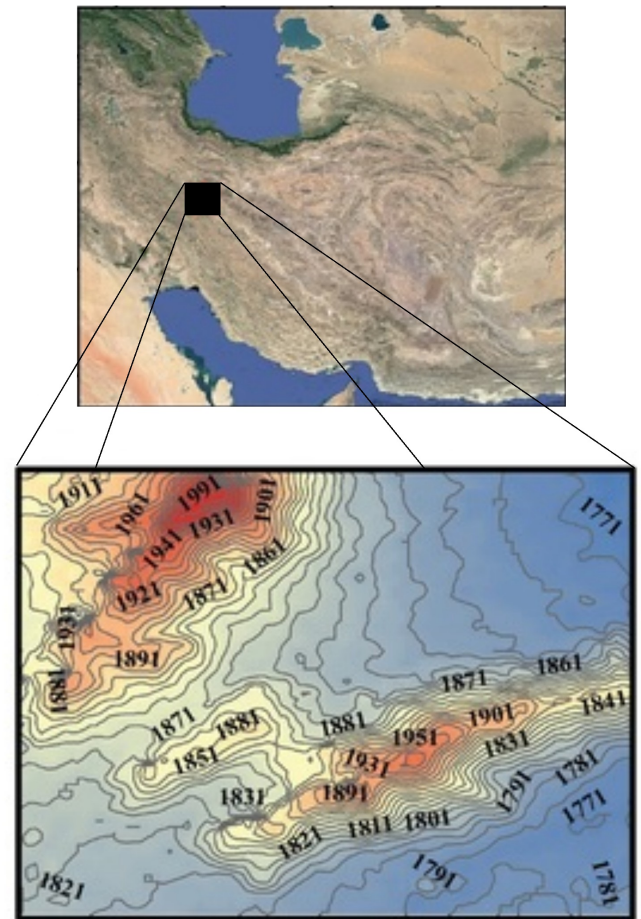


Fig. 2 Elevation variation of studied region (Babaadam et al., 2023)

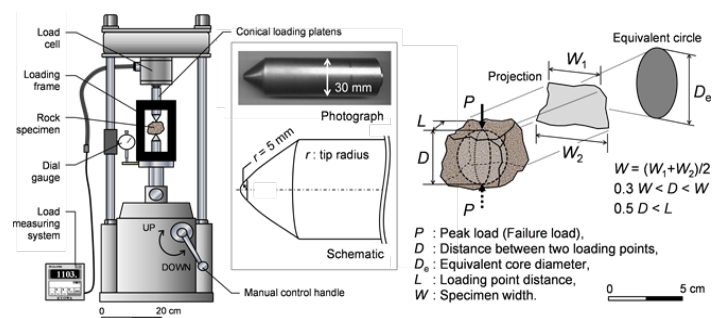


Fig. 3 A schematic view of a point load test (Kohno & Maeda, 2018)

After data acquisition, statistical analyses were performed to determine the mean and standard deviation of rebound values. The averaged RN values were then correlated with laboratory-measured UCS results using regression analysis. The predictive performance of the developed models was evaluated based on the R^2 . This correlation allows the Schmidt hammer test to be used as a predictive tool for estimating the UCS in field conditions, where performing full-scale compressive tests may be impractical due to cost or time constraints. The test procedure specifies the minimum number of impacts per site and prescribes corrective measures for variations in surface conditions.

Following sample collection within the study area and initial specimen preparation, each sample was systematically numbered, and its geographic location recorded for subsequent spatial analysis. The majority of the specimens were collected from Mostufi Mountain, located west of Arak City (Figure 1). Direct laboratory tests, including UCS and point load tests, were conducted under controlled conditions to minimize the influence of environmental variables. In parallel, Schmidt hammer tests were performed to obtain complementary surface hardness data for correlation analysis. The point load strength index values were normalized to a reference diameter of 50 mm (I_{s50}) as ISRM recommendations to ensure consistency and comparability. Loading rates in UCS tests were maintained within the limits prescribed by ASTM D7012 to guarantee uniform stress application. Prior to regression modeling, the dataset was screened for outliers and evaluated for normality to enhance statistical robustness. Both linear and nonlinear regression models were examined, and their predictive performance was assessed using appropriate goodness-of-fit indicators. To further improve data reliability, repeated measurements were carried out for selected specimens to evaluate test repeatability and measurement consistency.

