SQU Journal for Science, 2022, 27(1),52-62 DOI:10.53539/squjs.vol27iss1pp52-62
Sultan Qaboos University

Engineering Properties of Umm er Radhuma Limestone, Southeast Ataq, Yemen

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ABSTRACT: Limestone in southeast Ataq, Shabwah governorate in Yemen was studied to assess its engineering properties to ensure their compliance with the minimum construction requirements. This limestone is widely used as building stone in this area. Six different sites were selected for sampling appropriate limestone rock for building stone. 42 representative samples were collected and tested for water content, water absorption, dry density, saturated density, specific gravity, porosity, void ratio, and uniaxial compressive strength to ensure their suitability for use in the production of dimension stone. Tensile strength and elastic modulus were estimated. Their low water absorption, density and porosity values make them suitable for constructing building foundations. Their compressive strength, tensile strength and elastic modulus show their high resistance to crushing and bending effects. Engineering properties data from southeast Ataq limestone were compared with data from various parts of the world. The results showed that southeast Ataq limestone is of good quality and satisfies the ASTM requirements as building stone.

Keywords: Ataq; Building stones; Engineering properties; Limestone; Yemen.

الخَوَاص الهَندسيَّة لِحجر جِيري أُم الرَّضُومَة ، جنوب شرق عَتَق ، اليمن

إبراهيم عبدالحميد الأكحَلي وعبدالمنعم مِرصَاص حَبتُور

الملخص: تَمَّ دراسة الحجر الجيري جنوب شرق عَتق، محافظة شَبوة، اليَمَن، لِتَقييم خَواصِه الهَندسيَّة، لِضَمَان الالتزَام بِأقل المتطلبات الهندسيَّة. حيث يُستخدم هذا الصخر بشكلٍ واسعٍ في البناء في تلك المنطقة. أُختِيرت ستة مواقع لجمع العينات المناسبة من صخور الحجر الجيري المستخدمة كحجر بناء. حيث جُمعت 42 عينة ممثلة، وتمّ اِختبار المحتوى المائي، اِمتصاص الماء، الكثافة الجافة، الكثافة المشبعة، الوزن النوعي، المسامية، نِسبة الفراغ، والضغط أُحادي المحور، وتَمّ تقدير مقاومة الشد ومُعَاملات المُرونة، لمعرفة مدى ملاءَمتها للاستخدام كحجر بناء. فالامتصاص المنخفض للماء، الكثافة، والمسامية كانت ملائِمة لاستخدامها كصخور لبناء الأساسات. كما أن قِيم مقاومة الضغط، ومقاومة الشد، ومُعاملات المُرونة أَظهرت أنها صخور ذات مقاومة عالية لتأثيرات الكسر والانحِناء. قُورِنت النتائج التي تم الحصول عليها مع نتائج أُخرى لصخور الحجر الجيري في أماكن مختلفة من العالم. وأظهرت النتائج أن صخور الحجر الجيري المتواجدة في جنوب شرق عَتق ذات نوعية جيدة كحجر بناء ومُطابقة لمتطلبات مُواصفات الجمعية الأمريكيّة لاختباراتِ المواد.

الكلمات المفتاحية: عَتَق، احجَار البِنَاء ، الخَوَاص الهَندسيَّة ، الحَجر الجِيري ، اليَمَن.

1. Introduction

Dimension stone is a natural stone that has been quarried, selected and processed to specific sizes or shapes, with or without one or more mechanically dressed or finished surfaces, for use as building facing, curbing, paving stone, monuments and memorials, and various industrial products [1]. It includes igneous rocks such as basalt and granite; metamorphic rocks such as gneiss and marble; and sedimentary rocks such as limestone, dolomite and sandstone. The dimension stone sector is developing strongly. China, India, Turkey and Iran lead the world in quarry production while China and Italy lead in processed stone export [2]. The world quarry net product is expected to reach one hundred and twenty million tons in 2025 [3]. The main types of dimension (ornamental) rocks include granite, limestone, sandstone and marble [4]. Since ancient times, limestone has been known as an inexpensive, reliable building material and used as a decorative and constructional material. It is frequently used as a building material in architectural applications mainly because of its availability; it makes up approximately 10% of the total volume of all sedimentary rocks. Limestone rock can be granular or massive depending on the process of formation; generally, it is mainly composed of calcite and aragonite, which are different crystal forms of calcium carbonate. Limestone can also originate from deposits of skeletal fragments of marine organisms such as coral. Dolomite is formed when calcium carbonate (calcite) sediments are exposed to magnesium ions, which may be present in the groundwater. Dolomitic limestone is composed of 50 to 90% calcite ($CaCO_3$) and 10 to 50% of dolomite ($CaMg(CO_3)_2$) [5,6].

