Dicle University
Journal of Engineering
https://dergipark.org.tr/tr/pub/dumf
duje.dicle.edu.tr

Research Article

Mechanical and microstructural properties of stone units in the masonry building stock of Urla peninsula

Uğur DEMİR[1*]

[1] İzmir Institute of Technology, Architecture Department, ugurdemir@iyte.edu.tr, Orcid No: 0000-0001-8319-2535

ARTICLE INFO

Article history:

Received 22 August 2024
Received in revised form 26 October 2024
Accepted 31 October 2024
Available online 23 December 2024

Keywords:

BET, limestone, masonry, sandstone, SEM

Doi: 10.24012/dumf.1537224

* Corresponding author

ABSTRACT

This experimental study focuses on two most commonly used stone types in masonry building stock in the Urla Peninsula of İzmir: sandstone and limestone. The compressive behavior of these stones, which is critical to the structural integrity of historic and contemporary stone masonry buildings in the region, was analyzed in detail. To assess their mechanical performance under compressive stress, uniaxial compressive loads were applied to the stone samples, which were gathered after an extensive field survey. Scanning Electron Microscopy (SEM) and Brunauer-Emmett-Teller (BET) analyses were employed to characterize their microstructure. SEM analysis provided detailed insights into the surface morphology and microstructural composition of the stones, revealing differences in grain size and bonding. BET analysis was used to determine the specific surface area and pore size distribution, which are key factors influencing the stones' mechanical strength and durability. The results demonstrated that limestone exhibits significantly superior mechanical properties under compressive stress compared to sandstone. Specifically, the denser and more homogeneous microstructure of limestone, characterized by smaller pores and fewer micro-cracks, contributes to its higher compressive strength. This was corroborated by BET analysis, which showed that limestone has a larger surface area and less porous structure, enhancing its load-bearing capacity. In contrast, sandstone, with its relatively higher porosity, displayed lower resistance to compressive forces, making it more susceptible to deformation and failure under axial loads. The study underscores the importance of microstructural characteristics in determining the mechanical performance of natural building materials.

Introduction

The masonry building stock of İzmir predominantly consists of structures built with locally available stone types, primarily limestone, and sandstone. These materials have been favored for their availability, workability, and durability, making them ideal for the city's traditional construction practices. Limestone and sandstone are often categorized and used based on their finish and size, typically classified as ashlar or rubble stone. Ashlar masonry refers to finely dressed stones with even surfaces, usually cut into rectangular shapes. This type of masonry is often used in more formal, monumental, or high-status buildings due to its aesthetic appeal and the precision required in its construction. In İzmir, ashlar limestone and sandstone are common in historic buildings, such as government structures, religious buildings, and affluent residences. The smooth, regular appearance of ashlar masonry provides not only visual appeal but also structural integrity due to the tight fit between stones. Rubble masonry, on the other hand, involves using irregularly shaped stones that are either minimally dressed or left in their natural state. This type of masonry is more commonly found in vernacular architecture, including rural homes, boundary walls, and utility structures. Rubble limestone and sandstone are prevalent in İzmir's traditional buildings, particularly in areas where quick and cost-effective construction methods were necessary. Despite the irregular shapes, rubble masonry can be highly durable, especially when skilled masons ensure good bonding and packing of the stones.

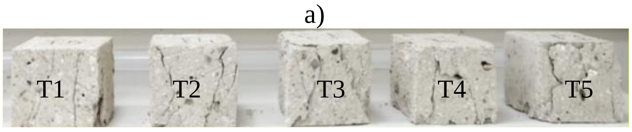
In response to the increasing seismic activities and associated losses observed recently around the Aegean Sea, the İzmir Metropolitan Municipality, authorized under the Provincial Risk Reduction Plans (IRAP), collaborated with Boğaziçi University to develop the İzmir Earthquake Master Plan (IEMP). Within the IEMP project framework, the focus was on estimating the structural damage and associated losses in buildings under the standard design earthquake (with a 10% probability of being exceeded in 50 years). In the scope of IEMP project, a comprehensive building inventory study was conducted with an aim for classifying buildings based on their structural characteristics, construction date, project and construction quality, and occupancy characteristics. According to the inventory study, a total of 217,824 buildings were investigated, involving 190,419 reinforced concrete buildings (87%), 23,362 stone masonry buildings (11%), and 4,043 buildings of other types (2%). Analyzing a pilot area in the city center under the IEMP project revealed that stone masonry structures constitute the most vulnerable ones within the building stock.