In the case of Schmidt hammer testing, multiple rebound readings were obtained at each location, and statistically inconsistent values were excluded based on standard deviation thresholds. Similarly, point load tests were performed along different loading orientations where applicable to reduce anisotropy effects associated with bedding planes and discontinuities. This approach minimized random variability and improved the representativeness of the derived strength indices. In addition, efforts were made to ensure that specimen selection adequately represented the lithological variability observed in the field. Samples were collected from different elevations and structural conditions within the study area to capture potential variations in weathering intensity, joint density, and textural characteristics. This systematic sampling strategy enhanced the robustness of the statistical correlations by incorporating a broad range of mechanical responses. Consequently, the developed empirical relationships reflect not only laboratory-controlled behavior but also the inherent heterogeneity of limestone formations in the region. To ensure data reliability, all testing equipment, including the compression machine, point load apparatus, and Schmidt hammer, was calibrated according to established standards prior to the experimental program. Periodic verification checks were carried out throughout the testing phase to reduce systematic errors and maintain measurement consistency.

V. RESULTS AND DISCUSSION

The experimental investigation of limestone samples from Mostufi Mountain, Arak, yielded significant insights into their mechanical properties, particularly their UCS, I_s , and RN values. The integration of these methods allowed for the establishment of empirical correlations that enhance the reliability of indirect strength estimation techniques. The results demonstrate the variations in strength characteristics due to inherent geological factors such as porosity, mineral composition, and structural discontinuities. The UCS test results, presented in Table 3,

indicate a range of compressive strength values for the tested limestone samples. The observed variations can be attributed to differences in sample density, cementation, and microcrack distribution. Higher UCS values correspond to well-cemented, low-porosity samples, whereas lower UCS values are linked to weathered and fractured specimens. The standard deviation of UCS values reflects the natural heterogeneity of the rock mass, which is a crucial factor in engineering applications.

The point load strength test results, shown in Table 4, reveal a strong correlation with UCS values. As expected, samples exhibiting high UCS values also recorded high I_s values. This correlation allows for UCS estimation using point load test results, particularly in field conditions where direct UCS testing is impractical. The ISRM conversion factor was applied to estimate UCS from I_s , reinforcing the reliability of this indirect method. Additionally, the Schmidt hammer rebound values provide a rapid assessment of surface hardness, which is indirectly related to compressive strength. The results in Table 5 indicate variations in rebound values across different samples. These variations are influenced by factors such as weather, moisture content, and microfractures. The observed trends suggest that Schmidt hammer tests can serve as a reliable preliminary assessment tool for UCS estimation in limestone formations. A comparative analysis of the three testing methods is presented in Table 5, demonstrating the relationships among UCS, I_s , and RN. The trends indicate that while direct UCS testing remains the most accurate method, point load and Schmidt hammer tests provide valuable indirect estimates, particularly for preliminary site assessments and rapid strength evaluations.

The comparative table highlights the consistency between direct and indirect testing methods. Although slight deviations exist due to sample heterogeneity and inherent test limitations, the overall correlation is strong. The estimated UCS values from both I_s and RN tests align closely with the directly measured UCS values, reinforcing the validity of these indirect testing approaches. The practical implications of these findings are significant for geotechnical engineering and infrastructure development. The ability to estimate UCS using point load and Schmidt hammer tests provides engineers with cost-effective and time-efficient alternatives to laboratory UCS testing.

The data presented in these tables reveal important insights into the relationship between different rock strength tests and their applicability in field and laboratory settings. Table 1 provides the UCS values for 75 limestone samples taken from Mostufi Mountain, with values ranging from 47.5 MPa to 62.1 MPa. These results provide the baseline for understanding the strength properties of the limestone in the region, offering direct insight into the rock's resistance to axial compression. The failure modes observed in the UCS test indicate that most of the samples failed through axial splitting, a common failure mode for rocks with moderate to high cohesion. In Table 4, the I_s test results for the same 75 samples are presented. These results show a strong correlation with the UCS data, as the estimated UCS values based on I_s are within a reasonable range of the directly measured UCS values. For instance, the estimated UCS from the point load test for Sample UCS-1 is 57.9 MPa, closely matching the measured UCS of 58.3 MPa.

