Case Studies in Construction Materials 18 (2023) e02128

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Influence of moisture content on the mechanical properties of an ancient high-porosity building sandstone: San Cristóbal's stone (Andalusia, Spain)

Juan Ramón Baeza [a], Víctor Compán [b,*], Pablo Pachón [b], Jaime Aguilar [b], Margarita Cámara [b]

[a] Department of Architectural Construction II, University of Seville, Seville, Spain
[b] Department of Building Structures and Ground Engineering, University of Seville, Seville, Spain

ARTICLE INFO

Keywords:
Sandstones
Building stone
Moisture content
Mechanical properties
Static elastic modulus
Dynamic elastic modulus
Uniaxial compressive strength
Empirical relationships

ABSTRACT

San Cristóbal's is a porous sandstone that is present in masonry structures of numerous historical buildings located in the southwest of Spain (15^{th}–18^{th} centuries). In order to guarantee conservation and structural integrity, most of these structures have been assessed during the last two decades after they presented severe damages in locations affected by moisture. In this study, static and dynamic elastic modulus and uniaxial compressive strength of San Cristóbal's stone are determined in the laboratory under dry and saturated states, as well as with a moisture content of 40%, to establish the influence of moisture on them. An experimental campaign was conducted on 16 samples of ancient stone, extracted from the core of structural walls and columns during a structural intervention. The results show how the moisture content directly affects the deformability of the stone, especially between dry and 40% moisture content states. The values of the elastic modulus, both static and dynamic, are reduced with average values of 16.98% and 22.85% respectively. The loss of uniaxial compressive strength between the dry and saturated states is established with a mean value of 29.82%. Additionally, empirical relationships between the studied mechanical properties have been developed, reaching coefficients of determination over 0.90 in most cases.

1. Introduction

Stone masonries are widespread as part of historical buildings, so they are usually under heritage protection criteria. This implies not only that they are needed to be conserved but also the responsibility of guaranteeing their structural integrity, especially when they are part of buildings that are still used. [1,2].

It is widely known that the mechanical properties of natural stones used as building structural materials are negatively affected by moisture [3]. Stone masonries in historical structures are on the outside, so they are subjected to environmental humidity changes. In addition, the structural elements that are in contact with the ground can reach higher moisture levels because of capillarity.

Due to structural assessments of historical buildings require a deep knowledge about the mechanical properties of the material, it is important to know the influence of moisture on the mechanical behavior of these natural stones to ensure adequate safety levels. In this

* Corresponding author.
E-mail address: compan@us.es (V. Compán).

https://doi.org/10.1016/j.cscm.2023.e02128
Received 19 February 2023; Received in revised form 2 May 2023; Accepted 6 May 2023
Available online 10 May 2023

sense, and in order to be respectful and consistent with the character of protection of this kind of structures, non-destructive techniques to obtain or predict mechanical properties would be especially interesting [4,5]. These techniques would increase their practical applicability, because they could be performed in situ in addition to in laboratory and data could be taken on numerous areas of the building, that is, more extensively than if it depended on the extraction of drilling specimens to be tested in laboratory [6].

Among the different non-destructive tests (NDT), the following stand out: Schmidt hammer, to obtain compressive strength from rebound number [7] and methods based on wave propagation, through which mechanical properties such as elastic modulus and uniaxial compressive strength can be predicted [8]. Several authors have established empirical relationships between P-wave velocity and elastic modulus [8] in sedimentary rocks and between P-wave velocity and uniaxial compressive strength [9] in squeezing rocks, both cases in a dry state. In addition, p-wave velocity is sensitive to water saturation [10], which allowed Karakul [11] to propose an empirical relationship between uniaxial compressive strength and P-wave velocity of several types of rocks at different degrees of saturation. In this case, and in order to improve the coefficient of determination of proposed equations, the percentage of clay minerals of the stone was considered as independent variable, due to it contributes to a decrease in mechanical properties after its interaction with water.

Likewise, there are also methods that allow obtaining in situ moisture content of the stone. The most common measurements are electrical-based methods. Moisture content can be obtained from electrical resistance or capacitance of the stone [12].

The existence of this kind of technique, which can be performed in situ, makes it useful to count on empirical relationships through which the mechanical behavior of historical stone masonries could be predicted from measurements experimentally obtained.

San Cristóbal's stone can be found in numerous historic buildings located in the western area of Andalusia (Spain) between the 15^{th}–18^{th} centuries. This mainly includes religious buildings, as well as civil and military ones. The Cathedral (1434) and the Monastery of San Jerónimo (1414), both in Seville [13,14]; Santiago Church (15^{th} century) and San Dionisio Church (15^{th} century), both in Cádiz [15,16], are some examples where San Cristóbal's stone has been used. During the last two decades, several of these buildings have been subjected to structural assessments after they presented severe damages that compromised their structural integrity. Thus, for examples, (i) two columns of the Cathedral of Seville needed to be replaced due to the decrease of their mechanical properties; (ii) Santiago Church presented instability problems because of the same reason and (iii) severe cracks appeared along the main cloister of the Monastery of San Jerónimo after an architectural intervention, especially in areas affected by moisture. Fig. 1 shows severe damages on one of the columns of Monastery of San Jerónimo (in Seville-Spain), where moisture content over 50% was identified [6].

In order to conduct structural assessments that ensure the structural integrity of the wide Andalusian built heritage made using San Cristóbal's stone, it is necessary to have a deep knowledge of the material. This sandstone is characterized by a low bulk density (1710–1860 kg/m^3) [15,17] and a high porosity (22.4–27%) [15,17]. Regarding their main mechanical properties, compressive strength has been established between 1.5 and 2.6 MPa [15], and elastic modulus is between 4000 and 10,000 MPa [15,17].

Other authors have studied the effect of moisture content on mechanical properties of different sandstones. C.G. Dyke and L. Dobereiner [18], tested nine specimens from three different sandstones under dry and saturated states, as well as three intermediate moisture content (32%, 63% and 96%). It was found that moisture content could change mechanical behavior of the sandstones signtificantly, reducing the elastic range of the material, which was often below 20% of peak strength in saturated conditions; A. B. Hawkins [19] presented a studies that included thirty five different sandstones from 21 British localities. In this case, some of the sandstones presented a significant decrease in uniaxial compressive strength from dry to saturated states. The loss of strength was established between 8.2% and 78.1% and a similar effect was observed on the elastic modulus.

