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ORIGINAL ARTICLE

Geomechanical, durability–hygrothermal and thermal shock properties of Kocaeli Kandira stone used as building stone in historical structures

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Abstract

This study investigated the mineralogical, chemical, physical, mechanical, durability–hygrothermal, thermal shock properties, and economic aspects of the Kandira stone, one of the well-known natural building stones, commonly used in many historical structures in the Marmara and Thrace regions. Especially, it has been preferred to Malta stone in historical structures in Istanbul due to economic reasons at the beginning of the 1900s. A similar appearance and lithology with Malta stone and closeness of the Kandıra stone to İstanbul made it attractive to be used as natural building stone in historical monuments and new structures. The mean physico-mechanical properties of Kandira stone yielded 2.24 g/cm^3 apparent density, 2.72 specific gravity, 19.21% total porosity, 5.8% water absorption by weight, 48 MPa compressive strength, 11.4 MPa bending strength. In terms of durability properties, Kandira stone has high resistance to aging by CaCl salt mist and no or low resistance to SO_2 aging in a humid environment. Also, the freeze–thaw test of Kandira stone yielded an exceptionally low mass loss (0.11%) indicating that the stone is resistant to freeze–thaw effect. Thermal shock tests indicated that Kandira stone is mainly resistant to thermal shock cycles. Economically, the calculated probable reserve of Kandira stone resulted in 40.8×10^6 tons of material and the potential economic value based on the probable reserve is calculated around 54.672×10^9 TL (approximately €7.2B). In conclusion, this study defined the petrographic, geomechanical, durability–hygrothermal and thermal shock properties essential for the use of Kandira stone as building stone and restoration material.

Keywords Kandira stone · Building stone · Limestone · Historical structures

Introduction

Natural building stones have been used in various areas for many years from the early ages to the present. The main natural stone types are available in various colors and patterns. Serpentine, diorite, syenite, granite, basalt, andesite, marble, sandstone, conglomerate, breccia, and carbonate rocks are the most common lithologies used as building stone. Natural building stones are one of the oldest building materials used by humans. Numerous monuments are made of natural stones in Anatolia, especially in the Ancient Greek, Roman, Byzantine, Seljuk and Ottoman periods. Limestones and tuffs are commonly used building materials in Seljuk and Ottoman architecture (Celik 2003). In addition to being used as building stones in buildings, they are also used for decorative purposes. Natural stones, which are preferred in many areas have an important place in landscape and architecture. One of them is the Kandira stone, which has been used in many historical structures in the Marmara and

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Thrace regions. In particular, the Kandıra stone has been preferred to Malta stone used widely in historical structures in Istanbul due to economic and durability reasons at the beginning of the 1900s. The most known usage areas of the Malta stone in Istanbul are the walls of Dolmabahce palace as facing stone (Dal et al. 2007) and in the whole structure of the Crimean Church located in the Beyoglu-Taksim district (Ellul 2010). A similar appearance and lithology with Malta stone and closeness of the Kandıra stone to Istanbul made it attractive to be used as a natural building stone in historical monuments and new structures. In addition, Kandira stone was used in the walls of Corlu (Tekirdag) Suleymaniye Mosque built in 1521 and in Fatih (Istanbul) Mosque built in 1453 and was preferred for the restoration of some historical monuments in Istanbul (Aydın İpekci and Aydın 2017). Additionally, natural stones have wide use in landscaping, especially for flooring, borders, covering material, decorative elements such as statues, vases, and water elements such as fountains and pools. Natural stones commonly used in landscape architecture work in historical gardens (palaces, pavilions etc.) in Istanbul are limestone, marble, sandstone, granite, travertine, Kandira stone, slate and pebbles. The aforementioned natural stones were mainly cut and processed, and sometimes used as they were mined from the quarry (Uğuryol 2020).

Several previous studies investigated the usage areas and properties of carbonate rocks used as natural building stones. National-wide previous studies include studies related to Kandira stone and other stones used as building stones in different parts of Turkey. Arman et al. (2007) have reported that the Kandira stone widely used as a building stone in the northwest part of Turkey included approximately 91% $CaCO_3$ and 9% clay minerals and investigated the mechanical and physical properties of the Kandira stone. Yagiz (2009) has examined the usability of the dolomitic limestone member of Bascesme formation outcropped between Bascesme and Yenibaglar located in the northeast of Denizli. For this study, geomechanical tests such as dry and saturated unit weights, effective porosity, uniaxial compressive strength, water absorption by weight, Schmidt hammer hardness value, P-wave velocity and slake durability index tests were conducted. As a result of the tests, it was concluded that dolomitic limestones are not suitable for use as building stone since they have dense cracks and veins. Arman et al. (2010) have explained that Kandira stone is used as a cladding material for the restoration of sidewalk, roads and historical buildings, backyard walls and other landscape arrangements in the study of the importance of the geological and geotechnical properties of Kandira stone. It is mentioned that Kandira stone does not transmit heat easily and it is preferred for decorative fireplaces. For such applications, the importance of knowing the geological and geotechnical properties was emphasized, the geological and some geotechnical properties of the Kandira stone were introduced and the importance of these properties in civil engineering applications was discussed. Bozkurtoglu and Mert (2012) have investigated the relationship between strength and durability, the rock change value (RCV), the physical and mechanical properties of Kandira stone. For this study, the physical values of the samples were determined, and slake durability tests were conducted. As a result of the study, the wearing behavior of Kandira stone carbonate cemented sandstone–micritic limestone, which has moderate to high porosity values, was characterized by the slake durability test and the average wearing values were determined to be between 2.99 and 7.04%. Ozkan (2018) has investigated the usability of limestones in Unlupınar (Kelkit-Gumushane) region as a natural building stone, the usability of limestones in Bergama formation belonging to Unlupınar region of Gumushane province and their suitability to TS-ASTM standards. Physico-mechanical laboratory tests were performed, and the results of the laboratory tests were compared with the standard limit values in the study. Selim et al. (2019) have studied the geological and geomechanical properties of the Lefke stone in Osmaneli (Bilecik) and its use as building stone. For this purpose, field and laboratory studies have been conducted to determine geological features and geomechanical properties. Lefke stone was defined as suitable for using as building stone based on its physical, mechanical, durability, and hygrothermal properties.