Table 3 UCS test results on samples

Sample ID	UCS (MPa)	Density (g/cm ³)	Failure Mode
UCS-1	58.3	2.65	Axial Split
UCS-2	62.1	2.68	Shear Failure
UCS-3	47.5	2.61	Axial Split
UCS-4	51.2	2.63	Shear Failure
UCS-5	56.7	2.64	Shear Failure
UCS-6	59.4	2.66	Axial Split
UCS-7	60.2	2.62	Axial Split
UCS-8	53.0	2.62	Axial Split
UCS-9	64.3	2.70	Shear Failure
UCS-10	55.8	2.67	Axial Split
UCS-11	61.5	2.69	Shear Failure
UCS-12	49.7	2.60	Axial Split
UCS-13	50.1	2.62	Shear Failure
UCS-14	55.1	2.65	Shear Failure
UCS-15	57.0	2.64	Axial Split
UCS-16	62.8	2.68	Axial Split
UCS-17	54.2	2.61	Shear Failure
UCS-18	60.3	2.66	Shear Failure
UCS-19	59.9	2.69	Axial Split
UCS-20	48.5	2.59	Shear Failure
UCS-21	53.6	2.63	Axial Split
UCS-22	51.9	2.64	Shear Failure
UCS-23	51.9	2.64	Shear Failure
UCS-24	57.3	2.64	Axial Split
UCS-25	63.2	2.67	Shear Failure
UCS-26	54.7	2.70	Axial Split
UCS-27	52.4	2.65	Shear Failure
UCS-28	61.0	2.69	Axial Split
UCS-29	55.6	2.64	Axial Split
UCS-30	60.8	2.66	Axial Split
UCS-31	59.1	2.68	Shear Failure
UCS-32	56.2	2.63	Axial Split
UCS-33	55.2	2.66	Shear Failure
UCS-34	51.9	2.62	Axial Split
UCS-35	48.5	2.63	Axial Split
UCS-36	51.9	2.64	Shear Failure
UCS-37	59.9	2.69	Axial Split
UCS-38	48.5	2.59	Shear Failure
UCS-39	53.6	2.63	Axial Split
UCS-40	51.9	2.64	Shear Failure
UCS-41	51.9	2.64	Shear Failure
UCS-42	57.3	2.64	Axial Split
UCS-43	63.2	2.67	Shear Failure
UCS-44	54.7	2.70	Axial Split
UCS-45	62.8	2.68	Axial Split
UCS-46	54.2	2.61	Shear Failure
UCS-47	48.5	2.59	Shear Failure
UCS-48	48.5	2.59	Shear Failure
UCS-49	62.1	2.68	Shear Failure
UCS-50	47.5	2.61	Axial Split
UCS-51	51.2	2.63	Shear Failure
UCS-52	59.1	2.68	Shear Failure
UCS-53	56.2	2.63	Axial Split
UCS-54	55.2	2.66	Shear Failure
UCS-55	57.3	2.64	Axial Split
UCS-56	63.2	2.67	Shear Failure
UCS-57	54.7	2.70	Axial Split
UCS-58	51.9	2.64	Shear Failure
UCS-59	51.9	2.64	Shear Failure
UCS-60	57.3	2.64	Axial Split
UCS-61	59.1	2.68	Shear Failure
UCS-62	56.2	2.63	Axial Split
UCS-63	55.2	2.66	Shear Failure

Table 3 Continued

Sample ID	UCS (MPa)	Density (g/cm ³)	Failure Mode
UCS-64	48.5	2.59	Shear Failure
UCS-65	62.8	2.68	Axial Split
UCS-66	54.2	2.61	Shear Failure
UCS-67	62.8	2.68	Axial Split
UCS-68	58.3	2.65	Axial Split
UCS-69	62.1	2.68	Shear Failure
UCS-70	47.5	2.61	Axial Split
UCS-71	51.2	2.63	Shear Failure
UCS-72	56.7	2.64	Shear Failure
UCS-73	59.4	2.66	Axial Split
UCS-74	60.2	2.62	Axial Split
UCS-75	60.2	2.62	Axial Split