More recent studies of the influence of moisture content on the mechanical properties of sandstones, like those performed by A. Shakoor (2009) [20], E. Verstrynge (2014) [3] and E. Kim (2016) [21] show results that lead to the same conclusions about the effect of

Fig. 1. Severe damages on columns of the Monastery of San Jeronimo (Seville - Spain) affected by moisture [6].

moisture content, although with different extent, depending on the specific stone. Shakoor [20] analyzed 8 types of stones with 18 specimens, obtaining a general range of unconfined compressive strength (UCS) reduction between 20% and 40% in dry and saturated states and reaching in two types of sandstones a strength decrease of 62.6% and 71.6% respectively. In this last work, some equations were defined to predict UCS from square roots of the degree of saturation. However, none of the 8 stones analyzed present physical properties close to those that characterize San Cristóbal's stone, with lower density and higher porosity. On the other hand, the study conducted by Kim [21] affirmed that the sandstones he analyzed reduced their compressive strength by approximately 20% from dry to saturated states. In this case, despite one of the sandstones studied by Kim (Buff sandstone) presented a porosity (22.7%) close to the range of San Cristóbal's stone and he studied several samples, no other of the physical properties of Buff sandstone are shown, so it is difficult to assess the correspondence between Buff and San Cristóbal's stones.

Among these studies, the work by Verstrynge [3] is pointed out not only because it includes the analysis of the influence of moisture content on mechanical properties of a sandstone, but also because it is an aging sandstone from a bell tower (17th century) that collapsed in Meldert (Belgium, 2006). The main physical properties of this sandstone (Diestian) are similar to those presented by San Cristóbal's stone, that is, a density of about 1800 kg/m^3 and a 22–27% porosity. However, their mineralogical composition differs. Diestian sandstone is mainly characterized by about 60% of quartz and 24% of glauconite [Verstringe, 2014], while San Cristóbal's stone contains 60% of calcium carbonate and around the 35% of quartz [22]. For the case of Diestian sandstone, Verstringe obtained a decrease of UCS within the range 40–59% considering dry and saturated states.

The novelty of this work lies on its study object, aging San Cristóbal's stone, the construction material of numerous and important historical buildings in the southwest of Spain. The mechanical properties of this natural stone have never been studied before under different moisture conditions, even though the affection of moisture on them seems to be evident because of damages such as those shown in Fig. 1. The objective is to determine how moisture affects this stone regarding both the deformability, through the elastic modulus, and the compressive strength. Static and dynamic elastic modulus have been distinct in order to consider the corresponding main roles of each one of them in structural assessments of historical constructions, that is, the static elastic modulus is useful to develop numerical models which structural analyses can be based on, and dynamic elastic modulus is easily and extensively determined in situ by implementing non-destructive techniques that use wave propagation. On the other hand, and as a secondary aim, correlations between the parameters will be addressed under different moisture levels.

To reach the described objectives, different tests have been conducted in laboratory on 16 San Cristóbal's stone specimens. Physical properties (density, porosity and absorption) and mechanical properties (static and dynamic elastic modulus and uniaxial compressive strength) of each one of the specimens were obtained through an experimental campaign considering different moisture contents. These specimens were extracted from the core of some columns and walls of Santiago Church, in Jerez de la Frontera (Cádiz - Spain) (15th century), during structural consolidation works that took place in 2007. Although, this implies a limitation of the work regarding the reduced number of specimens studied, this also constitutes a unique opportunity because it allows not only to count on specimens of the mentioned stone (they could have been extracted from the corresponding quarry) but also to study aging stone, as ancient as that to be assessed in any structural analysis that could be conducted on built heritage made up of San Cristóbal's stone.

2. Experimental program

To reach the proposed aims, experimental tests were performed in laboratory on 16 specimens which are described in section 2.1.

Section 2.2. details the series of tests that have been performed. They were conducted to obtain elastic moduli, both static and dynamic, and uniaxial compressive strength. These three mechanical properties were determined for different moisture contents, so section 2.2 includes the description of the procedures followed to control moisture in specimens as well. On other hand, and due to the main role of moisture content in this study, the absorption of the specimens was also determined to characterize them by this parameter.

Regarding the different moisture contents that have been considered for the specimens to be analyzed, elastic moduli were determined for three moisture contents: dry and saturated states and 40%. The consideration of this intermediate moisture value responds mainly to two reasons: (i) a preliminary study carried out by authors established that the higher loss of mechanical capacity

Fig. 2. Cylindrical specimens extracted from columns and walls of Santiago Church (Jerez de la Frontera, Cadiz - Spain).

takes place between dry and 40% in San Cristóbal's stone [23]; (ii) Moisture contents reaching the values in this range have been recognized in situ in structural elements made up of San Cristóbal's stone [6]. Uniaxial compressive strength has been analyzed considering dry and saturated states, as a reference of the limit states.

2.1. Material and samples

The specimens that have been analyzed are cylindrical and were extracted by drilling from columns and walls of Santiago Church in Jerez de la Frontera (Cádiz - Spain), during consolidation works (Fig. 2). Jerez de la Frontera has a warm Mediterranean climate, environmentally characterized by mean values of 17,75 degrees of temperature, 68,06% humidity and 524 mm of annual rainfall (mean values of the last 20 years)[24].

The extraction of the specimens was performed from the top of some of the columns and walls of the church and along their main load direction, that is, the longitudinal direction of both the specimens and the structural elements correspond (Fig. 3).

Table 1 shows the location and dimensions of each one of the 16 specimens. They present different dimensions because of the way of drilling stone from structural elements. However, all of them comply with the conditions established by the standards that have been taken as a basis during the experimental campaign. These specimens were used to determine mechanical and physical properties.

The analyzed specimens are dated to the same period as the elements which they were extracted from (late 1^{st} century and early 16^{th} century). The stone of Santiago Church was obtained from the quarry of San Cristóbal in the basin of Guadalete River, SW Andalucía. This is a chalcitic sandstone that is mainly composed of $CaCO_3$ (67%) and SiO_2 (30%) as an average composition.