Global-scale previous studies include studies related to sedimentary rocks used as building stones in different parts of the world. Bell (1993) has investigated the conservation of carbonate rocks as building stone, and environmental impacts on building stones such as freeze–thaw, atmospheric pollution, salt crystallization, and acid deposition on the rocks. Blows et al. (2003) have conducted a preliminary study on Caen Stone on the use, decomposition and repair stone in the old buildings in England and explained the lithology of Caen Stone, different weathering properties of stones in similar weathering environment to eliminate differences in stone artisan ship. Gatt (2006) has investigated the modeling of weathering and damage in the Maltase masonry walls constructed with the Malta Globigerina Limestone by considering its sedimentological and geotechnical properties. Rothert et al. (2007) have investigated the historical building stone of Maltese Globigerina Limestone along with its geologic and physico-mechanical properties and weathering induced by salt crystallization. Taghipour et al. (2016) have looked into the engineering properties and durability of two limestones (Dariyan and Ilam limestones) used in the Persepolis complex, Iran, against acid solutions. The samples taken from the ancient quarries were inspected for petrography, physical, mechanical, and durability properties. It was concluded that lower strength and durability properties of the Dariyan limestone are the main reasons causing

its higher wearing in the monument than Ilam limestone. Kock et al. (2017) have studied the heterogeneity of rock texture and its effect on the petro-physical properties of a sandy limestone named Lede stone quarried in Balegem as building stone. The importance of the Lede limestone as a historical stone in Belgium was explained. The pore and petro-physical properties of the rocks in Balegem are characterized in detail, and it was concluded that these properties can be referenced during the restoration and replacement of Lede stone.

Török and Přikryl (2010) have discussed the current methods and future trends in testing, durability analyses and origin studies of natural stones used in historical monuments and summarized the techniques available in situ and laboratory testing of natural stones used in historical monuments by combining the results of previous studies. The study explaining the physical and mechanical properties of dimension stones in terms of water absorption, thermal conductivity and expansion, hygric and hydric properties, strength, abrasion, the more modern aspect of breaking load at the dowel hole, and ultrasonic wave velocities by Siegesmund and Dürrast (2011) can be used as a basic reference in natural building stone studies. Additionally, some studies have concentrated on the thermal properties of building stones. For example, Hajpa´l and Török (2004) have investigated the mineralogical and color changes of quartz sandstones under the influence of heat. Another study by Siegesmund et al. (2000) researched the physical weathering of marbles caused by anisotropic thermal expansion.

This study mainly investigated the geomechanical, durability–hygrothermal, and thermal shock properties of the Kandira stone used as building stone in historical structures and the economic aspects of the Kandira stone. Field and laboratory studies were run to acquire the required information and data for evaluation of Kandira stone used as building stone. Studies have revealed that the usage areas of the stone should be paid attention based on its engineering properties. The large reserves and easy workability of the stone made it attractive in terms of economic aspects, but the interest to the stone has been decreasing for a long time.

Study area setting

The study area is located between the Akcaoava and Cercili villages in the central part of the Kandira district of Kocaeli province in the Marmara Region. Kandira has coasts in the Black Sea and its surface area is 933 km^2 (https://www.Kandira.bel.tr/). Kandira is surrounded by Agva-Istanbul in the west, by Kaynarca-Sakarya in the east, by the Black Sea in the north, by the central district of İzmit (Kocaeli) in the south. The study area is located on the 1/25,000 scale F23c3 and F24d4 geology sheets and has an area of approximately 5 km^2. The study area covers the area between Akcaova and Cercili villages where the Kandira stone outcrops. The topography of the study area is morphologically consistent with the morphology of Kocaeli peneplain. The study area is located in the northern part of Kocaeli and close to the provinces of Istanbul and Sakarya. For this reason, natural building stone products obtained from Kandira stones can be delivered to their usage areas in a short time after they are produced. In addition to the features of the stones removed, the transportation advantage played an important role in the preference of the quarries in the region. Kahraman and Arıkan (2016) indicated that the extracted stones were transported by sea and quarries were close to the piers where the loading made has become a geographical feature that provided an advantage to Kandıra and its surroundings. Recently, the road network is commonly used in the region for stone transportation. Figure 1 shows the location map of the study area.

Geological setting

Kandira, which is one of the counties of Kocaeli province, is located on the middle-north side of the Kocaeli Peninsula. In the Kocaeli Peninsula, Paleozoic (Ordovician–Early Carboniferous), Permo-Triassic (Late–Early Norian), Late Cretaceous–Middle Eocene, Late Oligocene–Early Miocene, Pliocene and Quaternary, sedimentary rocks and Permian, Permo-Triassic and Late Cretaceous igneous (plutonic and volcanic) rocks outcrop on the Kocaeli Peninsula, in different places (Coruk et al. 2011; Gedik et al. 2005). The geology of the Kandira region consists of Trakya Formation (Ct), Izmit Formation (TRi), Peksimet Formation (Kp), Cretaceous volcanics (Kv), Akveren Formation (KTa), Korucu Formation (Tk), terrestrial deposits (Tb-Belgrad Formation, Tac-Acısu Formation) and alluvium. Trakya Formation contains Lower Carboniferous brown, yellow sandstones, and dark gray shales and is located on the Lower Triassic Izmit Formation (TRi) seen in the south of the region and consists of red conglomerate, sandstones and mudstones. The Upper Cretaceous Peksimet (Kp) Formation overlays the İzmit Formation located in the northwest of the region and consists of sandstones, conglomerates and mudstones. The Cretaceous volcanics (Kv) of basalts and andesites cover the sedimentary units in the region. It is located in the northeast of the region. Upper Cretaceous–Paleocene Akveren Formation (KTa) overlies the Peksimet Formation. It consists of white, beige and pink colored, thin-medium bedded, micritic and clayey limestone, calcarenite, marl and greenish gray–green colored shales. The Akveren Formation is overlain by the Paleocene–Eocene Korucu Formation (Tk). Sandstone, claystone, and marl lithologies in the formation show an alternating structure. The Korucu Formation is stratigraphically