Although its usage has decreased in the last few decades with the emergence of new construction and techniques, stone is still widely utilized in many regions where it is abundant and alternative materials are not readily available. However, it is well-recognized that stone masonry structures predominantly constructed in rural areas using stone units (kayrak, andesite, granite, limestone, etc.) are highly vulnerable against earthquakes. Nevertheless, due to their high prevalence in the building stock, it seems economically unfeasible to demolish and rebuild all risky stone masonry structures. Therefore, an urgent comprehensive inventory study should be conducted on existing stone masonry structures, to classify them accordingly. Subsequently, risk prioritization activities should be carried out for each group, and relevant structures should be either demolished and rebuilt or strengthened. However, rich diversity in local materials and construction practices in stone masonry structures complicates implementation of this process, necessitating regional solutions. When the literature is mined, it is clearly observed that there are several studies reporting the properties of locally available stone units around İzmir [1-4]. Tunçoku et al. [5] classified rural structures in İzmir based on architectural features and identified stone masonry structures as one of the most commonly used types around İzmir. This study also mentioned that, in the rural building stock of İzmir, one to two-story stone masonry structures with different wall textures are frequently observed. Stones, such as neatly cut ashlar stones extracted for centuries from existing quarries in Balıklıova (Urla) and Alaçatı (Çeşme), are commonly used in the construction of stone masonry structures found in the narrow streets of the Urla peninsula. It is evident that the demand for these stones has increased due to their characteristics, such as not requiring plaster and whitewash applications. Biçer [6] characterized Alaçatı stone as a lightweight, porous sedimentary rock composed of volcanic ash, sand, and lava particles. The research pointed out the stone's limitations in structural applications due to its low compressive strength, high water absorption rate, and significantly higher abrasion rate when compared to other local stone types. Despite these weaknesses, the study proposed that the stone's low unit volume weight could make it an appealing option for use in earthquake-prone areas like İzmir. It should be noted that this claim is debatable, as the increase in axial stress on masonry walls does not necessarily deteriorate their seismic performance. Yavuz [7] also examined the durability of Alaçatı stone, reporting compressive strength, water absorption, and thermal conductivity values similar to that of Biçer [6]. In addition, in the studies by Milosevic et al. [8], Demir et al. [9], and Gönen and Soyöz [10], experiments were conducted under compressive loads, and the mechanical behaviors of stone masonry walls were experimentally obtained. When examining studies that investigate the behavior of masonry walls under compression, it is observed that the compressive strengths of stone units vary widely between 4 MPa and 160 MPa, the compressive strengths of walls can range between 1 MPa and 22 MPa, and the modulus of elasticity of the walls shows a distribution between 560 MPa and 7000 MPa. Upon reviewing studies within this broad spectrum, it is evident that the behavior of masonry structures under compressive effects varies significantly depending on the masonry unit, mortar, wall size, and number of layers. Therefore, it is crucial to consider these extensive local variations when determining the behavior of such structures. It is also noteworthy to mention that identifying the mechanical and microstructural properties of stone units forms the first step in order to understand the behavior of stone masonry structures under service and seismic loads. This study offers essential data on mechanical and microstructural behavior of locally available sandstone and limestone samples for consideration in design and structural performance assessment of existing vulnerable stone masonry buildings on Urla peninsula. According to the "Peninsula Sustainable Development Strategy" document prepared by the İzmir Development Agency [11], the Urla peninsula encompasses five of İzmir's thirty districts, namely Urla, Cesme, Karaburun, Guzelbahce, and Seferihisar, accounting for approximately 25% of the total area of the city [12]. Besides, in the last 20 years, İzmir has experienced 4 earthquakes with magnitudes of Mw=5.7 and above, all of which occurred in the Urla peninsula. This situation indicates the necessity and importance of the presented study. Moreover, despite the potential for severe casualties and economic losses in the stone masonry structures during a possible earthquake, there is a limited number of research on this topic for the Urla peninsula, particularly focusing on the relationship between the mechanical and microstructural properties of locally available stone units. As such, first, compressive behavior of different stone units gathered from the existing building stock was estimated under uniaxial compressive loads. At the second step, SEM analyses have been carried out for examination and analysis of micro and nanoparticle imaging characterization of the stone units. Finally, BET analyses were conducted for revealing specific surface areas and pore size distributions in stone units. Such a holistic approach, which has been performed for the first time to identify the characteristics of the locally available stone units in the investigated peninsula, has the potential to serve to eliminate the uncertainties on modelling the behavior of vulnerable stone masonry structures in the investigated region. The findings of the study may also aid the development of reliable risk mitigation strategies by serving to the inventory studies aligned with the current attempts within the region.