2.2. Methods

2.2.1. Procedure to control the moisture content of the specimens

Dry state was reached through the application of the EN 1936:2006 standard [25]. Saturated state was achieved after having specimens submerged for 24 h. After getting the 100% of water contain, specimens experimented with a controlled loss of moisture in the oven until their weight denoted a moisture content of 40% considering the difference in weights between dry and saturated states.

2.2.2. Physical properties: absorption, bulk density and porosity

Absorption. Standard EN 13755:2008 [26] was followed. This standard contains a method to determine the absorption of water by natural stone through water immersion at atmospheric pressure. The studied specimens comply with the geometric requirements of this standard, that is, mínimum apparent volume of 60 ml and a ratio of superficial area to volume within the range 0.08–0.20 mm^{-1}. Absorption is the ratio of the difference between the masses of a specimen in saturated and dried state to the mass of the dried one.

Porosity and bulk density. Standard EN 1936:2006 [25] was followed. This standard define density as the ratio of the weight of the dried specimen to its bulk volume. On the other hand, it defines porosity as the ratio of the volume of OPEN pores to the bulk volume of the specimen.

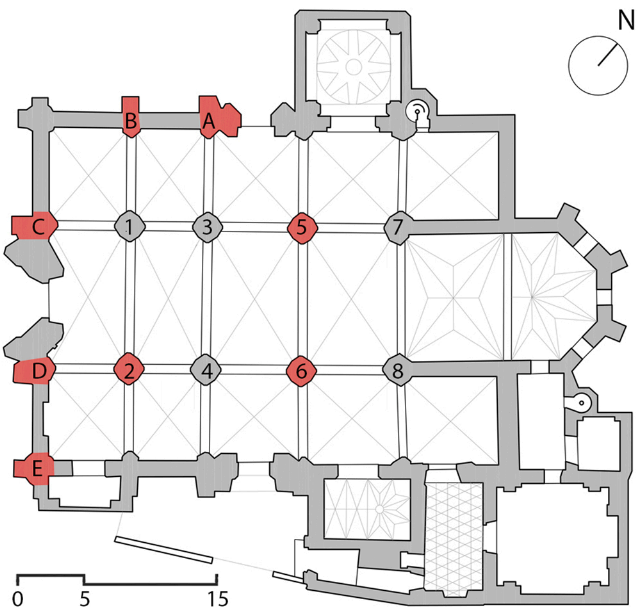

Fig. 3. Location of analyzed specimens from Santiago Church (Jerez de la Frontera, Cadiz - Spain).

Table 1
Location and dimmensions of analyzed specimens from Santiago Church.

Specimen	Extraction	Depth of ext. (m)	Length (mm)	Diameter (mm)	Length/diameter
N01	2	11.20	164	63	2.6
N02	2	19.27	165	69	2.4
N03	5	5.15	215	83	2.6
N04	6	2.18	183	82	2.2
N05	6	4.60	168	83	2.0
N06	6	6.80	194	83	2.3
N07	6	9.27	180	82	2.2
N08	6	11.55	204	83	2.5
N09	6	12.85	202	83	2.4
N10	6	21.21	144	71	2.0
N11	6	22.03	159	71	2.2
N12	A	9.75	131	58	2.3
N13	B	11.26	149	61	2.4
N14	C	21.59	156	61	2.6
N15	D	1.60	155	62	2.5
N17	E	2.67	149	62	2.4

2.2.3. Dynamic elastic modulus (E_{dyn})

Standard EN 14146:2004 [27] was followed to determine the dynamic elastic modulus (E_{dyn}) by means of sonic waves tests (Fig. 4). According to this standard [27], E_{dyn} can be obtained from the bulk density and the fundamental resonance frequency.

2.2.4. Static elastic modulus (E_{st}) and uniaxial compressive strength (UCS)

Standard EN 14580:2006 [28] was followed to determinate Static elastic modulus (E_{st}). Standard EN 1926:2006 [29] was applied to obtain uniaxial compressive strength (UCS). In both cases, an MTS Criterion Electromechanical Test System whose load capacity is of 100 KN (C45.105) was used to perform the corresponding mechanical tests (Fig. 5). Strains were measured through a device of National Instruments (cDAQ-9174, NI-9219) in addition to LVDTs Solartron AXR/2.5/S. MTS TestSuite TW and Signal Express 2015 softwares controlled load cycles and LVDTs deformation respectively [17].

3. Results and discussion

3.1. Physical properties

Table 2 shows the obtained results with respect to physical properties, specifically bulk density, open porosity, and absorption. Likewise, the mean and standard deviation values of each are shown.

The bulk density are between 1655 and 1867 kg/m^3 with a mean value of 1776 kg/m^3, values close to those established by other authors [6,15]. However, porosity and absorption are higher than expected, with mean values of 33.77% and 17.04% respectively.

By analyzing results from a statistical point of view, normal results were obtained in the case of bulk density and porosity. Results of absorption are close to normality, with 62.5% of specimens within Mean $\pm$ 2 SD. Fig. 6 shows Pareto diagrams of the physical properties studied to better describe the obtained ranges of resulting values.

A linear relationship between density and porosity had previously been found by the authors [17]. In the case of porosity and absorption, a linear relationship between them is clearly found considering 11 of the 16 specimens studied (Fig. 7), but the remaining specimens, which present similar values for porosity, showed corresponding values for absorptions also very similar.

Fig. 4. Test performed to obtain the dynamic elastic modulus.

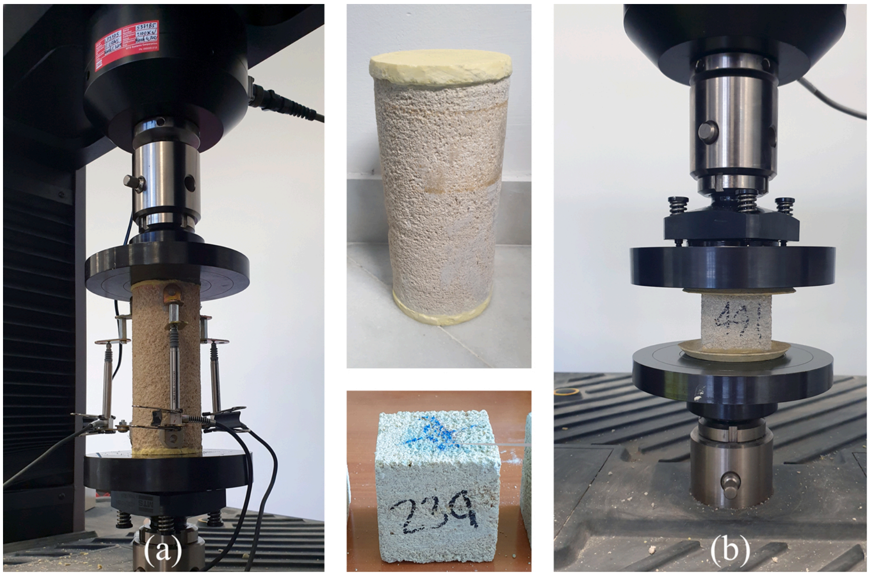

Fig. 5. Tests performed to determine (a) the static elastic modulus and (b) the uniaxial compressive strength.