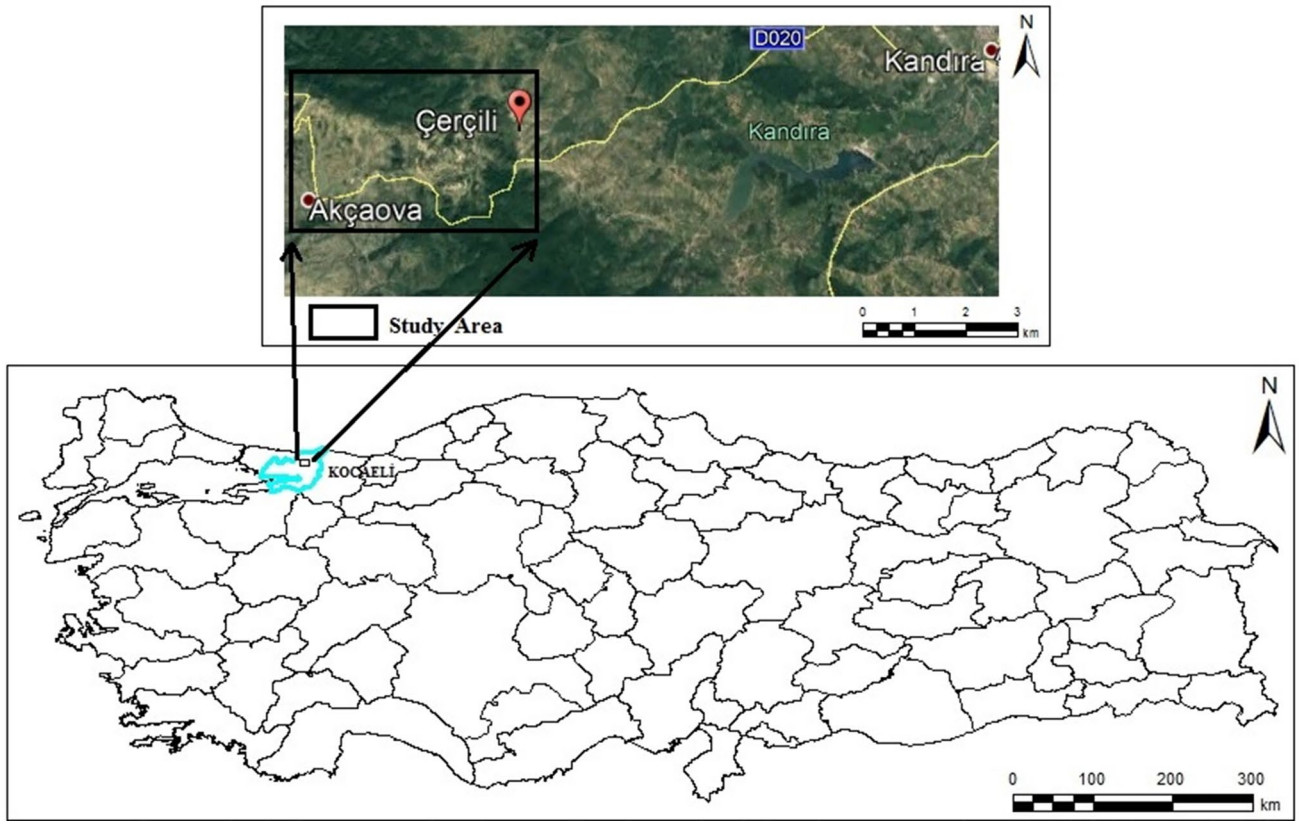


Fig. 1 Location map of the study area

overlain by the terrestrial Belgrad and Acısu Formations. The youngest unit in the region is the alluvium (Qal) consisting of silt, sand and gravel materials. Figure 2 shows the geology of the Kandira region and the study area.

A well-known natural building stone widely used in the Marmara region is the Kandira stone. This stone is located in the Akveren Formation in the Kandira region and has different lithological descriptions (Arman et al. 2007; Aydındag and Erkanol 2011; Bozkurtoglu and Mert 2012;

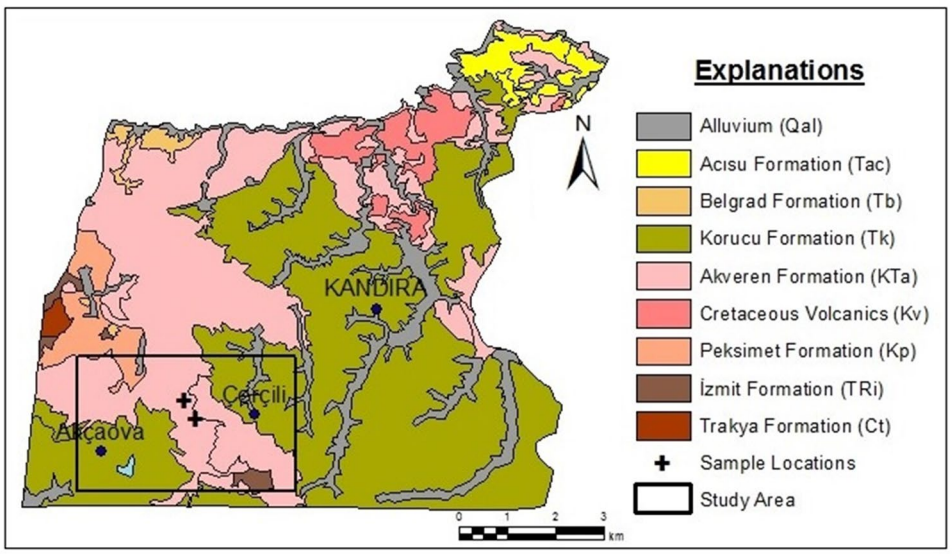


Fig. 2 Geology map of the Kandira region and study area (Coruk et al. 2001)

Moralı 2019). The trade name of the yellowish gray-beige limestone levels of the Akveren formation is called Kandira stone in the literature and commercial stone market. The Kandira stone outcrops are seen between Akcaova and Cercili villages of Kandira (Fig. 2). During the fieldwork, it was defined that Kandira stone falls into the medium strong-strong rock classes according to simple field identification of compressive strength table defined by ISRM (1981). The Kandira stone is mainly sound in fresh outcrops (Fig. 3), but in some locations, the weathering degree of Kandira stone is observed from slight to moderate (Moralı 2019). The uses of Kandıra stone in historical monuments and old structures are shown in Fig. 4.

Materials and methods

Materials of the study are the Kandira stone outcrops extending from Akcaova to Cercili areas. Kandira stone is the main material source of the study which was investigated in the field and tested in the material laboratory. The limestone samples used in this study were obtained from one of the quarries located between Akçaova and Çerçili east of Kandira from two locations that best represent lithology. During the field trips, in two locations, several Kandira stone blocks were removed from the outcrops and transferred to a marble-cutting workshop where the samples were cut to a specific geometry required by the standards. The studies were conducted in three stages: the desk study, fieldwork and laboratory tests. Previous studies, maps and reports were compiled in the desk studies. Field work consisted of recognition the geological formations and units, the detailed geological examination of the Kandira stone levels of the Akveren Formation and taking block samples in the study area and preparation of samples for laboratory tests. In the laboratory studies, mineralogical, physical, chemical, mechanical, durability–hygrothermal, and thermal shock tests were performed in accordance with the purpose of the study. These tests were carried out by an accredited natural stone assessment laboratory of AKU-NSL (Afyon Kocatepe University-Natural Stone Laboratory) and rock mechanics laboratory of the geological engineering department at Kocaeli University in accordance with the TS EN and ASTM standards. The results of the tests obtained for the properties were compared with the limit values defined in the building stone standards. Material characterization of Kandira stone as building stone was achieved based on the fieldwork and laboratory test results of the physical, mechanic, chemical, and durability–hygrothermal properties and thermal shock effects.