Table 4 Point load Index (I_s) test results for selected samples

Sample ID	I_s (MPa)	UCS _{Estimated} (MPa)	Load Orientation
PLT-1	4.3	57.9	Axial
PLT-2	4.6	62.5	Axial
PLT-3	3.5	48.2	Diametral
PLT-4	3.8	50.9	Axial
PLT-5	4.1	55.8	Diametral
PLT-6	4.2	56.5	Diametral
PLT-7	3.9	52.1	Axial
PLT-8	3.9	53.5	Axial
PLT-9	4.5	60.1	Diametral
PLT-10	4.0	54.6	Axial
PLT-11	4.3	57.9	Diametral
PLT-12	3.7	50.3	Axial
PLT-13	3.9	52.1	Axial
PLT-14	4.0	54.0	Axial
PLT-15	4.2	56.3	Diametral
PLT-16	4.1	55.6	Diametral
PLT-17	3.8	51.0	Axial
PLT-18	4.4	59.1	Axial
PLT-19	4.3	57.7	Diametral
PLT-20	3.6	49.4	Axial
PLT-21	4.0	54.2	Axial
PLT-22	4.1	52.4	Axial
PLT-23	4.0	54.2	Diametral
PLT-24	4.1	55.7	Axial
PLT-25	4.5	60.4	Axial
PLT-26	4.2	56.2	Axial
PLT-27	3.8	51.3	Diametral
PLT-28	4.0	54.3	Diametral
PLT-29	3.7	50.6	Axial
PLT-30	4.4	59.3	Axial
PLT-31	4.2	56.3	Axial
PLT-32	4.1	55.5	Diametral
PLT-33	3.9	53.7	Axial
PLT-34	4.1	52.3	Diametral
PLT-35	4.3	58.2	Diametral
PLT-36	4.3	57.9	Axial
PLT-37	4.6	62.5	Axial
PLT-38	3.5	48.2	Diametral
PLT-39	3.8	50.9	Axial
PLT-40	4.1	55.8	Diametral
PLT-41	4.2	56.5	Diametral
PLT-42	3.9	52.1	Axial
PLT-43	4.4	59.1	Axial
PLT-44	4.3	57.7	Diametral
PLT-45	3.6	49.4	Axial
PLT-46	3.7	50.3	Axial
PLT-47	4.3	57.7	Diametral
PLT-48	4.3	57.9	Axial

Table 4 Continued

Sample ID	I_s (MPa)	UCS _{Estimated} (MPa)	Load Orientation
PLT-49	4.2	56.2	Axial
PLT-50	4.2	56.2	Axial
PLT-51	3.8	51.3	Diametral
PLT-52	4.0	54.3	Diametral
PLT-53	3.7	50.6	Axial
PLT-54	4.4	59.3	Axial
PLT-55	4.2	56.3	Axial
PLT-56	4.1	55.5	Diametral
PLT-57	3.9	53.7	Axial
PLT-58	4.1	52.3	Diametral
PLT-59	3.9	52.1	Axial
PLT-60	4.4	59.1	Axial
PLT-61	4.3	57.7	Diametral
PLT-62	4.3	57.9	Diametral
PLT-63	3.8	50.9	Axial
PLT-64	3.8	50.9	Axial
PLT-65	4.1	55.8	Diametral
PLT-66	4.2	56.5	Diametral
PLT-67	3.9	52.1	Axial
PLT-68	3.9	53.5	Axial
PLT-69	4.5	60.1	Diametral
PLT-70	4.0	54.6	Axial
PLT-71	4.3	57.9	Diametral
PLT-72	3.7	50.3	Axial
PLT-73	3.9	52.1	Axial
PLT-74	4.0	54.0	Axial
PLT-75	4.2	56.2	Axial

This confirms that the point load test is a reliable and cost-effective method for estimating UCS, especially when direct testing is not feasible. Figure 4 contains the results of the RN test, performed on a larger set of 120 samples. While the Schmidt Hammer is a quick, non-destructive test, its estimated UCS values are generally lower than those obtained from UCS and point load tests. This is consistent with the fact that RN measures the surface hardness, which can be affected by weather, moisture, and surface roughness. For example, Sample RL3 has a lower RN value of 42, corresponding to a slightly weathered surface, which results in a lower estimated UCS of 44.9 MPa compared to the direct UCS value of 47.5 MPa. Finally, Table 5 compares the UCS values from all three methods: UCS, I_s , and RN.

The results show that direct UCS testing provides the most accurate strength measurements, while point load and Schmidt hammer tests yield consistent indirect estimates within an acceptable range of variation. Although UCS remains the reference method, the indirect approaches offer practical alternatives for preliminary evaluation and field-based applications in limestone formations. The differences observed between measured and estimated values are primarily attributed to rock heterogeneity and surface condition effects.

Descriptive statistics of the UCS dataset indicate a relatively constrained strength distribution for the tested limestone. UCS values range from 47.5 to 64.3 MPa, with a mean of 55.86 MPa and a standard deviation of 4.73 MPa ($n = 75$). The frequency distribution of UCS values is illustrated in Figure 5, showing that most specimens cluster around the mid-range of the measured strengths, consistent with the limited variability observed across the sampled formation. In addition to strength variability, the relationship between UCS and density was evaluated using the laboratory measurements provided in Table 3.