Knowledge of the engineering properties (physical and mechanical) of rock material is important to the construction industry. No safe design of a soundly engineered construction can be accomplished without the evaluation of the engineering properties of the materials used [7]. The physical properties of rocks are the fundamental properties, which influence strength and durability [8,9]. The amount of water absorbed by a stone can be indicated by porosity [8]. The durability of building stones depends chiefly on effective porosity, water absorption and strength, which indirectly influences the resistance of rock materials to crystallization pressure [10,11].

Generally, their strength is used to categorize various rock types and determine their suitability for various end uses, especially for building stone. Strength is the ability of a material to resist deformation induced by external forces, whereas the durability of building stone is the measure of its ability to endure and maintain its distinctive characteristics of strength and resistance under its working conditions of cyclic variations of temperature and moisture content, and in its chemical environment [12].

The consumption of natural resources has increased due to the increasing demand for their recent use in building decoration. At present, there are many operational dimension stone quarries of limestone in Yemen, from which raw blocks are extracted and processed as building and ornamental stones. The reserves are virtually unlimited. Therefore, it is very important to evaluate the rock quality and to determine the engineering properties of such limestone. This information could help present or future engineering projects using limestone in or around the quarry areas. Limestone rocks dealt with in the present study belong to the Paleocene [13]. Despite their widespread occurrence in the southeastern part of Yemen, there is a lack of studies on the engineering properties of these rocks as it applies to their commercial uses as building and ornamental stones.

For local housing and construction, easily workable rock is required in preference to rock with attractive aesthetic qualities. The stone is shaped and worked to finished products (building blocks). The large scale economically viable use of rock for various building purposes requires that cheap and simple technology can be employed to reduce the cost.

The limestone sector in Yemen has a huge potential to play a key role in the economic development of the country. Hence, testing such rocks for their engineering properties is imperative. This study aims to assess limestone of southeast Ataq in Shabwah governorate in Yemen, based on some engineering properties, which are often considered fundamental for evaluating rock as building stone.

Study Area

The studied area is located about 8 km southeast of Ataq city between latitude 14^o 27' 32" and 14^o 32' 46" N and longitude 46^o 51' 38" and 46^o 55' 52" E as shown in Figure 1. It has a typical arid desert climate, being hot in summer and cold in winter. Vegetation is scare but there are some desert plants scattered in the wadis and other flat areas. Elevations in the area range from 1121 to 1594 m above sea level (Figure 2). The studied limestone belongs to the Paleocene Umm er Radhuma Formation (Figures 3 and 4).

Geology

Yemen has a great variety of rock units which can be considered as important sources of dimension stones and to be of economic importance. Limestone is one of these rocks which is widely used in Yemen as raw material in the cement industry and construction, and for ornamental stones.

The study area has been studied geologically by many investigators. Isakinet *et al*. [14] prepared a geological map of Ataq quadrangle at scale 1:100,000 including the studied area. Al-Obaydee and Al-Dabbagh [15] have studied the geology of the area south of Ataq. Engineering geological studies have been carried out by Al-Dabbagh and Al-Obaydee [16].