Mechanical and Microstructural Properties

As a part of an extensive field survey conducted in Urla peninsula, the most observed stone samples were taken with the aim of identifying their mechanical and microstructural properties. Compressive tests were conducted to determine the mechanical properties of the stone units. For these tests, the specimens were prepared in accordance with the ASTM C170M [13] standard. As per this standard, cross sectional dimensions of the rectangular prism specimens should be at least 50.8 mm and the height to width ratio should be at least one. Therefore, in the scope of this study, 100×100×100 mm cube samples were cut using a rotating saw from specimens gathered during the field survey. The specimens were kept under ambient conditions for about 2 weeks to ensure that they reached their natural water content prior to compressive tests. Besides, unit weights of the specimens were measured at three successive days until weight change due to the humidity variations has been stabilized. Unit weights of the limestone and sandstone specimens were measured to be around 2384 kg/m3 and 1789 kg/m3, respectively. Sandstone specimens were tested with a 250 kN capacity Schimadzu AG-I universal testing machine, whereas limestone samples were tested using a Utest compression press with a capacity of 3000 kN, since they necessitated a higher capacity. A total of 10 specimens were tested namely, five out of 10 specimens were sandstone whereas the remaining five were limestone. Displacement-controlled tests were performed for the purpose of uniaxial compressive loading of the specimens. The rate of loading should not exceed 690 kPa/s, but this requirement may be considered as being met if the speed of the loading head is not more than 1.3 mm/min. as per ASTM C170M [13]. Considering this phenomenon, a loading rate of 0.3 mm/min. was applied and kept constant during the uniaxial compressive tests. Figure 1 demonstrates the appearances and failure modes of the limestone and sandstone samples, respectively. Sandstone samples exhibited a relatively more ductile behavior which can be identified with a smooth descending branch in the stress-strain responses. On the other hand, limestone samples explosively failed corresponding to a considerably brittle response. This difference can be attributed to the alteration of the natures for the stone samples in terms of chemical and pore composition, which is investigated below in the present study. Axial stress - strain responses of the limestone and sandstone specimens are shown in Figures 2 and 3, respectively. In these figures, the stress was calculated as the ratio of the applied load to the initial cross-section area (100×100 mm^2) of the specimen, whereas the axial strains were calculated as the ratio of the average vertical deformation measured with the two LVDTs integrated within the test machine over a full gage length between the loading plates (along 100 mm height).

a)



b)

Fig. 1. Appearances of a) limestone, b) sandstone samples after compression tests.