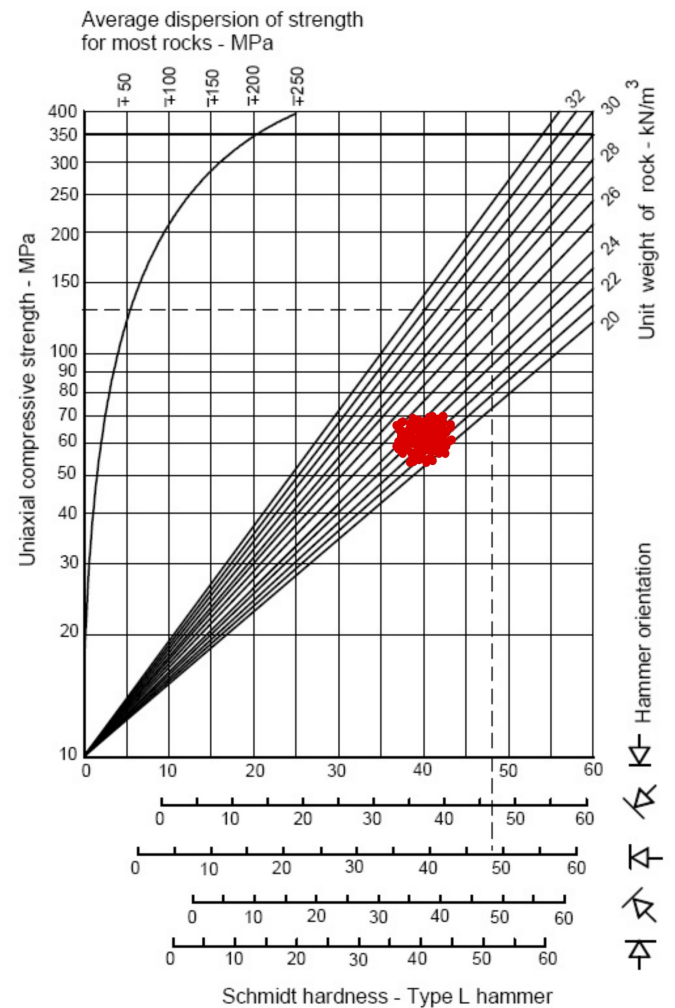


Fig. 4 Schmidt hammer hardness index test results for studied area

Density values vary from 2.59 to 2.70 g/cm³ (mean = 2.646 g/cm³), and a positive trend is observed between UCS and density. Linear regression yields the following relationship:

$$UCS = -24.246 + 17.114 \rho \quad (1)$$

where ρ is density in g/cm³. The corresponding goodness of fit is $R^2 = 0.53$, indicating that density explains a substantial portion of UCS variability within the tested dataset. This relationship and its scatter are presented in Figure 6. For indirect strength estimation based on the point load test, the relationship between the I_s and the UCS values estimated from I_s (as reported in Table 4) was quantified. The dataset indicates that I_s values range from 3.5 to 4.6 MPa (mean = 4.07 MPa), while the corresponding UCS estimates range from 48.2 to 62.5 MPa. Regression analysis results in the empirical relationship:

$$UCS = 3.34 + 12.65 I_s \quad (2)$$

with $R^2 = 0.95$, demonstrating a strong linear association between I_s and the UCS estimates reported for the studied limestone. The regression trend and data scatter are shown in Figure 7. Finally, the UCS failure modes reported in Table 3

were summarized to evaluate the observed failure behavior under uniaxial loading conditions. Axial splitting and shear failure occurred with comparable frequency (37 and 38 specimens, respectively). The UCS distributions associated with each failure mode are compared in Figure 8, showing broadly similar strength ranges across the two categories, with only minor differences in central tendency and dispersion.

Figure 9 illustrates the empirical relationship between UCS and the RN for the selected limestone samples from Mostufi Mountain. A clear positive linear trend is observed between rebound hardness and compressive strength. Linear regression of the paired dataset ($n = 30$) produced the following site-specific correlation:

$$UCS = 1.90 (RN) - 28.29 \quad (3)$$

with a $R^2 = 0.97$, indicating a very strong statistical relationship. Although the rebound-based estimates show slightly greater scatter than the UCS– I_{s50} relationship, the overall agreement confirms that the Schmidt hammer test can provide a reliable preliminary indicator of compressive strength for the studied limestone. Minor deviations from the regression line are mainly attributed to surface condition effects and inherent rock heterogeneity.