Results

Mineralogy

Mineralogy studies included macroscopic and microscopic evaluations of samples of the Kandira stone. These studies presented the macro- and micro-characteristics of the samples. Handheld samples were used for macroscopic evaluations, while thin sections produced from block samples were used in the microscopic examination. Mineralogy of



Fig. 3 Outcrop views of the Kandıra stone in the field (Moralı 2019)

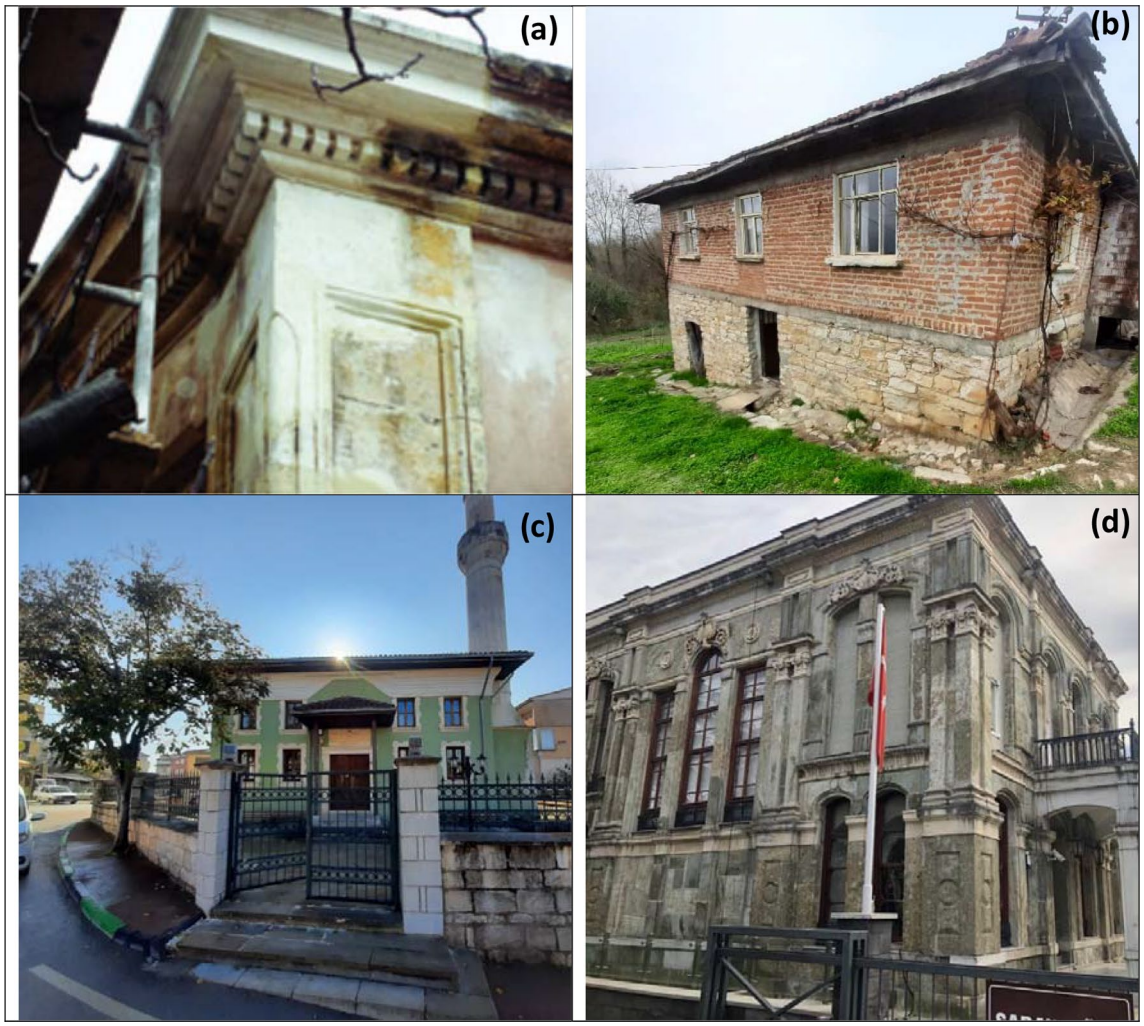


Fig. 4 Uses of Kandira stone in monuments and old structures; **a** in the Restoration of Istanbul Cendere-Hamidiye Pump Station completed in 1902, **b** as block stone in the lower part of the old masonry brick house in Kandira Center, **c** in the restoration of the Kandıra Orhan Mosque in 1887, **d** in the facing of Izmit hunting lodge built in 1873

the Kandira stone has been revealed to define the mineral contents, types, sizes, ratios, and microstructures of the samples needed for the characterization of the rock material.

Macroscopic examination

The macroscopic definition of rocks is based on the origin, color, texture, grain size, cracks, pore, and macrofossil factors. In the macroscopic identification of the Kandira stone, the origin was found to be sedimentary with yellowish gray-beige color, microcrystalline texture, and fine grain size. No cracks, pores, and macrofossils were observed in the hand-held samples.

Microscopic examination

During the microscopic identification of rocks, minerals, and fracture systems in rocks are examined based on TS EN 12407 (2013). As a result of the thin section analyzes, 97% calcite, and less than 3% opaque minerals were observed in Kandira stone. Grain sizes of calcite mineral are minimum 1.9 µm, maximum 6.2 µm, and average 3.82 µm. No fracture and crack systems were observed in the sections. Figure 5 shows the thin section views of Kandira stone and its minerals. According to the examinations on thin sections prepared from four samples taken from different locations, Kandira stone's main mineral was determined as calcite. Cement (ortochem) is 40% microcrystalline (< 4 µm) in size, and 55–58% clasts are silts and fine sands. The samples contain 2–5% pores. Clasts are composed of carbonate clasts (intraclasts) and fossil clasts (bioclasts). According to