Mechanical properties of limestone and sandstone units are summarized in Table 1. In this table, f_{c0} is the compressive strength, ε_{c0} is the compressive strain corresponding to the peak stress and E is the elastic modulus of the stone samples. Letters L and T stand for limestone and sandstone units of each series (i.e., L1 is the first limestone specimen), respectively, M is the median value, SD refers to the standard deviation and CoV is coefficient of variation (SD/M). It should be noted for Table 1 that properties of L5 sample were excluded from the calculations of compressive strength and elastic modulus of the limestone samples due to the problems encountered during the test of this specimen. As seen in Figs. 2- 3 and Table 1, limestone displayed a better behavior compared to sandstone in terms of encountered compressive strength. The average compressive strength, f_{c0}, calculated from the tests were 83.1 MPa and 11.2 MPa for limestone and sandstone samples, respectively. The modulus of elasticity, E, for the specimens are determined as the secant modulus in the range of 30% and 60% of the ultimate compressive strength in the ascending branch of the stress–strain diagram as indicated by Binda et al. [14]. The average values for the elastic modulus were calculated to be 7611 MPa and 696 MPa for the limestone and sandstone, respectively. Due to the lower axial stiffness of the sandstone samples, strain corresponding to the peak stress is remarkably larger for these samples with respect to the limestone units. This behavior led to a more ductile response for the sandstone samples. The high compressive strength makes limestone more suitable for load-bearing applications in construction, especially in historical and monumental structures. On the other hand, sandstone should be used in construction for decorative purposes or in areas where load bearing is less critical. The studies conducted after the 2023 Kahramanmaraş earthquakes also indicated that the stone masonry buildings with poor quality of materials exhibited a worse earthquake performance [15]

With an aim to better understand the reason behind the variation in the mechanical behavior, SEM analyses were used for high-resolution imaging and composition analysis by energy-dispersive X-ray microanalysis (EDS) on a FEI Quanta FEG 250 instrument present in Centre for Materials Research in İzmir Institute of Technology. Figures 4-9 show SEM results at 1000x, 2500x and 5000x magnification for the limestone and sandstone samples, respectively. The result of several SEM analyses through different portions of the grained stone powder indicated the presence of elements of Ca, C, and O, which are components of carbonate phases $CaCO_3$ (calcite) in the limestone samples, whereas the analysis of sandstone indicated silicon dioxide or quartz (SiO_2) formations as shown in Figures 10-11 via their EDS spectra at a selected point.

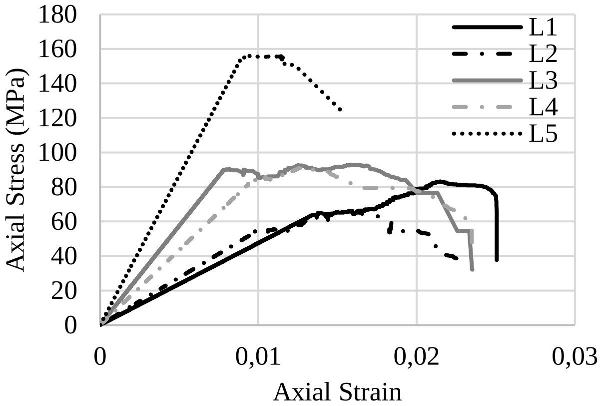


Fig. 2. Axial stress – strain response of the limestone samples.

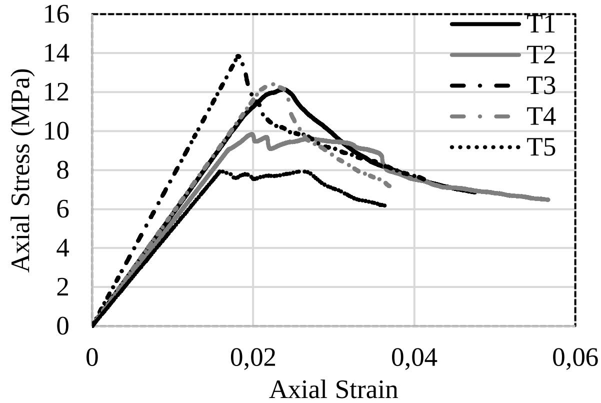


Fig. 3. Axial stress – strain response of the sandstone samples.

Table 1. Mechanical properties of stone units.

Type	f_{c0} (MPa)	ε_{c0}	E (MPa)
L1	82.9	0.022	4754
L2	65.7	0.016	5507
L3	92.5	0.016	11498
L4	91.1	0.013	8685
L5*	155.8	0.012	17337
M	83.1	0.016	7611
SD	10.7	0.004	2686
CoV	0.13	0.25	0.35
T1	12.1	0.024	575
T2	9.6	0.026	688
T3	13.8	0.018	947
T4	12.4	0.023	586
T5	7.9	0.026	684
M	11.2	0.023	696
SD	2.4	0.003	134
CoV	0.21	0.13	0.19

* The properties of L5 specimen were not considered in the calculations.