Figure 5 illustrates the frequency distribution of UCS values for the tested limestone specimens. The histogram shows a relatively narrow and unimodal distribution, with most samples concentrated in the mid-strength range. This clustering pattern indicates limited lithological variability within the Mostufi

Mountain limestone and suggests generally consistent cementation and fabric among the tested specimens. The absence of extreme outliers further supports the reliability of the dataset for regression-based strength estimation. Figure 6 presents the relationship between UCS and bulk density. A moderate positive trend is observed, indicating that specimens with higher density tend to exhibit greater compressive strength. This behavior is consistent with the reduction of pore space and improved grain interlocking in denser limestone. However, the observed scatter around the regression line suggests that density alone does not fully control strength variability, and that microstructural features such as microcracks and cement quality also contribute to the mechanical response. Figure 7 shows the correlation between the I_s and the estimated UCS values. The data points display a strong linear alignment with limited dispersion, confirming the proportional relationship between index strength and compressive strength for the studied limestone.

The high goodness of fit indicates that the point load test provides a reliable indirect measure of UCS under the tested conditions. Minor deviations from the regression line can be attributed to differences in loading orientation and inherent material heterogeneity. Figure 8 compares UCS values grouped by observed failure mode (axial splitting versus shear failure). The two groups exhibit broadly overlapping strength ranges, indicating that failure mode does not strongly partition the UCS magnitude within the tested strength domain. Nevertheless, axial splitting failures tend to occur more frequently in specimens with relatively uniform texture, whereas shear failures appear in samples with slightly higher structural complexity.

Table 5 Comparative analysis of UCS, I_s , and R results estimated on selected samples (30 samples provided)

Sample Number	UCS (MPa)	I_s (MPa)	UCS _{Estimated} from I_s (MPa)	RN value	UCS _{Estimated} from RN (MPa)
L1	58.3	4.3	57.9	45	56.2
L2	62.1	4.6	62.5	48	60.8
L3	47.5	3.5	48.2	40	48.7
L4	51.2	3.8	50.9	42	50.9
L5	56.7	4.1	55.8	44	54.2
L6	59.4	4.2	56.5	46	57.5
L7	53.0	3.9	53.5	43	52.4
L8	64.3	4.5	60.1	49	62.3
L9	55.8	4.0	54.6	44	54.0
L10	61.5	4.3	57.9	47	59.1
L11	49.7	3.7	50.3	41	49.8
L12	50.1	3.9	52.1	42	50.6
L13	55.1	4.0	54.0	44	53.9
L14	57.0	4.2	56.3	45	56.7
L15	62.8	4.1	55.6	48	60.0
L16	54.2	3.8	51.0	43	52.0
L17	60.3	4.4	59.1	47	58.5
L18	59.9	4.3	57.7	46	57.2
L19	48.5	3.6	49.4	41	48.5
L20	53.6	4.0	54.2	43	52.6
L21	51.9	4.1	55.7	42	51.4
L22	57.3	4.5	60.4	45	56.8
L23	63.2	4.2	56.2	48	61.5
L24	54.7	3.8	51.3	43	52.1
L25	52.4	4.0	54.3	42	51.7
L26	61.0	3.7	50.6	46	57.8
L27	55.6	4.4	59.3	44	53.6
L28	60.8	4.2	56.3	47	58.0
L29	59.1	4.1	55.5	46	57.1
L30	56.2	3.9	53.7	44	54.4