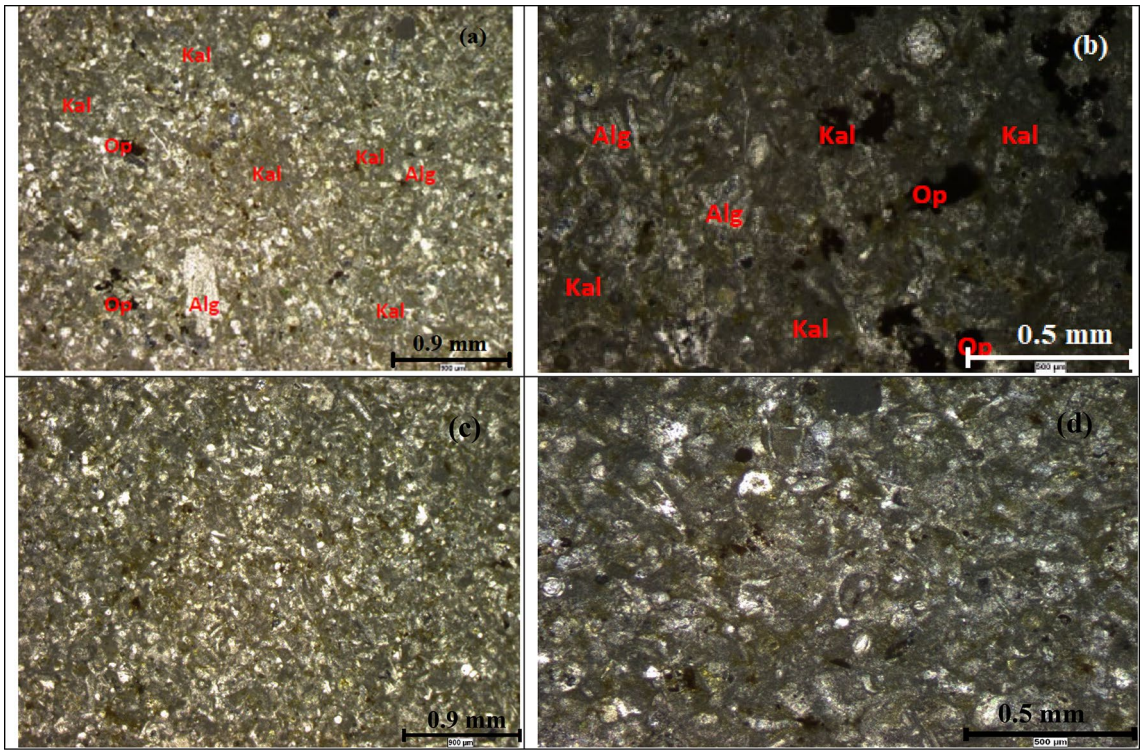


Fig. 5 Microscopic images of four different samples of the Kandira stone [*Kal* calcite, *Alg* algae, *Op* opaque minerals in the rock (double nicol-left (**a**), right (**b**), (**c**) intrabiomicrite, (**d**) biointramicrite)]

the Folk (1968) classification, the samples were named as "Intrabiomicrite–Biointramicrite." Fossil clasts are mainly composed of algae and to a lesser extent crinoid and crinoid stem clasts or fragments. The carbonate clasts are slightly rounded with fine sand and silt sizes.

Chemical composition

To determine the chemical composition of the rock, a chemical analysis was performed in the laboratory. For the identification of the chemical composition, chemical analysis by the XRF method (TS EN 15309 2008) was performed. The chemical analysis results of the Kandira stone are given in Table 1. The XRF chemical analysis of Kandira stone yielded 57.3473% of major and minor compounds and 42.6527% loss on ignition (LOI). The largest chemical component of the Kandira stone is CaO with 51.7684%. The percentages of other major compounds are SiO_2 (2.7926%), Fe_2O_3 (1.1034%), MgO (0.6500%) and Al_2O_3 (0.640%). The numerical values of the major and minor components were recorded as four digits after the decimal point due to the precise measurement of the XRF device. The LOI loss occurred due to the removal of mainly carbon di-oxide (CO_2), organic material, and sulfur components from the limestone composition.

Table 1 Chemical analysis values resulting from XRF for Kandira stone

Content (%)	Value (%)
SiO_2	2.7926
Al_2O_3	0.6402
Fe_2O_3	1.1034
CaO	51.7684
MgO	0.6500
P_2O_5	0.0257
K_2O	0.0664
Cl	0.0041
MnO	0.0635
TiO_2	0.0288
Cr_2O_3	0.0175
Na_2O	0.0350
NiO	0.0061
SO_3	0.0466
SrO	0.1010
Total of components (%)	57.3473
LOI (%)	42.6527
Total (%)	100

Physical properties

Laboratory tests were conducted to determine the physical

properties of Kandira stone. These experiments are real and apparent densities, total and open porosities (TS EN 1936 2010), the determination of water absorption at atmospheric pressure (by weight) (TS EN 13755 2014), water absorption determination due to the capillary effect (TS EN 1925 2000), specific gravity by gas pycnometer (ASTM D 5550-06 2009), determination of water absorption in boiling water (TS 699-Article 6.3 2009), determination of ultrasonic pulse velocity (UPV) propagation (TS EN 14579 2015) and slip resistance determination with the help of pendulum test at dry and wet conditions (TS EN 14231 2004). Physical test results with arithmetic mean and standard deviation values of Kandira stone are given in Table 2.

Mechanical properties

Some laboratory mechanical tests were performed to determine the mechanical properties of Kandira stone. These tests are uniaxial compression test for compressive strength (TS EN 1926 2013), flexural strength under constant moment (TS EN 13161 2014), flexural strength under a concentrated load (TS EN 12372 2013), a determination of the Knoop hardness (TS EN 14205 2004), wide wheel disc (WWD) for the determination of abrasion resistance (TS EN 14157 2017), determination of rupture energy (TS EN 14158 2004) and breaking load in the Dowel hole (TS EN 13364 2003) tests. The mechanical test results of the Kandira stone are given in Table 3.

Durability and hygrothermal properties

The durability of rocks varies under atmospheric conditions. To determine the effect of these properties on Kandira stone, durability–hygrothermal experiments were performed. Accredited AKU-NSL laboratory runs the necessary tests. The durability and hygrothermal properties of the Kandira stone were defined by the associated laboratory tests following the standards. First, the durability properties of the Kandira stone were determined. The laboratory tests were carried out to determine the resistance to salt crystallization (TS EN 12370 2001), the resistance to wear with salt vapor (TS EN 14147 2004), the resistance to SO_2 wear in a humid environment (TS EN 13919 2004), and the resistance to frost effects (56 cycles) (TS EN 12371 2011). The resistance to the SO_2 agent test of Kandira stone was conducted in a humid environment with two solutions of A and B based on TS EN 13919 (2004) standard (Fig. 6). As a result of the tests, it was found that the original rock specimen with 120 × 60 × 10 mm dimensions (Fig. 6a) immersed in solution A is nonresistant and adversely affected by the SO_2 agent (Fig. 6b) and the rock specimen in solution B has low resistance to the SO_2 agent (Fig. 6c) in a humid environment. After the durability tests, the hygrothermal properties

Table 2 Laboratory test results of the physical properties of the Kandira stone

	Real density by regular pycnometer (kg/m^3)	Apparent density (kg/m^3)	Porosity (%)		Water absorp. at atmospheric pressure (%)	Water absorption in boiling water (%)	Water absorp. coeff. by capillarity (g/m^2 s$^{0.5}$)	Specific gravity of solids by gas pycnometer (g/cm^3)	Ultrasonic pulse velocity (UPV) (km/s)	Roughness (mm)	Slip resistance by means of pendulum tester (SRV)	
			Total	Open							Wet	Dry
Applied Standard	TS EN 1936	TS EN 1936	TS EN 1936		TS EN 13755	TS EN 699 Matter 6.3	TS EN 1925	ASTM D-5550-06	TS EN 14579	Handheld surface roughness tester	TS EN 14231	
# of specimen	6	6	6	6	6	6	6	6	6	6	6	6
Arithmetic mean	2776	2242	19.21	12.18	5.80	5.85	20.53	2.726	3.87	2.732	37.2	35.5
Standard deviation	11	40	1.43	0.98	0.60	0.88	2.43	0.007	0.24	0.557	0.8	0.8
Class	–	Moderate	High 15–30	–	–	<4%	Moderate absorption	–	Moderate	Rough surfaced	Moderate slipping risk (35–44)	
Classification	–	Anon (1979)	Anon (1979)	–	–	TS 11137	Unal and Altınok (2019)	–	Anon (1979)	Barton (1978)	AS 4586 (Australian Standard)	