Table 2
Physical parameters obtained from tests in lab [17].

Specimen (Sp)	Bulk density (Kg/m^3)	Porosity (%)	Absorption (%)
N01	1760.75	34.49	19.63
N02	1843.26	29.58	16.08
N03	1759.05	34.73	19.78
N04	1742.76	35.08	13.90
N05	1831.65	31.65	17.31
N06	1693.98	36.97	21.87
N07	1777.66	33.88	12.83
N08	1655.74	38.66	23.40
N09	1867.62	30.75	16.50
N10	1766.65	34.08	12.50
N11	1791.88	33.03	12.52
N12	1761.35	34.30	19.51
N13	1752.66	34.50	19.73
N14	1798.32	33.11	18.45
N15	1753.07	34.83	12.14
N17	1861.19	30.68	16.52
Mean	1776,09	33.77	17.04
SD	56.69	2.32	3.53

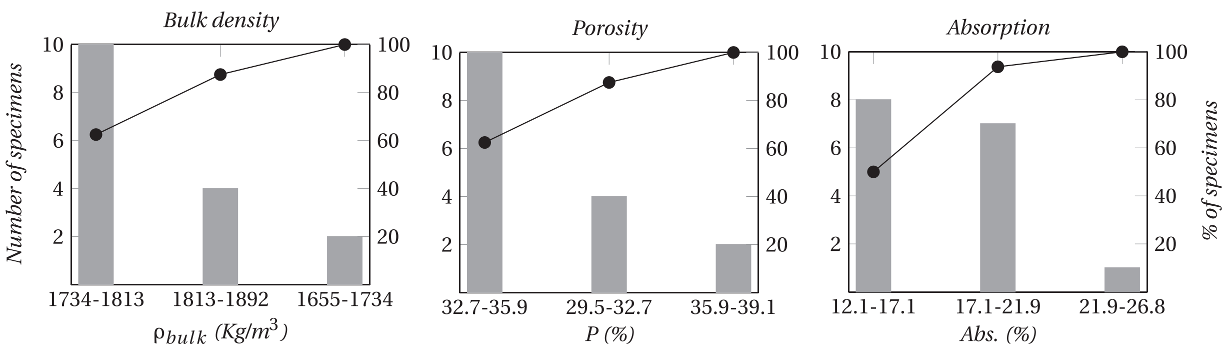

Fig. 6. Physical properties of San Cristobal's stone: Pareto diagrams.

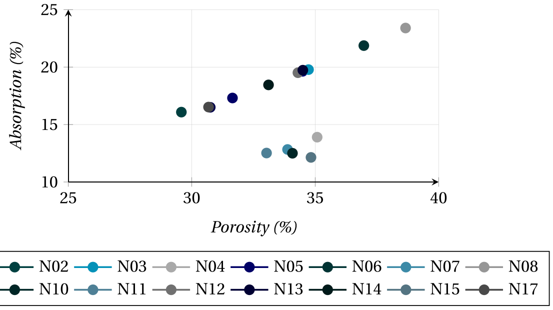

Fig. 7. Relationship between absorption and porosity.

3.2. *Deformability (Static (E_{st}) and Dynamic (E_{dyn}) elastic modulus)*

Table 3 shows the static elastic modulus of stone specimens under different moisture conditions: dry state (E_{st}), 40% moisture content (E_{st40}) and saturated state (E_{st100}). The variation percentages between them, the mean and the standard deviation values are also included. On other hand, Fig. 8 plots E_{st} obtained from the specimens for the studied moisture contents.

Values obtained for E_{st}, E_{st40} and E_{st100} present an acceptable dispersion, with 11/16 specimens (68.7%) within the range Mean ± SD. The same 11 specimens keep this condition for E_{st} in the three moisture states. As shown in Table 3 and Fig. 8, every specimen presented a higher decrease in E_{st} in the range of 0–40% of moisture content than in the range of 40–100%, except for the specimen N13, presents an especially high loss of E_{st} (22.07%) in the range 40–100%. Likewise, it can be seen that 75% of the studied specimens lost 70% or more of their total loss of E_{st} in the range 0–40% of moisture content. These results can be extended to dynamic elastic modulus, as Table 4 and Fig. 9 show. Thus, the same 11 specimens keep the condition of an acceptable dispersion for E_{dyn}, E_{dyn40} and E_{dyn100}. Likewise, the main decrease in dynamic elastic modulus occurs between dry state and 40% of moisture content (Fig. 9). However, this last aspect is more pronounced in the case of E_{dyn} than in the case of E_{st}, with a mean value for the decrease of $E_{dyn0-40}$ of 22.85% versus a mean of 16.98% in the case of E_{st0-40}.

Other authors have noted likewise an increase in the deformability of other sandstones as the moisture content increase through the decrease of elastic modulus (see Section 1). In this sense, wide ranges were defined by them for this mechanical property (e.g. 32.2–65.7% [30]; 20.63–80.73% [11] from dry to saturated states in both cases). In this study, the range of this variation is reduced for San Cristóbal's stone and a decrease between dry and saturated states has been established between 11.1% and 34.3% in the case of E_{st}, and between 12.3% and 39.3% in the case of E_{dyn}. Fig. 10 shows Pareto diagrams with the most frequent ranges to describe the results obtained for the elastic moduli beyond their means and standard deviations.