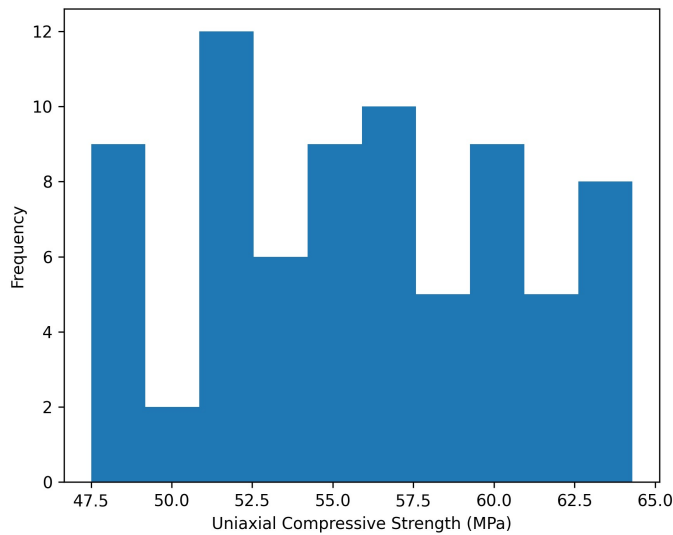


Fig. 5 Frequency distribution of UCS values for the studied limestone

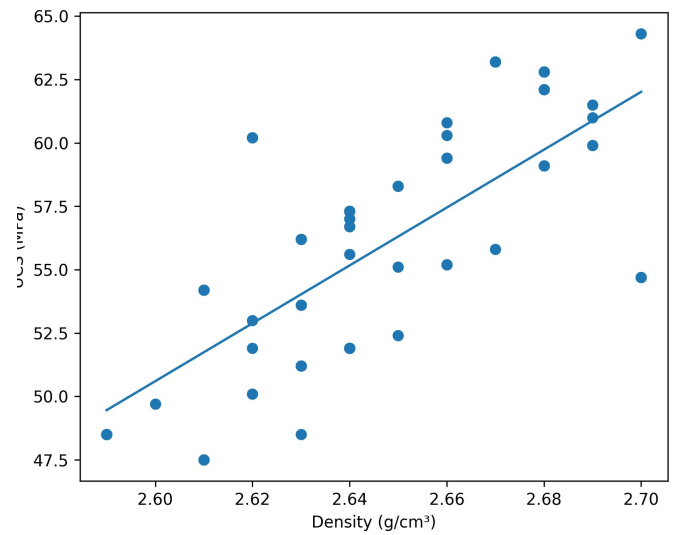


Fig. 6 Relationship between UCS and bulk density

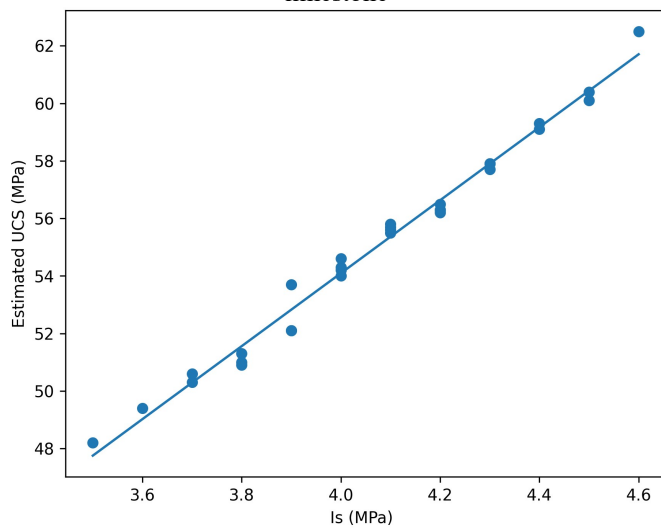


Fig. 7 Correlation between I_s and estimated UCS

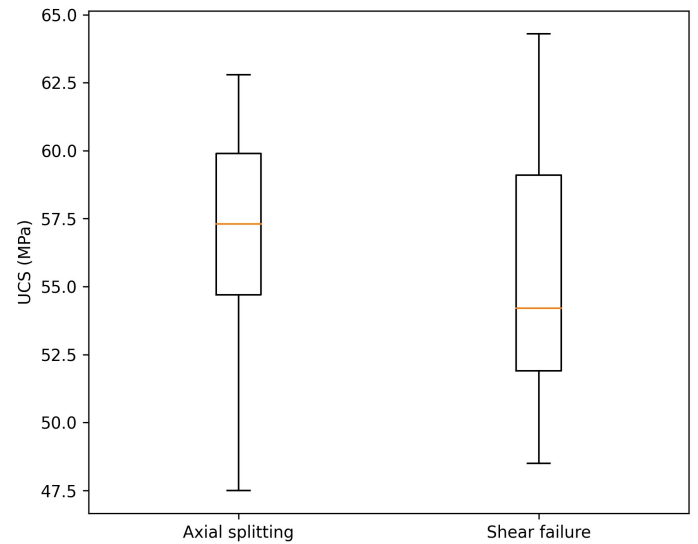


Fig. 8 UCS variation by observed failure mode

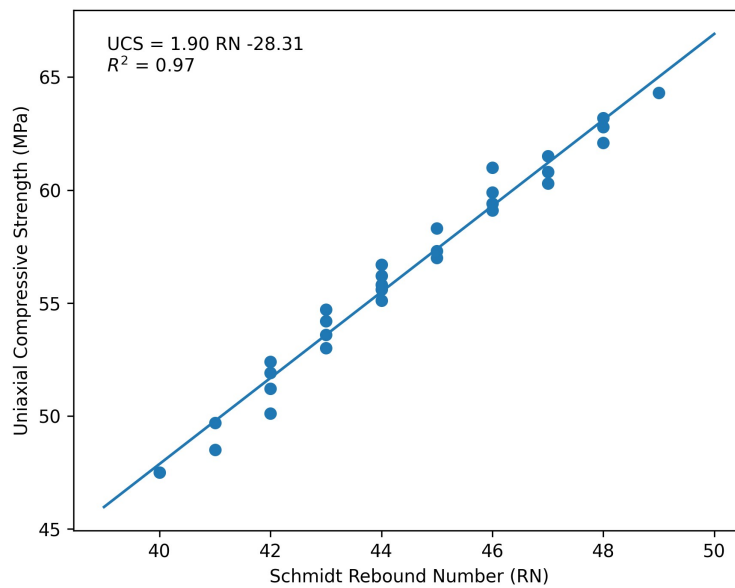


Fig. 9 Relationship between UCS and RN for limestone samples

Generally, the figure confirms that both failure mechanisms are representative of the brittle behavior of the studied limestone under uniaxial loading conditions. Figure 9 presents the empirical relationship between UCS and the RN for the limestone samples from Mostufi Mountain. The scatter plot shows a clear positive correlation between rebound hardness and compressive strength, indicating that higher RN values generally correspond to stronger rock specimens. Compared with the UCS– I_s relationship, the data exhibit slightly greater dispersion, reflecting the known sensitivity of Schmidt hammer measurements to surface conditions, including minor weathering, moisture, and surface roughness. Nevertheless, the overall trend supports the applicability of the Schmidt hammer as a rapid field-based indicator of rock strength in the studied area. The regression line derived for the local dataset provides a site-specific correlation that can be used for preliminary UCS estimation in similar limestone formations, particularly where direct laboratory testing is limited.

VI. CONCLUSION

This study presents a comprehensive analysis of the UCS, I_s , and RN test results for limestone samples from Mostufi Mountain in Arak. The data obtained through these tests demonstrate the varying strengths of limestone and provide insight into the reliability of different testing methods in estimating UCS. The UCS test, being the most accurate and direct method, provides reliable measurements of the compressive strength of limestone, with values ranging from 47.5 MPa to 62.1 MPa. The I_s test, which serves as a cost-effective alternative, shows a strong correlation with