Table 3 Test results of the mechanical properties of the Kandira stone

	Unified compressive strength (UCS) (MPa)	Flexural strength under constant moment (MPa)	Flexural strength under concentrated load (MPa)	Knoop hardness (HK)	Wide wheel abrasion (WWD) (mm) (Capon test)	Rapture energy (Joule)	Breaking load at dowel hole (N)
Applied Standard	TS EN 1926	TS EN 13161	TS EN 12372	TS EN 14205	TS EN 14157	TS EN 14158	TS EN 13364
# of specimen	10	10	10	10	6	6	10
Arithmetic mean	48	7.5	11.4	78	23.5	3.96	1141
Standard deviation	8	3.8	3.1	32	1	0.60	81
Class	25–50 (low strength)	1.76 times > the limit value of 4.26 MPa	2.67 times > the limit value of 4.26 MPa	Low (2.5–3)	WA ≥ 22 (high wearability)	Moderate rupture energy	Moderate breaking load
Classification	Deere and Miller (1966)	TS 699	TS 699	Mohs hardness scale	Cobanoglu and Celik (2017)	–	–



Fig. 6 Views of Kandira stone before (**a**) and after the test of resistance to aging by SO_2 effect in the presence of humidity, (**b**) view of the specimen immersed to solution A, (**c**) view of the specimen immersed to solution B, (specimen dimensions: 120 × 60 × 10 mm)

were determined by four different tests performed on three 160 × 160 × 10 mm-sized specimens in accordance with TS EN ISO 12572 (2016). These tests are water vapor flow rate (mg/h), water vapor transmission rate (mg/m^2 h), water vapor permeability (mg/m^2 Pa), and water vapor diffusion resistance factor (μ) tests. The wet cup method was applied in the measurements of water vapor transport parameters (TS EN ISO 12572). The mean and standard deviation values of durability and hygrothermal test results of the Kandira stone are given in Tables 4 and 5, respectively.

Thermal shock effect

An additional test for defining durability of the stone under the heat differences, the resistance to aging with thermal shock effect test, was undertaken according to TS EN 14066 (2015) standard with ten rock specimens in 300 × 50 × 50 mm dimensions. TS EN 14066 (2015) standard specifies a method for assessing possible changes of natural stones under the effect of sudden changes in temperature (thermal shock) in a twenty-cycle. This test evaluated the change in mass (g), flexural strength (MPa), ultrasonic pulse velocity (km/s), open porosity (%) properties of the Kandıra stone specimens. At the end of the test, physically no oxidation, discoloration, spotting, fracture-cracking, exfoliation, and swelling–blistering effects were observed in the Kandira stone. As a result of this test, the average mass (g), average flexural strength (MPa), average ultrasonic pulse velocity (km/s), average open porosity (%) properties after the thermal shock test and changing percentages in these properties between before and after thermal shock tests for the Kandira stone are determined (Table 6).

Economical assessment of Kandira stone

Within the scope of the study, the possible reserve of Kandira stone outcropped between Akcaova and Cercili villages was calculated. The data required for this calculation are spreading area, thickness, and apparent density of the Kandira stone (Table 7). The study area covers approximately 5 × 10^6 m^2 (5 km^2). The human settlements in the study area cover a total area of 1.84 × 10^6 m^2. Since the

Table 4 Test result values of the durability properties of the Kandira stone

	Resistance to salt crystallization (%)	Resistance to aging by CaCl salt mist (%)	Determination of resistance to aging by SO_2 agent in humidity		Frost resistance (56 cycles) (%)
Applied Standard	TS EN 12370	TS EN 14147	TS EN 13919		TS EN 12371
# of specimen	6	6	3	3	10
Average mass change (%)	−0.005	−0.08	1.722	0.312	−0.11
Standard deviation	1.349	0.04	0.607	0.090	0.07
Explanation	Resistant to salt crystallization	No oxidation, discoloration, spotting, exfoliation, swelling-blistering, crack	Solution composition A: 150 ml distilled water + 500 ml H_2SO_3	Solution composition B: 500 ml distilled water + 150 ml H_2SO_3	< 2%
Remarks	A negligible minor loss occurred	Resistant to CaCl salt mist	Not resistant to SO_2 aging, SO_2 gas adversely affect the rock	Low resistance to sodium sulfate salt crystallization due to spotting of the specimen	TS 11137

Table 5 Test result values of the hygrothermal properties of the Kandira stone

	Water vapor flow rate (mg/h)	Water vapor transmission rate (mg/m^2 h)	Water vapor permeability (mg/m^2 Pa)	Water vapor diffusion resistance factor (μ)
Applied Standard	TS EN ISO12572	TS EN ISO12572	TS EN ISO12572	TS EN ISO12572
# of specimen	3	3	3	3
Arithmetic mean	159.65	6244.03	174.22	0.30
Standard deviation	22.31	871.38	24.31	0.04
Class	–	Very low capillary water absorption	–	High breathability
Classification	–	Snethlage (2005)	–	$\mu \leq 1$

Table 6 Test results before and after conditions of the Kandira stone against wear by thermal shock

	Test results before thermal shock	Test results after thermal shock	Changing (%)
Average mass (g)	1850.99	1813.87	2.054 reduction
Average flexural strength (MPa)	11.40	8.40	26.64 reduction
Average measurement of ultrasonic pulse velocity (km/s)	3.87	4.03	4.44 increase
Average open porosity (%)	12.18	13.80	13.30 increase

Table 7 Possible reserve of the Kandira stone

Net area (m^2) × 10^6	Thickness (m)	Apparent density (ton/m^3)	Reserve (ton) × 10^6	Geological loss (ton) × 10^6 (%20)	Net reserve (ton) × 10^6
3.16	7.2	2.242	51	10.2	40.8

materials in the settlement area cannot be included in the production, the production area of 3.16×10^6 m^2 is obtained for the reserve calculations, subtracting the settlement area of 1.84×10^6 m^2 from the total area of 5×10^6 m^2. The average thickness of the Kandira stone is approximately 7.2 m, as can be seen in the measured stratigraphic section (Fig. 7). The apparent density was obtained as a result of the test performed according to TS EN 1936 (2010) standard in the laboratory. Probable reserve of the Kandira stone within the study area is calculated using Eq. (1):

$$\text{Reserve} = \text{Area}\left(\text{m}^2\right) \times \text{Thickness (m)} \times \text{Apparent density}\left(\text{ton/m}^3\right). \quad (1)$$

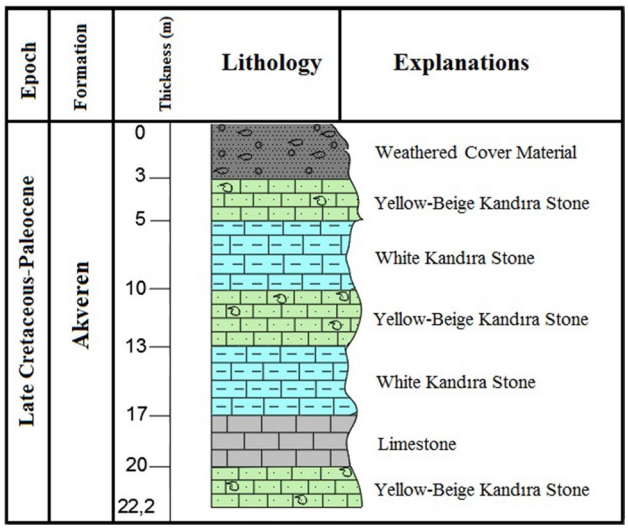


Fig. 7 A measured stratigraphic section in a Kandira stone quarry located in Çerçili

The possible reserve amount for the Kandira stone is calculated as 51×10^6 tons. A 20% geological loss out of total reserve (10.2×10^6 tons) is considered in reserve calculations. To obtain the net reserve, the geological loss value is subtracted from the reserve value and the net reserve is obtained as 40.8×10^6 tons (Table 7).