3.3. *Uniaxial compressive strength (UCS)*

Table 5 and Fig. 11 show the loss of UCS obtained between dry and saturated states for each one of the studied specimens. A mean value for this loss of 29.82% show a notable decrease in the compressive mechanical capabilities of San Cristóbal's stone affected by moisture. This mean value is like others obtained for different sandstones. It could be seen in Section 1, where mean values for UCS loss of 20% [20], 40% [20] or 22.7% [21] were referred. These results correspond to new sandstones extracted from their corresponding

Table 3
Mechanical parameters: Static elastic modulus under different moisture conditions (0%, 40% and 100%).

Sp	E_{st} (MPa)	E_{st40} (MPa)	E_{st100} (MPa)	$\%_{0-40}$	$\%_{40-100}$	$\%_{0-100}$	$\%_{0-40}/\%_{0-100}$
N01	5970	4557	3970	23.67	12.88	33.50	0.71
N02	10,081	8094	7262	19.71	10.28	27.96	0.70
N03	4715	3812	3723	19.15	2.33	21.04	0.91
N04	4889	4152	3899	15.07	6.09	20.25	0.74
N05	9218	7956	7038	13.69	11.54	23.65	0.58
N06	4204	3636	3205	13.51	11.85	23.76	0.57
N07	5511	4168	3982	24.37	4.46	27.74	0.88
N08	3409	3065	2903	10.09	5.29	14.84	0.68
N09	6752	4939	4768	26.85	3.46	29.38	0.91
N10	3058	2605	2403	14.81	7.75	21.42	0.69
N11	7718	6735	6498	12.74	3.52	15.81	0.81
N12	5754	5290	5115	8.06	3.31	11.11	0.73
N13	5206	4835	3768	7.13	22.07	27.62	0.26
N14	6430	4972	4818	22.67	3.10	25.07	0.90
N15	4479	3933	3913	12.19	0.51	12.64	0.96
N17	4628	3335	3041	27.94	8.82	34.29	0.81
Mean	5751	4755	4394	16.98	7.33	23.13	0.74
SD	1937	1607	1451	6.62	5.45	6.99	0.18

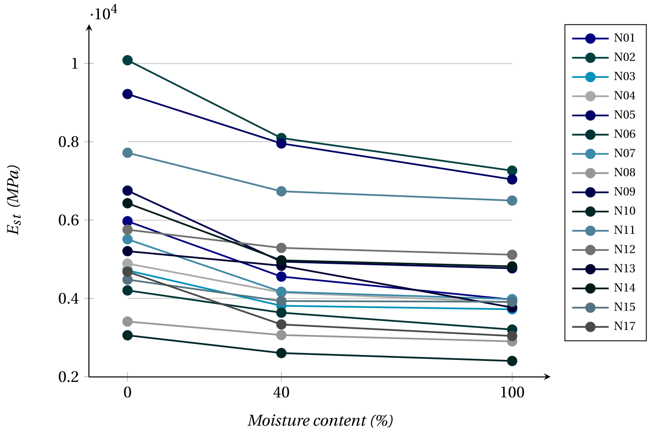

Fig. 8. Static elastic modulus values under different moisture states.

Table 4
Mechanical parameters: Dynamic elastic modulus under different moisture conditions (0%, 40% and 100%).

Sp	E_{dyn} (MPa)	E_{dyn40} (MPa)	E_{dyn100} (MPa)	$\%_{0-40}$	$\%_{40-100}$	$\%_{0-100}$	$\%_{0-40}/\%_{0-100}$
N01	7509	5444	5399	27.50	0.83	28.10	0.98
N02	11,543	9776	9529	15.30	2.53	17.45	0.88
N03	6357	4591	4462	27.78	2.80	29.81	0.93
N04	6401	4344	4038	32.13	7.04	36.91	0.87
N05	11,948	9415	8851	21.19	6.00	25.92	0.82
N06	5212	3989	3436	23.47	13.86	34.08	0.69
N07	7459	6063	5667	18.72	6.53	24.02	0.78
N08	3755	3109	2931	17.20	5.73	21.94	0.78
N09	8370	7244	6549	13.45	9.60	21.76	0.62
N10	3990	2825	2501	29.20	11.47	37.32	0.78
N11	9579	7737	7558	19.23	2.31	21.10	0.91
N12	6155	5299	5168	13.91	2.47	16.04	0.87
N13	6687	4970	4061	25.68	18.29	39.27	0.65
N14	8787	5432	5403	38.18	0.53	38.51	0.99
N15	6007	4061	3928	32.39	3.28	34.61	0.94
N17	5113	4589	4485	10.25	2.27	12.28	0.83
Mean	7179	5555	5247	22.85	5.97	27.45	0.83
SD	2390	2040	2010	7.98	5.06	8.67	0.11

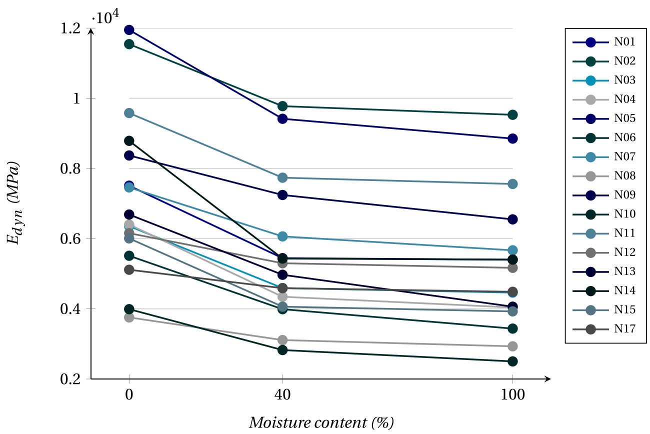

Fig. 9. Dynamic elastic modulus values under different moisture states.

quarries. It has compared results obtained from the studied ancient specimens to those obtained by Verstringe for Dienstian sandstone, from ancient specimens [3] (Section 1). Verstringe studied 3 specimens of Dienstian ferruginous sandstone and obtained a loss of UCS between 50% and 59%. The range obtained for San Cristóbal's stone from a larger population is between 2.03% and 64.14%, so greater