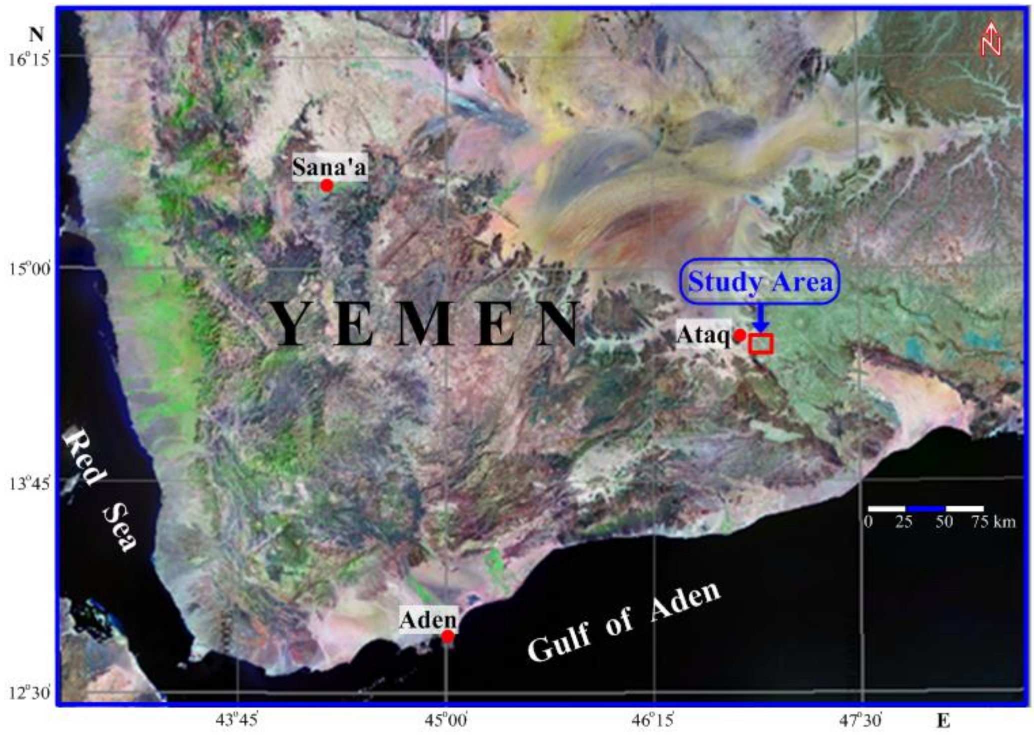

Figure 1. Satellite image showing the location of the studied area.

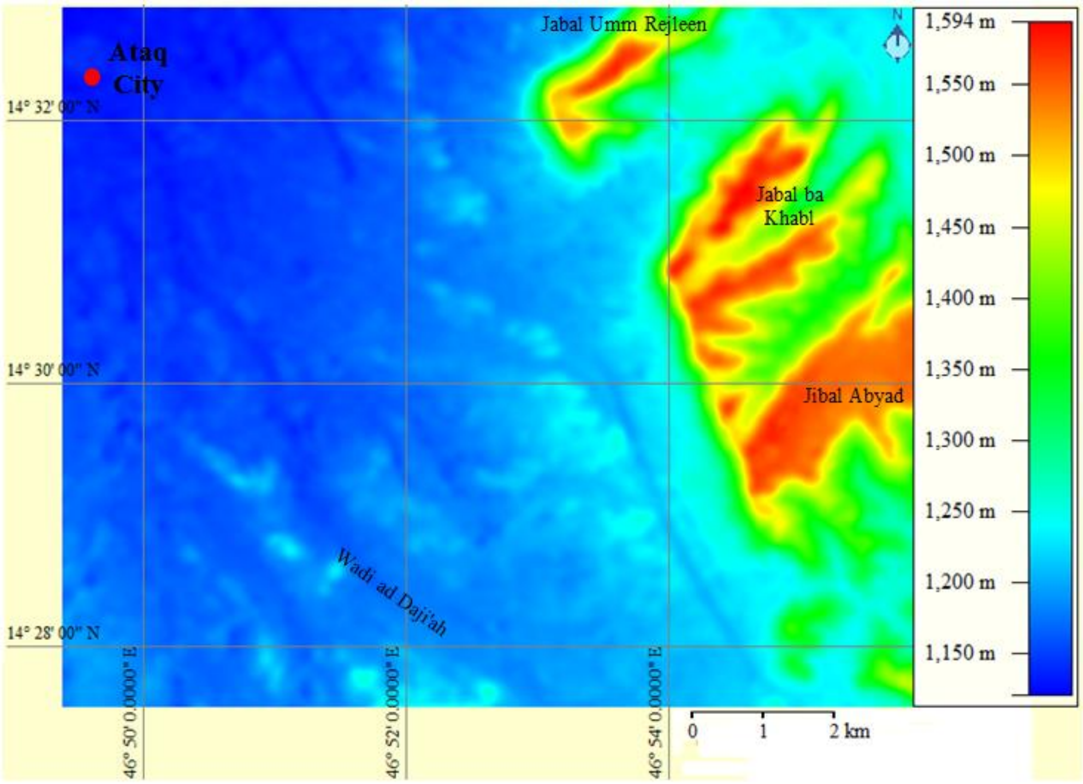

Figure 2. Digital elevation model (DEM) of the study area.