In addition, weight and atomic percentages of the elements for limestone and sandstone samples obtained from the EDS microanalysis are shown in Tables 2-3, respectively. Figs. 4-9 show that the microstructure of the limestone samples appears to be compact and very tightly knit compared to sandstone. The homogeneity of limestone's microstructure contributes to its higher compressive strength and durability compared to sandstone. On the other hand, as seen in Figs. 7-9, the presence of the pores in sandstone samples resulted in a more porous microstructure with respect to the limestone. The porous nature of sandstone led to a lower compressive strength. The cementing material between the grains can significantly affect sandstone's mechanical properties. A weaker cement results in more voids and cracks, leading to lower strength. The presence of pores also enabled material to deform more remarkably under compressive stress, resulting in higher compressive strain but lower stiffness. These gaps in the microstructure also allowed the sandstone samples to absorb some of the stress through deformation, which spreads the load over time and reduces the exhibited peak strength. On the other hand, the homogeneous structure of limestone, with fewer gaps, results in higher axial stiffness (Fig. 2). This behavior indicated that limestone could resist greater stress without deforming as much as sandstone, leading to a higher peak compressive strength. However, this also means that limestone fails at lower compressive strain, as the material is less capable of absorbing stress through deformation. As a result, the SEM analyses effectively illustrated why limestone, with its more compact and uniform structure, exhibits higher compressive strength and lower strain, whereas sandstone's more porous structure results in the opposite behavior. The presence of microcracks in limestone samples is less prominent compared to sandstone, indicating better overall structural integrity. This bond between the microstructure and the mechanical properties is crucial in understanding how these materials will perform in different structural applications.

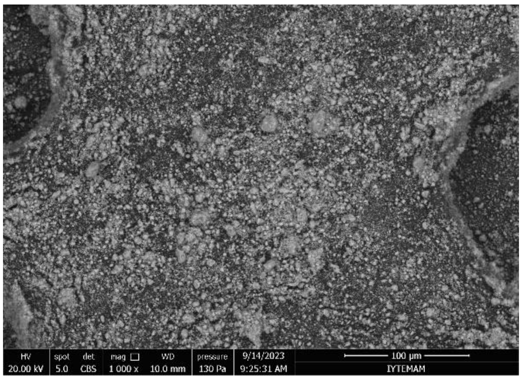


Fig. 4. Limestone after 1000x magnification.

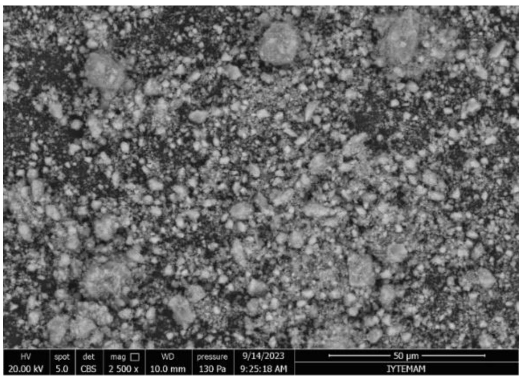


Fig. 5. Limestone after 2500x magnification.

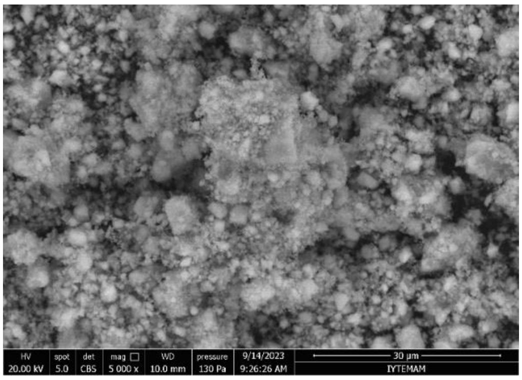


Fig. 6. Limestone after 5000x magnification.