the UCS results. The estimated UCS from the I_s values were close to the directly measured UCS, confirming its usefulness for rapid field evaluations. Additionally, the RN test, while non-destructive and fast, tends to underestimate UCS values, as it is affected by surface weather and conditions. The comparative analysis of UCS, I_s , and RN tests reveals that while the UCS test remains the gold standard for determining rock strength, both the Point Load and Schmidt Hammer methods offer practical alternatives for estimating UCS, especially in large-scale geotechnical projects where time and cost constraints are a consideration. The results underscore the importance of using multiple testing methods to obtain a more comprehensive understanding of the rock's mechanical properties, ensuring more accurate and reliable assessments for engineering and construction purposes. In conclusion, the integration of UCS, I_s , and RN test methods provides valuable insights into the mechanical properties of limestone, aiding in the safe and efficient planning of construction projects in limestone-rich areas.

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DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon reasonable request. No publicly archived dataset was generated.

ETHICS APPROVAL

This study did not involve human participants, personal data, or animal subjects. No specific ethical approval was required.

FUNDING

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AUTHORS' CONTRIBUTIONS

Fatima Omid and Nader Ebrahimi Rad conducted the main data analysis, contributed to the data collection, preprocessing, and interpretation, and were responsible for drafting the initial manuscript. Parviz Bolandi performed supervision, conceptual guidance. Nader Ebrahimi Rad and Parviz Bolandi conducted critical revision of the manuscript, and final approval of the version to be published. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The authors have not disclosed any competing interests.

USE OF AI

AI tools were not used in data generation, analysis, results, or decision-making.

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