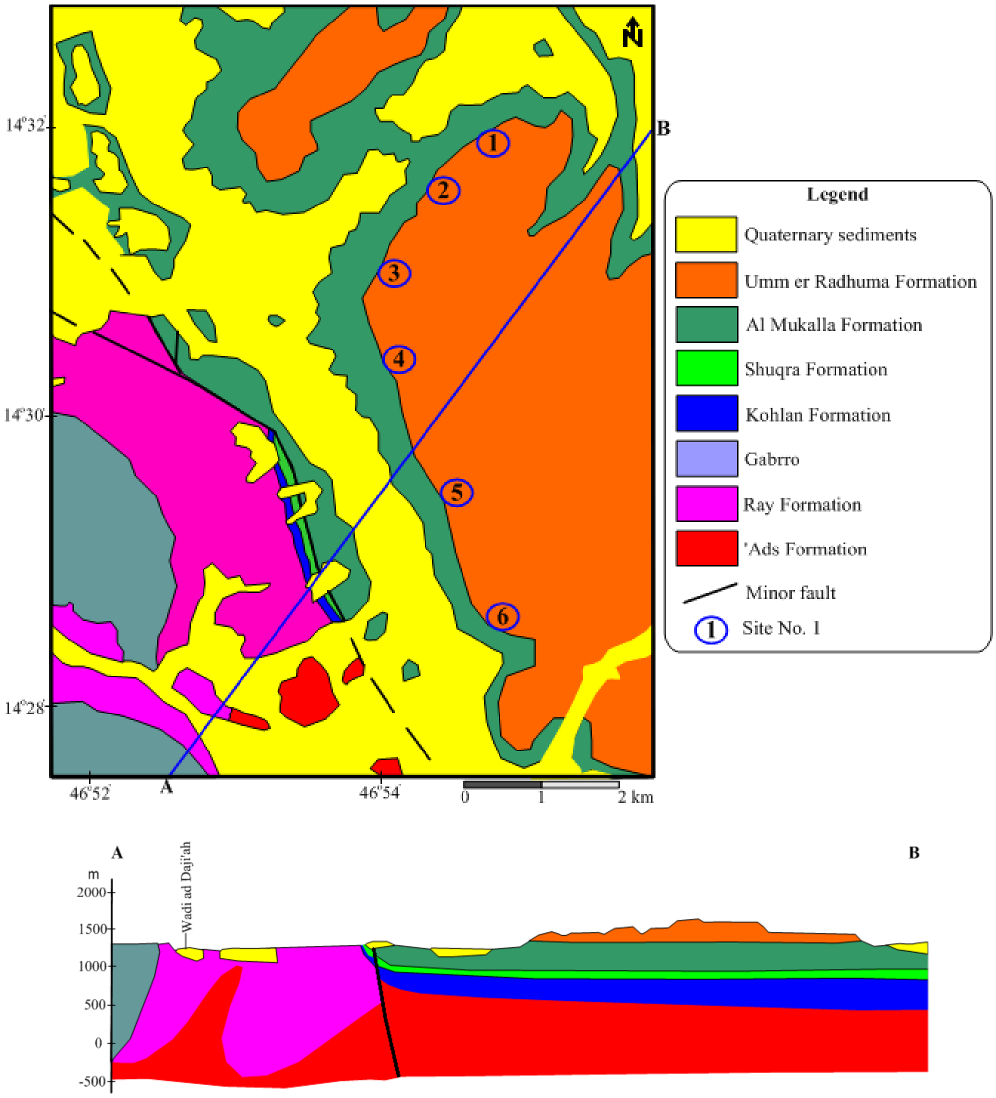

Figure 3. Geological map of the study area and cross-section from A-B [14].

Figure 4. Photograph showing the Umm er Radhuma Formation in the studied area.

Figure 5. Photograph showing concretions of chert in Umm er Radhuma Formation in the studied area.

The basement complex (Proterozoic) is found in the southwestern part of the study area, and consists of biotite quartz feldspar schist ('Ads Formation), metabasalt, metarhyolite, biotite quartz feldspar and amphibolite schist with bands of marble (Ray Formation) and Ataq magmatic complex (gabbro) [14].

The Kohlan Formation lies with nonconformity on the basement rocks. It consists of calcareous quartz and quartz sandstone with scattered quartz and granite pebbles. The Shuqra Formation (Jurassic) lies with stratigraphic unconformity on the Kohlan Formation. It is represented by limestone with *Catinulina sandalina, Ceratomya concentrica, fimbria quennelly Cox, Lopha costata* and other fossils. The Al Mukalla Formation (Cretaceous) lies with unconformity on the Shuqra Formation. It is represented by fine grained to gravelly sandstone. The Al Mukalla Formation is red, brown and brownish to reddish in the varieties containing hematite in cement and cross bedding with scattered quartz pebbles, and includes a partly violet colored interlayer of siltstones. The Umm er Radhuma Formation (Paleocene) lies with unconformity on the Al Mukalla Formation (Figure 3) [14]. It contains *Campanile briarti Rutot et Van den Brocck, Gisortia murchisoni Arch, et Haime, Tiburnus aulacophorus Cossm,* and other fossils [14].