The annual net production is approximately 1000 m^3 for Kandira stone. This volume value corresponds to 2240 tons as weight. Production loss is assumed 30% for Kandira stone, which corresponds to 672 tons. Mineable net reserve amount should be calculated to determine the operability duration of this reserve. Thus, the annual production of Kandira stone is obtained approximately 3000 tons (2240 tons + 672 tons) and the operability duration of the net reserve (40.8×10^6 tons) is calculated as 13,600 years (Table 8). The fabricated products of Kandira stone irregular blocks in stone cutting workshops are used in many areas such as walls, building faces, fireplaces, landscaping purposes, floor covering, chimneys and on the window sides.

The current market unit cost of the Kandira stone is 3000 TL/m^3 and it is calculated as 1340 TL/ton (verbal interview with Gunay Acıkgoz on 12.10.2019). The Kandira stone has a net reserve of 40.8×10^6 tons and this value is multiplied by the unit cost of production and its potential economic value is calculated as 54.672×10^9 TL (approximately €7.2B calculated from the June 2020 Euro currency rate) (Table 9). The calculated reserve is only for the region between Akcaova and Cercili villages. In the field, it was observed that this reserve would increase more since the spread of Kandira stone continues outside the study area.

Table 8 Production numbers for Kandira stone

Net production (m^3/year)	Net production (ton/year)	30% of production losses (ton/year)	Total material used (ton/year)	Operability projection time based on net reserve
1000	2240	672	~3000	13,600 years

Discussion

This study evaluated the geomechanical, durability, hygrothermal properties, and aging under the thermal shock effect of Kandira stone. For this purpose, mineralogical, physical, mechanical, durability, hygrothermal, and thermal shock properties were defined by laboratory tests in an accredited natural stone laboratory. Mainly, the physical and mechanical properties of the Kandira stone are evaluated by some mostly used engineering classifications and standard limit values of TS 699 (Table 10) and TS 11137 (Table 11) in terms of usage as natural building stone. According to physical laboratory test results, the apparent density corresponds to the moderate class and total porosity is classified as high, and ultrasonic pulse velocity is in the moderate class according to Anon (1979) classification. In terms of mechanical laboratory test results, abrasion resistance according to Cobanoglu and Celik (2017) classification, Kandira stone falls into high abrasion class. The mean compressive strength value of Kandira stone falls into low strength class according to Deere and Miller (1966) classification. The mean Knoop hardness value (78) corresponds to 2.5–3 Mohs hardness class value, which defines the hardness of Kandira stone low (Rickman and Street 2008). The average bending strength of the Kandira stone (11.4 MPa) is 2.67 times the limit value of load-bearing purposes according to TS 699 standard. AS 4586 (2013) classification for slip risk on walking surfaces based on the wet pendulum test is used to classify the Kandira stone for determination of potential usage area. The slip resistance of the Kandira stone using the pendulum tester based on TS EN 14231 (2004) standard yielded a 37.2 SRV in wet conditions. This value falls into P3 class of pedestrian surface materials and the moderate class of slipping risk (AS 4586 2013; HB 198 2014). Typical uses in this category are shopping center food courts, hotel

Table 9 Potential economic values of the Kandira stone

Kandira stone	Production unit price (ton/TL)*	Net reserve (ton) $\times 10^6$	Total amount (TL)-(Euro)**
	1340	40.8	54.672×10^9-~7.2B

*Unit price is valid for 06.2019–06.2020 time-span,

**Conversion of TL to Euro was calculated by the currency rate in June 2020

Table 10 Evaluation of suitability for building stone usage according to TS 699 (2009) standard

Property	TS 699 natural stone standard limit values	Kandira stone	Result
Water absorption by weight (maximum, %)	4.0	5.8	Not suitable
Apparent density (minimum, g/cm^3)	2.16	2.20	Suitable
Compressive strength (MPa)	Load-bearing: 49.0 Cladding: 29.4	48.0	Suitable
Flexural strength (MPa)	Load-bearing: 4.26 Coating: 2.94	11.4	Suitable

Table 11 Evaluation of the Kandıra stone properties according to TS 11137 (1993) standard

Property	Natural stone standard limit values for limestone (TS 11137)	Kandira stone	Result
Mineralogical composition (%)	At least 90% calcite should be present	97	Suitable
Apparent density (g/cm^3)	Not less than 2.16 g/cm^3	2.20	Suitable
Water absorption in boiling water (%)	No more than 4.0% by weight	5.85	Not suitable
Loss in frost (%)	The mass reduction value of frost should not be more than 2%	0.11	Suitable
Compressive strength (N/mm^2)	At least 50 N/mm^2 for load-bearing and 30 N/mm^2 for surfacing	48.00	Suitable for surfacing, not suitable for load-bearing
Bohme abrasion (BA) resistance (cm^3/cm^2)	Up to 10 cm^3/50 cm^2 in load-bearing places such as floors and pavements. Up to 15 cm^3/50 cm^2 as decoration, ornament and coating	23.50 (wide wheel abrasion) 29.50 (BA) Aydındag and Erkanol (2011)	Not suitable

lobbies, public changing rooms, interior area stairs (Coskun et al. 2017).

Durability properties were identified by a series of laboratory durability tests. The resistance to salt crystallization test (TS EN 12370) caused a negligible minor mass loss indicates that the stone is resistant to salt crystallization. No oxidation, discoloration, spotting, exfoliation, swelling–blistering and crack developed during the resistance to aging by CaCl salt mist test (TS EN 14147) proved that the stone is resistant to CaCl salt mist. The resistance to aging by SO_2 agent in the presence of humidity test (TS EN 13919) yielded that the stone is not or low resistant to SO_2 aging because SO_2 gas adversely affected the stone by breaking and spotting the specimens. Frost resistance (56 cycles) test (TS EN 12371) resulted in a 0.11% mass loss, which is less than the 2% mass loss defined in TS 11137 standard defines that the stone is resistant to freeze effects.