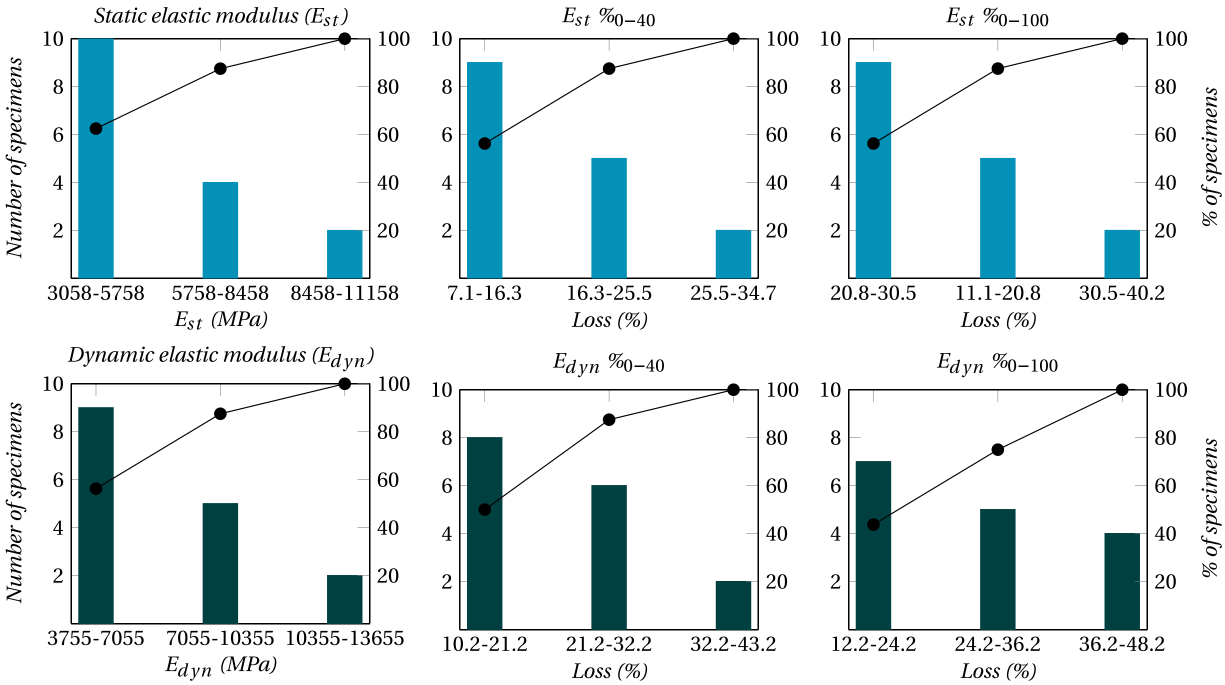

Fig. 10. Pareto diagrams of static and dynamic elastic modulus values.

Table 5
Mechanical parameters: Uniaxial compressive strength under different moisture conditions (0% and 100%).

Sp	UCS (MPa)	UCS_{100} (MPa)	Loss (MPa)	Loss (%$_{0-100}$)
N01	4.304	2.997	1.31	30.35
N02	8.338	2.990	5.35	64.14
N03	5.283	4.611	0.67	12.72
N04	5.898	3.436	2.46	41.74
N05	8.730	5.374	3.36	38.45
N06	4.845	3.878	0.97	19.95
N07	4.913	4.760	0.15	3.11
N08	3.087	2.754	0.33	10.78
N09	8.199	5.035	3.16	38.59
N10	5.533	5.421	0.11	2.03
N11	6.084	4.640	2.04	30.58
N12	6.029	3.256	2.77	45.99
N13	4.536	2.253	2.28	50.33
N14	4.656	3.683	0.97	20.90
N15	4.241	2.587	1.65	38.99
N17	5.884	4.214	1.67	28.39
Mean	5.697	3.868	1.83	29.82
SD	1.601	1.024	1.39	17.43

loss of UCS are reached in this case with respect to Dienstian sandstone. In addition to it has been obtained loss of UCS for San Critóbal's stone (64.14%) close to the highest losses found for other sandstones (78.1% [19] or 71.6% [20]), the low values obtained for UCS in dry state are also notable. The range obtained, between 3.09 MPa and 8.73 MPa is similar to that obtained by Verstringe for Dienstian sandstone, but quite lower than the UCS in dry state of other sandstones like those studied by Hawkings (74.5–195.2 MPa) [19], Dyke (11–70 MPa) [18] or Kim (74.5–195.2 MPa) [21]. Fig. 12 shows a Pareto diagram with the most frequent ranges of results. Note the abnormal values of UCS loss obtained for specimens S07 and S10.

The same moisture content (100%) does not produce a similar effect on the loss of UCS of the studied specimens. This can be seen in Fig. 13, which represents UCS of dry specimens in a crescent order (blue line) versus the loss of UCS in saturated state (orange line).

Results also show that porosity is not the only factor to be considered in the total loss of mechanical properties of the studied stone when it is affected by moisture content. In Fig. 14, it can be seen that the narrow range obtained for porosity does not correspond to the dispersion obtained for the total loss (saturated state) of UCS, E_{st} and E_{dyn} (%) in each one of the specimens studied.

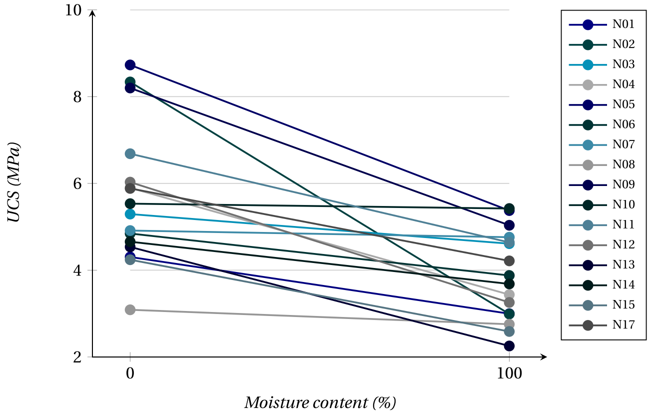

Fig. 11. Uniaxial compressive strength values under different moisture states.