In the study area, limestone consists of nodular limestone. Concretions of chert are common, and up to 3 to 10 cm across, of rounded and elliptical shape (Figure 5). Its thickness is about 60 m and joint spacing ranges from 2 to 3 m (extremely wide spacing and very large block sizes) and it is characterized by the presence of three orthogonal joint sets (NE-SW, NW-SE and E-W). The continuity of joints in the rock mass is more than 20 m. The joint surfaces are generally planar and rough and have strong to very strong wall strength, and very narrow to wide aperture. The infilling materials are rock fragments and clay. The upper surface of the limestone is slightly weathered and the thickness of the weathered material ranges from 1 cm to about 2 cm. The limestone beds are inclined 5^{o} in NE direction.

Quaternary sediments consisting of loose or partly consolidated sediments of alluvial gravel deposits cover a great part of the study area. The thicknesses of these sediments may reach 5-10 m.

2. Materials and Methods

Limestones were extracted from Umm er Radhuma Formation rocks in southeast Ataq using hand tools, blasting and motorized machines. Chemical analysis of 6 representative samples of limestone were carried out by XRF, unit model ARL 9800 XP SIM-SEQ in Quality laboratory of Amran Cement Plant, Amran, Yemen.

18 cube specimens of dimensions 5×5×5 cm were collected from the study area at 6 different sites (Figure 3). The specimens were subjected to standard physical properties for rock, namely water absorption, dry density, saturated density, specific gravity, porosity, void ratio according to American Society for Testing and Material, ASTM C97 [17]. 18 lump samples were collected to determine water content. 18 cube specimens of 10×10×10 cm dimensions were collected and prepared to determine uniaxial compressive strength (UCS) according to ASTM C170 [18]. Each experiment was conducted on at least three specimens and the average of the obtained values was recorded. These experiments were carried out in the Engineering Geology Department laboratories, Faculty of Oil and Minerals, Aden University.

Hardness testing involves the use of a Schmidt Impact Hammer of type L for the hardness determination of in situ rock, with an impact energy of 0.74 Nm applied following ISRM [19]. The rebound value of the Schmidt Hammer is used as an index value for the intact strength of rock material, but it is also used to give an indication of the compressive strength of rock material [19]. The major advantage of the Schmidt Hammer is that it is portable enough to be easily transported to, and used in, the field. The measured test values were arranged in a descending order (20 reading points were taken and the mean value of the highest 10 points was considered). This average of rebound hardness of rock multiplied by the correction factor obtained by calibration test is recorded [19].

Tensile strength was calculated according to Al-Derdi and Al-Harthi's equation [7]. Tangent Young's modulus was determined according to the chart of Deere and Miller [20], and then the dynamic modulus of elasticity was calculated according to Al-Derdi and Al-Harthi's equation [7].

3. Results and discussion

3.1 Chemical Characteristics

The results of chemical analysis of the limestone samples are presented in Table1. The CaO content ranges from 42.32 to 54.89 % with an average value of 48.17 % (Table 1). The MgO content ranges from 0.51 to 7.23 % with a mean value of 3.70 %. A value of MgO greater than 1% in limestone suggests that the mineral dolomite is present [21].

The $CaCO_3$ content ranges between 75.33 and 97.70% and the $MgCO_3$ content ranges between 1.07 and 15.11 %. The SiO_2 content in the limestone samples ranges from 0.68 to 8.16 %. These values are comparable to those of similar limestone rocks elsewhere (Table 1). The relatively higher content of SiO_2 can be attributed to chert nodules resulting from the influx of near shore materials into the basin of deposition.

The concentration of Al_2O_3 is very low, less than 0.25 %. The concentration of Fe_2O_3 is also very low, at less than 0.06 %. Concentrations of Al_2O_3 and Fe_2O_3 are low and may be indicative of the absence of phyllosilicates (clay) in the limestone.

The concentration of the total alkalis (Na_2O+K_2O) in the limestone rocks in the studied area is very low, less than 0.34 %. This value is similar to the alkali content of typical limestone bodies in Pakistan [22] and Nigeria [23] (Table 1). Loss on ignition (LOI) ranges between 41.67 and 45.62 % (Table 1). It reflects the content of volatiles (CO_2, H_2O) present in the limestone rocks.

Table 1. Major element components of the limestone samples.