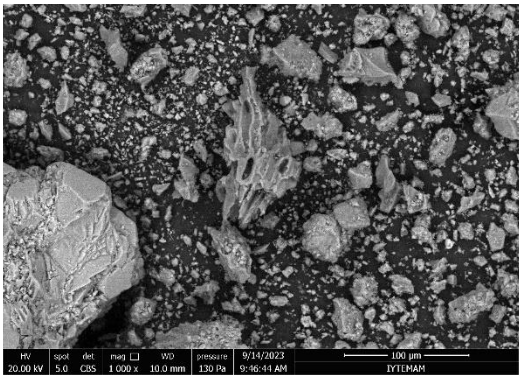


Fig. 7. Sandstone after 1000x magnification.

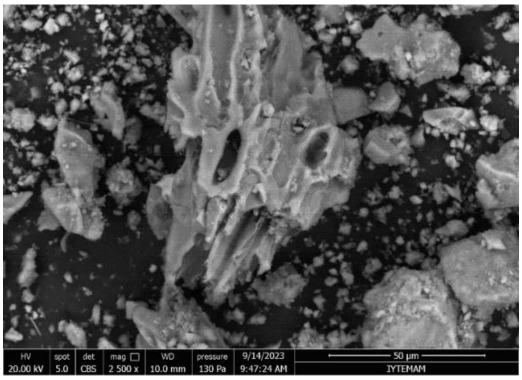


Fig. 8. Sandstone after 2500x magnification.

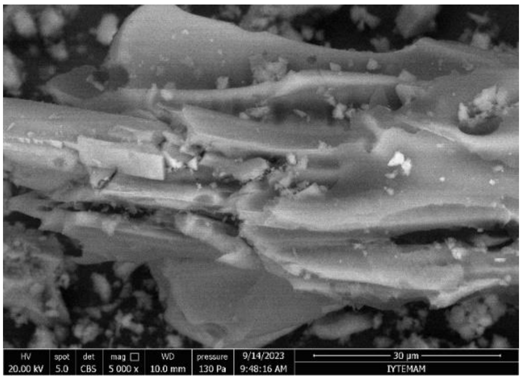


Fig. 9. Sandstone after 5000x magnification.

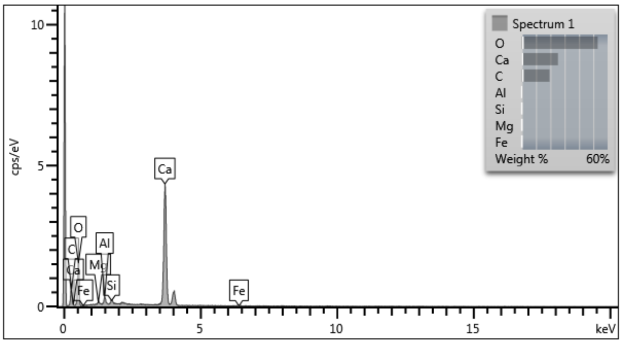


Fig. 10. EDS spectra of limestone.

Table 2. Weight and atomic percentages of the elements in limestone samples.

Element	Weight (%)	Atomic (%)
O	53.06	58.79
Ca	25.35	11.21
C	19.45	28.71
Al	0.87	0.57
Si	0.49	0.31
Mg	0.40	0.29
Fe	0.38	0.12

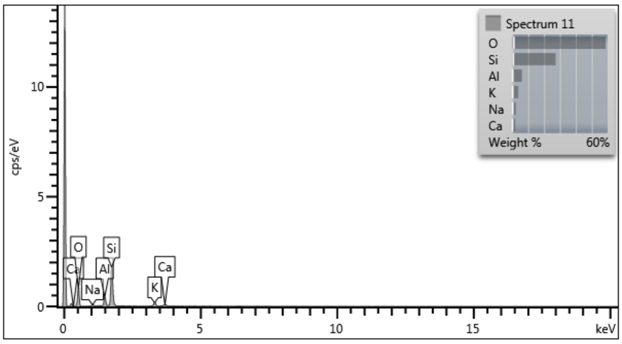
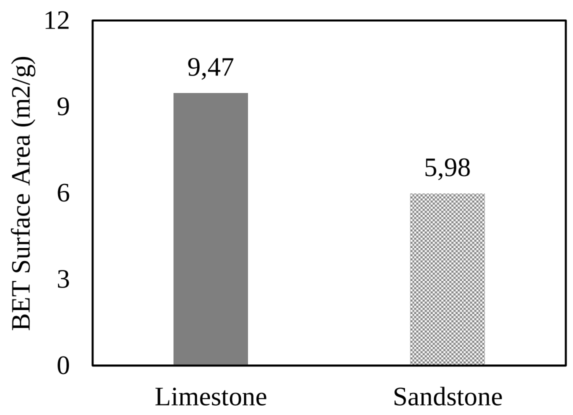