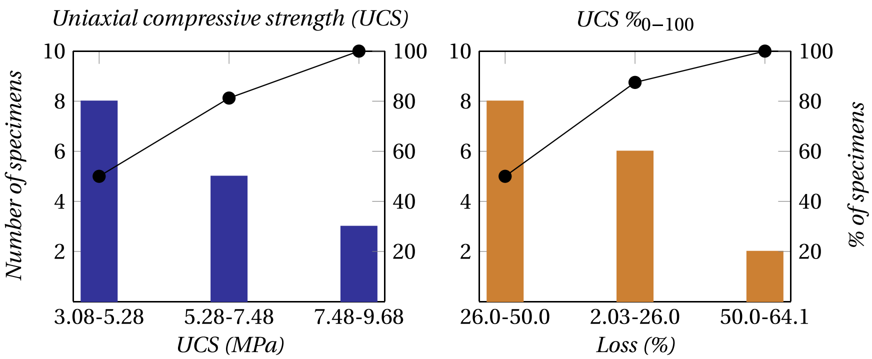

Fig. 12. Pareto diagrams of uniaxial compressive strength values.

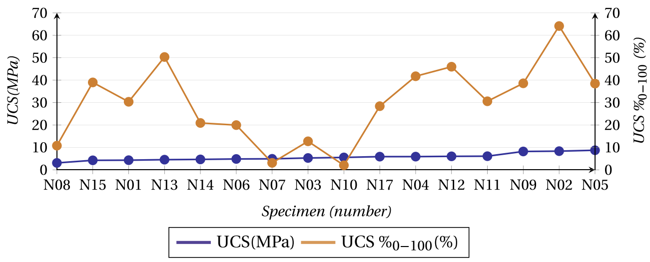

Fig. 13. Dispersion between porosity and absorption.

3.4. Relationships between results in dry state and wet states (0%, 40% and 100%)

Once it has been confirmed the variation of the main mechanical properties of San Cristóbal stone (E_{st}, E_{dyn} and UCS) under different moisture states, in this section different equations are proposed to correlate them.

The first approach was to establish direct horizontal correlations between E_{st}, E_{dyn} and UCS under different moisture states through simple regressions (Equations 1–3, 6–8 and 11). After achieving equations with high levels of confidence apart from Equation 11, other equations of correlation were explored to assess if their coefficient of determination could be increased by considering other parameters, such as bulk density or porosity, and/or other types of correlations, such as multiple regressions (Equations 4, 5, 9, 10 and 12). Finally, cross-correlations between the different parameters are exposed (Equations 13–16). Table 6 shows these correlation ecuations including both the type and the correlation coefficient (R^2).

As can be seen in Table 6, in general, simple regression is sufficient to reach high values of the coefficient of determination (R^2). It is only necessary to use multiple regression to significantly improve the existing correlation coefficient between UCS and UCS_{100}, adding both bulk density and porosity (Equations 11 and 12). However, and despite this improvement, the high correspondence achieved for relationships between elastic muduli with different moisture content are not found between UCS in dry and saturated states, and the

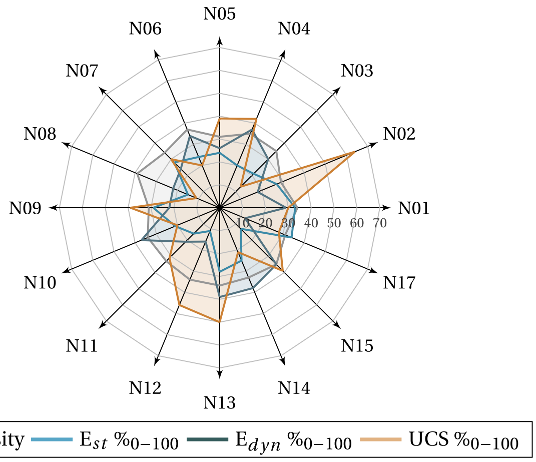

Fig. 14. Spiderweb Diagram (Porosity (%), E_{st} $\%_{0-100}$ (%), E_{dyn} $\%_{0-100}$ (%), UCS $\%_{0-100}$ (%)).

Table 6
Equations of correlation between mechanical propierties under different moisture states for San Cristobal's stone.

	Equation	Type	R^2
(1)	$E_{st} = 173.327 + 1.173$ *E_{st40}	Simple regression	0.95
(2)	$E_{st} = 91.192 + 1.288$ *E_{st100}	Simple regression	0.93
(3)	$E_{st40} = -31.889 + 1.089$ *E_{st100}	Simple regression	0.97
(4)	$E_{st} = -10{,}575.1 + 1.058$ *E_{st40} + 6,35801 * ρ_{bulk}	Multiple regression	0.97
(5)	$E_{st} = 6453.21 + 1.029$ *E_{st40} - 165,766 *P	Multiple regression	0.97
(6)	$E_{dyn} = 939.136 + 1.123$ *E_{dyn40}	Simple regression	0.92
(7)	$E_{dyn} = 1201.32 + 1.139$ *E_{dyn100}	Simple regression	0.92
(8)	$E_{dyn40} = 267.129 + 1.007$ *E_{dyn100}	Simple regression	0.98
(9)	$E_{dyn} = 3945.99 + 1.156$ *E_{dyn40} - 1.797 * ρ_{bulk}	Multiple regression	0.92
(10)	$E_{dyn} = 1385.49 + 1.173$ *E_{dyn40} - 60.53 *P	Multiple regression	0.92
(11)	UCS = 26.24 + 0.794 *UCS_{100}	Simple regression	0.50
(12)	UCS = 1177.28 + 0.608 *UCS_{100} − 0.383 * ρ_{bulk} − 13.717 *P	Multiple regression	0.75
(13)	$E_{st} = 0.03 + 0.80$ *E_{dyn}[17]	Simple regression	0.96
(14)	$E_{st40} = 612.528 + 0.745$ *E_{dyn40}	Simple regression	0.90
(15)	$E_{st100} = 795.827 + 0.685$ *E_{dyn100}	Simple regression	0.90
(16)	$E_{st} = 570.716 + 0.932$ *E_{dyn40}	Simple regression	0.96

E_{dyn} (MPa); E_{st} (MPa); UCS (MPa); ρ_{bulk}: bulk density (kg/m^3); P: porosity (%)

lower coefficients of determination correspond to those obtained for UCS. This matches to the results obtained for UCS and discussed in section 3.3. It is highlighted the high correlation that exists between the static elastic modulus and dynamic elastic modulus under different moisture states (Equations 13 and 16).