Site No.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	LOI	$CaCO_3$	$MgCO_3$
1	5.87	0.25	0.06	47.07	4.54	-	0.04	0.01	42.00	83.78	9.49
2	0.68	0.06	0.03	54.89	0.51	-	0.01	-	43.76	97.70	1.07
3	2.46	0.22	0.04	52.00	1.82	-	0.02	0.01	43.10	92.56	3.80
4	8.16	0.23	0.04	42.32	7.23	0.16	0.03	0.01	41.67	75.33	15.11
5	5.29	0.09	0.03	47.98	3.93	0.34	0.02	-	42.01	85.40	8.21
6	5.05	0.11	0.03	44.74	4.15	0.13	0.02	-	45.62	79.64	8.67
Min.	0.68	0.06	0.03	42.32	0.51	0.13	0.01	0.01	41.67	75.33	1.07
Max.	8.16	0.25	0.06	54.89	7.23	0.34	0.04	0.01	45.62	97.70	15.11
Ave.	**4.59**	**0.16**	**0.04**	**48.17**	**3.70**	**0.21**	**0.02**	**0.01**	**43.03**	**85.74**	**7.73**
Pakistan [22]	3.72	1.16	0.41	49.68	2.79	0.15	0.07	-	42.05	88.43	5.83
Nigeria [23]	3.71	1.10	1.78	50.20	0.85	0.01	0.05	0.07	41.70	89.36	1.78

3.2 Engineering Properties

Physical and mechanical characteristics of the limestone samples were determined, using procedures and specifications of ASTM, which are applicable in Yemeni geotechnical tests. The tests carried out include the water content, water absorption, dry density, saturated density, specific gravity, porosity, void ratio and UCS.

3.2.1 Physical Properties

A summary of the physical characteristics of the studied limestone compared to other limestone elsewhere is presented in Table 2.

3.2.1.1 Water Content

The water content of limestone is determined according to ASTM C97 [16]. From the laboratory results the water content by weight has a range of value of between 0.25 and 0.92 % with an average of 0.65 % (Table 2). These values are within the range for limestone in Portugal [24] (Table 3).

3.2.1.2 Water Absorption

The water absorption of limestone is determined according to ASTM C97 [16]. From the laboratory results the absorption by weight has a range of value between 0.73 and 4.12 % with an average of 2.38 % (Table 2). These values are within the range for limestone in Jordan [25] and Pakistan [26]. The values are however higher than those of limestone in Turkey [27] (Table 3).

The ASTM standard [28] on the use of limestone for dimension stone recommends a maximum water absorption of 3% for high density limestone, 7.5 % for medium density limestone and 12% for low density limestone. Limestone in southeast Ataq area has high density according to ASTM specifications [28] (Table 3).

Table 2. Results of the physical properties of southeast Ataq limestone.

Site No.	Water content (%)	Water absorption (%)	Dry density (gr/cm^3)	Saturated density (gr/cm^3)	Specific gravity	Porosity (%)
1	0.92	2.93	2.37	2.39	2.38	2.36
2	0.73	2.05	2.37	2.40	2.38	2.57
3	0.45	1.41	2.46	2.50	2.46	2.64
4	0.25	0.73	2.50	2.54	2.51	2.22
5	0.71	3.05	2.41	2.48	2.41	4.89
6	0.81	4.12	2.39	2.49	2.39	6.58
Min.	0.25	0.73	2.37	2.39	2.38	2.22
Max.	0.92	4.12	2.50	2.54	2.51	6.58
Ave.	**0.65**	**2.38**	**2.42**	**2.47**	**2.42**	**3.54**

3.2.1.3 Density

Rock density is a measure of mass of the rock contained in a given unit volume**.** The density of limestone is measured according to ASTM 97 [16]. Dry density values range between 2.37 and 2.50 gr/cm^3 with an average of 2.42 gr/cm^3, whereas saturated density values range between 2.39 and 2.54 gr/cm^3 with an average of 2.47 gr/cm^3 (Table 2). These values are lower than those of limestone in Pakistan [26], Portugal [24], Iran [29] and Turkey [27]. The values are however higher than those of limestone in Saudi Arabia [7] (Table 3).

Table 3. Comparison of the engineering properties of southeast Ataq limestone with other limestones.

Properties	This study	Pakistan [26]	Jordan [25]	Portugal [24]	Iran [29]	Turkey [27]	Saudi Arabia [7]	ASTM specification requirements for limestone for dimension stone	
Water content (%) (average)	0.25-0.92 (0.65)	-	-	0.39-0.95	-	-	-	< 3	[28]
Water absorption (%) (average)	0.73-4.12 (2.38)	0.50-6.54	2.62	-	-	0.02-0.10	-	HDL 3 MDL 7.5 LDL 12	
Dry density (gr/cm^3) (average)	2.37-2.50 (2.42)	2.56-2.89	-	2.60-2.64	2.31-2.70	2.63	2.16	HDL 2.56 MDL 2.16 LDL 1.76	
Specific gravity (average)	2.38-2.51 (2.42)	2.20-2.70	2.46-2.78	-	-	-	2.20	> 2.50	
Porosity (%) (average)	2.22-6.58 (3.54)	-	-	1.05-2.55	0.27-9.76	0.06-0.26	18.5		
UCS (MPa) (average)	70-140 (99)	44-58	44-79	43-99	33-95	54-110	32-39	HDL 55 MDL 28 LDL 12	[28]
Tensile strength (MPa) (average)	4.36-11.10 (7.63)	-	-	-	5.30-13.80	-	2.38-3.30	HDL 6.9 MDL 3.4 LDL 2.9	
Tangent Young's modulus (GPa) (average)	44.13-56.54 (48.73)	-	-	-	7.27-13.26	42-50	16.25-19.22		

Table 4. Classification scheme for porosity of rocks [31].