Fig. 11. EDS spectra of sandstone.

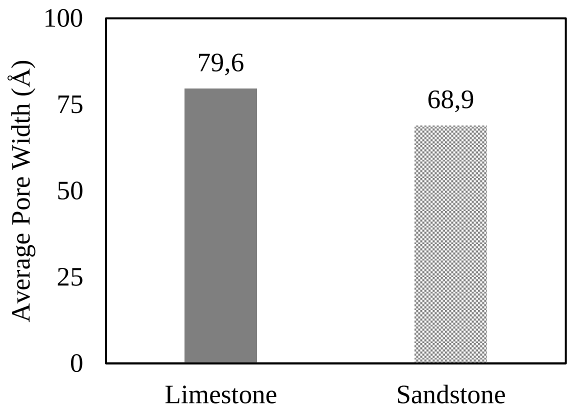
Table 3. Weight and atomic percentages of the elements in sandstone samples.

Element	Weight (%)	Atomic (%)
O	58.77	71.88
Si	27.34	19.05
Al	6.07	4.41
K	3.77	1.89
Na	2.22	1.89
Ca	1.83	0.89

Performing BET (Brunauer-Emmett-Teller) analyses on limestone and sandstone samples would provide valuable insights into the surface area and pore structure of the materials, which could further correlate with SEM observations and compressive responses of the samples. Therefore, enriched by BET analysis, variation in crystal morphology of the stone samples can be understood more clearly. Figure 12 shows the variations in BET surface area and average pore width between limestone and sandstone samples. As seen in Fig. 12a, specific surface areas for the limestone and sandstone samples are 9.47 and 5.98 m^2/g, respectively. Based on BET analyses, Fig 12b shows that a similar trend was observed in the average pore widths such that limestone and sandstone samples had 79.6 Å and 68.9 Å of average pore width, respectively. When the BET surface areas and average pore widths are compared, it was observed that these values tend to decrease with increasing porosity, which was observed in SEM analyses in the stone samples as well (Figs. 4-9, 12). In other words, the particles having smaller pores also may have a larger specific surface area and average pore width as stated in the literature [16]. A1though these relationships are not well defined due to a limited number of analyses conducted within the scope of the present study, a trend may exist that warrants further investigation.



a)



b)

Fig. 12. Results of BET analyses a) BET surface areas, b) average pore width.

Conclusions

In the scope of the study, mechanical and microstructural properties of stone units in the masonry building stock of Urla peninsula was investigated. In the light of the experimental results, the following conclusions can be drawn.

1. Limestone units exhibited a better compressive behavior in terms of encountered compressive strength, but in a quite brittle failure mode with respect to sandstone samples. Due to the lower axial stiffness of the sandstone samples, strain corresponding to the peak stress is remarkably larger for these samples with respect to the limestone units. This behavior led to a more ductile response for the sandstone samples. The average compressive strengths were 83.1 MPa and 11.2 MPa for limestone and sandstone samples, respectively, pointing out the significant difference of the units under compression.

2. SEM analyses indicated that the microstructure of the limestone samples was compact and tightly knit compared to sandstone, whereas the presence of the large pores in sandstone samples resulted in a more porous microstructure. This behavior led to a lower compressive strength for the sandstone samples as well as enabled sandstone samples to deform more remarkably under compressive stress, resulting in higher compressive strain but lower stiffness. Besides, BET analyses showed that BET surface areas and average pore widths tend to decrease with increasing porosity.