The hygrothermal properties were determined by four different tests performed in accordance with TS EN ISO 12572 (2016). Snethlage (2005) classified the rocks in terms of the capillary water absorption values (w) in kg/m^2 h unit. If $w < 0.5$ kg/m^2 h, the capillary water absorption is very low, if $0.5 < w < 3.0$ kg/m^2 h, the capillary water absorption is medium and if $w > 3.0$ kg/m^2 h, the capillary water absorption is high. The water vapor permeability rate (~6244 mg/m^2 h) of the investigated rock samples was calculated as approximately 0.0062 kg/m^2 h when the water vapor permeability rate unit was converted to the corresponding to the capillary water absorption unit. According to this value, Kandira stone is defined as a rock with very low capillary water absorption according to the Snethlage (2005) classification. The low water absorption capacity of the rock indicates that the permeability of the stone is also low. The water vapor diffusion resistance factor of the Kandira stone is approximately 0.3 and being less than one ($\mu \leq 1$) indicates the high breathability of the stone.

As a result of thermal shock test applied to Kandira stone specimens, there was no deterioration in the outer structure of the samples, only the mass change occurred, but some changes occurred in the internal structure, increasing ultrasound velocity and open porosity and a decrease in flexural strength. The mass change that occurred after the thermal shock effect in Kandira stone decreased 2.054%. As a result of experimental studies, there was no physical weathering in Kandira stone samples on a macroscale. Here, due to the low mass change, it is concluded that the Kandira stone is mainly resistant to thermal shock cycles. The ultrasound method is one of the methods of determination of microcracks and pores developing in the material that occurs after aging tests of natural stones based on the TS EN 14579 standard. The average ultrasound propagation velocity, which was 3.87 km/s in the sound fresh samples

before the test, increased to 4.03 km/s after the test causing a 4.44% increase. This increase can be due to the development of microcracks, the increase of existing pores and the change in their size in the Kandira stone with the effect of thermal shock. In fact, this test proved that the average open porosity in Kandira stone has increased from 12.18 to 13.80%, increasing 13.3%. With increasing number and size of micro discontinuities in the specimens, the average flexural strength decreased from 11.4 to 8.4 MPa, decreasing 26.64%.

The Kandıra stone has been preferred due to economic and durability properties over the Maltase stone. The field appearance of the Maltase stone is similar to Kandira stone. The weak points and properties of the Maltase stone are emphasized to compare the two stones. Maltase stone has been used in most monuments and buildings in the Maltase Islands and the stones of these monuments and buildings experienced damages by salt crystallization due to Malta's marine environment. Also, an abundance of Globigerina microfossils in the stone is the main reason in the occurrence of alveolar weathering causing considerable damage in many buildings (Rothert et al. 2007). Due to these lithological and economic reasons, the use of the Maltase stone in the historical monuments and structures in Istanbul has probably been left. Additionally, rising transportation costs from Malta Islands to Istanbul decreased the demand for Maltase stone. Instead of the Maltase stone, the Kandıra stone, which is more durable rock material than the Maltase stone has been transported from a much shorter distance. Since then, the Kandira stone has been used in many historical places located in Kocaeli and Istanbul and has become a good source of natural building stone for Istanbul and around cities in the Marmara region.

Conclusions

Kandira stone is a building stone used in many historical structures for a long time. Many historical monuments were built with Kandira stone due to its durability, the economic advantage, and it being easy to shape. In this study, the mineralogical, chemical, physical, mechanical, durability–hygrothermal, thermal shock properties, and economic aspects of the Kandira stone outcropped between Akcaova and Cercili were investigated. The material properties of Kandira stone used as building stone were searched through field and laboratory work and evaluated for suitability with specific building stone standards.

Two physical properties of the Kandira stone, total porosity (19.21%) and water absorption in boiling water by weight (5.85% > 4% in TS 11137) yielded higher values than the limit values indicated in TS 11137 standard. Although the total porosity value is high, the thermal shock and freeze–thaw cycles resulted in a resistant material. This outcome proposes that the pores and discontinuities are not interconnected causing also low stone permeability, which is mainly associated with geological stone formation. Additionally, the high porosity causing a porous surface adds an appealing to the outer appearance of the stone and provides ease of cutting and workability to the stone. Also, the moderate class of slipping risk based on wet pendulum test suggested that the typical uses of this category are shopping center food courts, hotel lobbies, public changing rooms, interior area stairs, undercover concourse areas of sports stadiums, bathrooms and ensuites in hospitals and aged care facilities.

As a result of thermal shock test studies, the Kandira stone is mainly resistant to thermal shock cycles due to the lack of physical weathering in the macroscale samples, low mass change, and reasonable increases in ultrasound and open porosity and decreases in bending strength. Identifying petrographic, geomechanical, durability–hygrothermal, and thermal shock properties revealed the Kandıra stone's positive and negative attributes considered in material selection for building stone or restoration purposes. The tests undertaken in this study provided basic information on the geomechanical, durability–hygrothermal, and thermal shock properties of the Kandira stone, which were frequently used in the historical and new buildings in the Marmara region. The obtained data revealed very significant information about the properties of Kandira stone. Material characterization analysis highlighted the necessity of mineralogic, geomechanical, durability–hygrothermal, and thermal shock data before the application of materials in a stone-related project.

According to the results of mechanical tests, it was determined that Kandira stone is not suitable for load-bearing places such as flooring purposes. In addition, it is rather suitable for use in decoration, restoration, and landscape architecture as it complies with TS 11137 standard. Also, it should not be used in places where there is heavy pedestrian traffic because of its high abrasiveness, it can cause a high abrasion in the stone. In terms of durability properties, the Kandira stone has high resistance to aging by CaCl salt mist and no or low resistance to SO_2 aging in a humid environment. Also, the freeze–thaw test of Kandira stone yielded an exceptionally low mass loss (0.11%) indicating that the stone is resistant to freeze–thaw effect. These properties revealed that the Kandira stone can be used in areas under the effects of sea climate or along the seaside places, but it can be risky when used in areas having SO_2 in air.

Within the scope of this study, the economic potential and reserve of Kandira stone were evaluated. A possible reserve of 40.8×10^6 tons in the study area was calculated in the region between Akcaova and Cercili villages. This reserve should last about 13,600 years if the Kandira stone is mined approximately 3000 tons in a year. The calculated

economic value of the probable reserve is approximately 54.672×10^9 TL (approximately €7.2B). The local and regional natural building stone end-users such as municipalities, landscaping, restoration and construction firms should consider the Kandira stone for its low cost, abundance reserve, and suitable properties as building stone. By knowing various stone properties help decide on specific usage areas of the stone more precisely. Official support should be given to establish the connection lost between suppliers and end-users and boost the market of Kandira stone in the natural building stone market of Turkey.

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Data availability Data used in the manuscript were obtained from an accredited natural building stone laboratory (AKU-NSL) and are given through the Tables in the manuscript.

Compliance with ethical standards

Conflict of interest Not applicable.

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