Classification	Porosity (%)
Compact	<1
A few pores	1–2.5
Slightly porous	2.5–5
Significantly porous	5–10
Many pores	10–20
A lot of pore space	>20

The standard specification of ASTM [28] on the use of limestone for dimension stone is put at minimum of 2.56 gr/cm^3 for high density limestone, 2.16 gr/cm^3 for medium density limestone and 1.76 gr/cm^3 for low density limestone. Limestone in southeast Ataq area has medium density of oven dried and saturated conditions (Table 2).

Generally, a higher density rock is probably harder, less porous and stronger. The density is important in calculating the weight of the rock in a wall constructional element.

3.2.1.4 Specific Gravity

Specific gravity values range between 2.38 and 2.51 with an average of 2.42 (Table 2). These values are within the range for limestone in Pakistan [26]. The values are, however. lower than those of limestone in Jordan [25]. The values are higher than those of limestone in Saudi Arabia [7] (Table 3).

The specific gravity is important in calculating the weight of the rock in a wall constructional element. The standard specification of ASTM [28] on the use of limestone for dimension stone is put at minimum of 2.50 (Table 3).

3.2.1.5 Porosity

Porosity is one of the most important physical properties that determines the mechanical characteristics of rock, such as strength and deformability [30].

Porosity is defined as being the ratio of the volume of void spaces within a rock to the total bulk volume of the rock. However, these spaces do allow for a little absorption of moisture and other liquids which can corrode or stain the limestone. Water and acid rain can affect the appearance of limestone and its durability. Limestone in the studied area has a porosity between 2.22 and 6.58 % with an average of 3.54 % (Table 2). These values are within the range for limestone in Portugal [24] and Iran [29]. The values are however higher than those of limestone in Turkey [27] (Table 3). The values are lower than those of limestone in Saudi Arabia [7] (Table 3).

Low porosity values make limestone suitable for various construction purposes. A low porosity of limestone gives it a low absorption value. A low absorption value in turn means that the rock has a high resistance to the disintegrating effect of frost.

Porosity has a direct and indirect effect on most of the physical properties of rocks, and is often considered an important rock parameter. An increasing porosity has an unfavorable influence on the weathering characteristics. Moos and Quervain [31] developed a classification scheme for porosity of rocks (Table 4). According to this classification, the studied limestone rated as ‘few pores’ to ‘slightly porous’ (except that from site No. 6 which rated as ‘significantly porous’) and the effect of weathering will be of little implication.

Limestone in southeast Ataq area has low porosity and medium density under oven dried and saturated conditions which indicate that it is a good quality strongly cemented and compacted rock unit.

3.2.2 Mechanical Properties

Compressive strength and tensile strength parameters are the widely used rock strength parameters for geotechnical analyses.

3.2.2.1 Compressive Strength

Strength is the ability of a material to resist deformation induced by external forces. The strength of a material is the amount of applied stress at failure [32]. The laboratory UCS is the standard strength parameter of intact rock material. Rock strength is a very important criterion for classification of rocks in order to optimize construction usage and surface and/or subsurface structure designs [33].

The main purpose of this test is to ensure that the limestone is capable of withstanding external forces and shocks that may occur during installation and transportation ASTM C170 [17]. Strength is crucial factor for the selection of rocks for building stones.

The required value for limestone according to ASTM is 55 MPa for high density limestone. From the laboratory results the samples showed a range of UCS values between 70 and 140 MPa (Table 6). These values are higher than those of limestone in Pakistan [26], Jordan [25], Portugal [24], Turkey [27], Iran [29] and Saudi Arabia [7] (Table 3) and meet the specification for use as construction stone and ornamental stone. The International Society of Rock Mechanics (ISRM) [34] classify rocks in the range of ‘extremely strong’ to ‘extremely weak’ depending on the compressive strength (Table 4). Limestone rocks in the studied area are strong to very strong according to ISRM [34].

3.2.2.2 Tensile Strength

Tensile strength describes the capacity of the rock to resist tensile stress. It is a key parameter for determining the load bearing capacity of rock, and is resistance to deformation or fracturing, during crushing, drilling, tunnel boring, and blasting, and is used to analyze the stability and serviceability of rock structures [35-37]. The tensile strength of rocks is much lower than the compression strength. There are direct and indirect methods for measurement of tensile strength. The indirect methods have been dominant in determining tensile strength of rocks due to their ease in sample preparation and testing procedure.