3. Superior compressive behavior makes limestone more suitable for load-bearing applications in construction, especially in historical and monumental structures, whereas sandstone should be used in construction for decorative purposes or in areas where load bearing is less critical.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article to be prepared.

There is no conflict of interest with any person / institution in the article prepared.

Acknowledgement

The help of Elif Naz Çelik and staff of Integrated Research Centers (Tümleşik Araştırma Merkezleri, TAM) in İzmir Institute of Technology, particularly Dr. Şeyda Horzum Şahin, Mutlu Devran Yaman and Burcu Akdağ Çağlar, is gratefully acknowledged.

References

[1] M. Y. Çelik, “Characterization of İscehisar Andesite (Afyonkarahisar-Turkey), Used as a Building Stone Source of Historical Heritages from Ancient Times to the Present”. *Geoheritage*, *16*(3), 1-19, 2024.

[2] A. B. Yavuz, N. Turk, & M. Y. Koca, “Material properties of the Menderes massif marbles from SW Turkey”. *Engineering geology*, *82*(2), 91-106, 2005.

[3] E. Teomete, E. Aktaş, “Structural analyses and assessment of historical Kamanlı Mosque in Izmir,

Turkey". *Journal of Performance of Constructed Facilities*, 24(4), 353-364, 2010.

[4] E. T. Uzun, I. Gucu, T. Arslan, & S. O. Kalkan, "Retrofitting of masonry structures considering the architectural perspective: A case study in Foca, Izmir". In *IOP Conference Series: Materials Science and Engineering* (Vol. 471, No. 2, p. 022003). IOP Publishing, 2019.

[5] S. S. Tuncoku, U. Incekose, T. Akis, M. A. Yalcin, "Assessment of construction techniques and material usage in İzmir rural houses". *International Journal of Architectural Heritage*, 9(8), 1005–1022, 2015.

[6] A. Biçer, "The thermal and mechanical properties of building stones from the Afyon, Izmir, Muğla and Denizli region". *Naturengs*, 3(1), 1, 2022.

[7] A. B. Yavuz, "Durability assessment of the Alaçatı tuff (Izmir) in western Turkey". *Environmental Earth Sciences*, 67(7), 1909–1925, 2012.

[8] J. Milosevic, A. S. Gago, M. Lopes, & R. Bento, "Experimental assessment of shear strength parameters on rubble stone masonry specimens". *Construction and Building Materials*, 47, 1372-1380, 2013.

[9] C. Demir, & A. Ilki, "Characterization of the materials used in the multi-leaf masonry walls of monumental structures in Istanbul, Turkey". *Construction and Building Materials*, 64, 398-413, 2014.

[10] S. Gonen and S. Soyoz, "Investigations on the elasticity modulus of stone masonry", *Structures*, 30, 378-389, 2021.

[11] URL: www.izka.org.tr, accessed on 22/08/2024.

[12] M. Emiroğlu, "Urla yarımadasında nüfusun gelişmesi". *Ankara Üniversitesi Dil ve Tarih-Coğrafya Fakültesi Dergisi*, 32(1-2), 237-267, 1988 (In Turkish).

[13] ASTM C170M-17, "Standard test method for compressive strength of dimension stone". ASTM International, West Conshohocken, PA, 2017.

[14] L. Binda, J. Pina Henriques, A. Anzani, A. Fontana and P. B. Lourenço, "A contribution for the understanding of load-transfer mechanisms in multi-leaf masonry walls: Testing and modelling", *Engineering Structures*, 28, 1132-1148, 2006.

[15] B. Bozyigit, A. Ozdemir, K. Donmez, K. D. Dalgic, E. Durgut, C. Yesilyurt, … & S. Acikgoz, "Damage to monumental masonry buildings in Hatay and Osmaniye following the 2023 Turkey earthquake sequence: The role of wall geometry, construction quality, and material properties" *Earthquake Spectra*, 87552930241247031, 2024.

[16] D. Benavente, M. G. Del Cura, R. Fort & S. Ordóñez, "Durability estimation of porous building stones from pore structure and strength", *Engineering Geology*, *74*(1), 113-127, 2004.