Modulus of rupture is a measure of the tensile strength induced by bending; it is highly affected by the stone's surface condition on the face that is in tension. The modulus of rupture of rock generally increases as the water absorption decreases for rocks of equal grain size. The samples tested had a modulus of rupture within a range of values of between 4.36 and 11.10 MPa (Table 6). These values are within the range for limestone in Iran [29] and meet the specification for use as construction stone and ornamental stone. The values are, however, higher than those of limestone in Saudi Arabia [7] (Table 3).

The ASTM standard [28] on the use of limestone for dimension stone recommends a minimum of 6.9 MPa for high density limestone, 3.4 MPa for medium density limestone and 2.9 MPa for low density limestone. Limestone in southeast Ataq area has medium to high density compared to ASTM standard [28].

Limestone with high tensile and compressive strengths indicates properties of absolute resilience and durability. On the basis of tensile strength all the samples of southeast Ataq limestone are acceptable or good.

3.2.2.3 Elastic Modulus

Elastic modulus is an important parameter to describe the stress and strain relationship [38]. The type L Schmidt Hammer may be used to estimate the UCS and modulus of elasticity. Deere and Miller [19] developed a chart for estimating the tangent Young's modulus (E) of the tested material. The E of the studied limestone ranged from 44.13±2 to 56.54±2 MPa with an average of 48.73±2 MPa (Table 6). These values are within the range of limestones in Turkey [27] and meet the specification for use as construction stone. The values are however higher than those of limestone in Iran [29] and Saudi Arabia [7] (Table 3).

According to Al-Derbi and Al-Harthi's equation [7] the dynamic modulus of elasticity of the studied limestone ranged between 55.59±2 and 70.37±2 MPa with an average of 61.07±2 MPa (Table 6). These values are higher than those of limestone in Saudi Arabia [7] (Table 3).

The modulus ratio (E/UCS) of the studied rocks was calculated and ranged between 404 and 802 with an average of 539 (Table 6). The modulus ratio is around 300 for most rocks and more than 500 for strong rocks [39]. Hence, the studied limestone is strong according to its modulus ratio [39].

Table 5. Engineering classification of intact rock on basis of strength [34].

Classification	UCS (MPa)
Extremely Strong	> 250
Very Strong	100 – 250
Strong	50 – 100
Medium Strong	25 – 50
Weak	5 – 25
Very Weak	1 – 5
Extremely Weak	< 1

Table 6. Results of the mechanical properties of southeast Ataq limestone.

Site No.	UCS (MPa)	Average corrected rebound No. of Schmidt Hammer	Tensile strength (MPa)	Static Young's modulus (Tangent) (GPa)	Dynamic modulus of elasticity (GPa)	Modulus ratio	Classification of strength depend on ISRM [34]
1	70	50	4.36	44.13±2	55.59±2	802	Strong
2	85	51	6.74	46.89±2	58.88±2	552	Strong
3	117	52	9.28	53.09±2	66.26±2	454	Very strong
4	140	53	11.10	56.54±2	70.37±2	404	Very strong
5	97	51	7.69	46.89±2	58.88±2	483	Strong
6	83	51	6.58	44.82±2	56.41±2	540	Strong
Min.	70	50	4.36	44.13±2	55.59±2	404	-
Max.	140	53	11.1	56.54±2	70.37±2	802	-
Ave.	98.6	51.33	7.63	48.73±2	61.07±2	539	-

4. Conclusion

Due to the wide occurrence, availability and low cost of limestones that pass the requirements stated by ASTM for building materials, they are widely used in the construction industry as building stone. The chemical, physical and mechanical characteristics of the southeast Ataq limestone have been investigated to highlight its potential uses in construction. The chemical data of the limestone show that the limestone is comprised dominantly of calcite with some dolomite and it has a low level of impurities. The studied physical and mechanical properties show that southeast Ataq limestone is of good quality compared with the ASTM requirements for building stone. An abundant quantity of the excellent quality limestone can be easily extracted. The net recovery may reach more than 90% of the actual quarry production.

With the increase in demand for dimension stone in various building construction projects ranging from outdoor sculpture through interior and exterior cladding to floor covering, etc., the exploitation of limestone for dimension stone production will make a huge contribution to the development and growth of the Yemeni economy, considering its good engineering properties as enumerated and discussed in this paper.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgment

We would like to thank anonymous reviewers for their valuable comments which helped to improve the manuscript.

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Received 12 September 2021
Accepted 30 October 2021