As a way of validating results and to better understand the significance of obtained relationships, some of the equations in Table 6 have been analysed. Fig. 15 shows the simple regression of Equations (1), (2), (3), (6), (7) and (8), the simplest ones that show higher correlation coefficient (R^2). It can be seen that the high R^2 obtained of these equations corresponds to results that are distributed along the corresponding lines of regression. This fact contributes to validate results since the correlation coefficients are obtained from a quite homogeneous distribution of the 16 result points (16 specimens) along each one of the lines.

Likewise, Fig. 15 shows Equations (1), (2), (6), and (7) with slopes higher than 1, evidencing how elastic modulus is higher in dry state than in wet states, as expected. The slope in equations (3) and (8) is closer to 1. This shows the low decrease of both static and dynamic moduli between 40% moisture content to saturated state (Fig. 8 and Fig. 9). The similarity between the slopes of equations (1) - (2), for E_{st}, and (6) - (7), for E_{dyn}, indicates the homogeneous response of San Cristóbal's stone elasticity to moisture content (from dry state to a moisture content of 40% or above).

Despite the consistency of the results, mainly for elastic moduli, the main limitation of this study lies on the application range of them. They can be considered for mechanical behaviour of natural stones characterized by a high porosity (around 30%) and a low elastic modulus (6000–10,000 MPa). However, results obtained for the influence of moisture content on UCS differ from those obtained by Verstringe [3], even though Diestian sandstone counts on a similar porosity. The main difference between this stone and San Cristóbal's stone was found in their mineralogical composition (see Section 1), so future research will explore relationships between chemical composition and mechanical properties of this stone under different moisture conditions.These relationships could explain trends and patterns found in the present study.

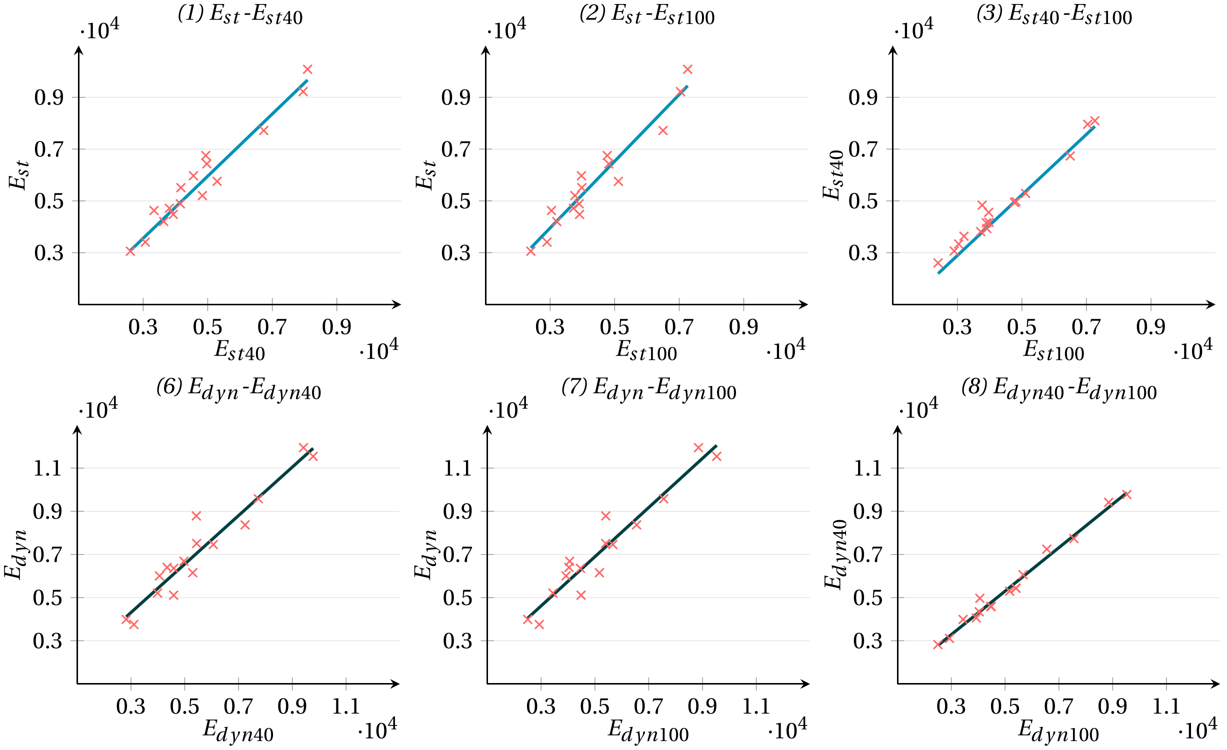

Fig. 15. Graphical representation of the equations of correlation (simple regression).

4. Conclusions

After having studied some physical properties of ancient San Cristóbal's stone and its main mechanical properties (static and dynamic elastic moduli and uniaxial compressive strength) under different moisture contents, the most important conclusions are enumerated as follows:

- Ancient San Cristóbal's stone is characterized by a mean density of 1776 Kg/m^3, a mean porosity of 33.77% and a mean absorption of 17.04%. Despite the linear relationship found between density and porosity, the linearity between porosity and absorption is not clearly recognized due to results obtained from 5 of the 16 studied specimens (31% of them).
- Deformability increases with the increase of moisture content. Both, static and dynamic elastic moduli decrease in the range dry to 40% of moisture content than between 40% of moisture to saturated state. This is more pronounced in the case of dynamic elastic modulus, with a decrease of 22.85% between dry state to 40% of moisture content, while the static elastic modulus decreases a mean of 16.98% in the same range of moisture content.
- Uniaxial compressive strength decrease notably from dry to saturated state. A mean value of UCS loss is established in 29.82%. However, UCS losses of more than 30% were found in 9 of the 16 studied specimens (56%), reaching a maximum loss value of 64.14%.
- Empirical relationships have been found for San Cristóbal's stone between the studied mechanical properties under different moisture contents: (i) High coefficients of determination (R2) were achieved for relationships between elastic moduli by means of simple regressions and without the need of using multiple regressions, which does not improve simpler equations in general. Coefficients of regression of 0.97 and 0.98 were reached with simple regressions; (ii) The experimental equations obtained to correlate uniaxial compressive strength in dry and saturated states do not count on a reliable coefficient of determination (0.50 through simple regression and 0.75 with a multiple regression
- Equations between dynamic and static elastic moduli have been defined in this study for dry state, 40% of moisture content and saturated state (Eq (13) to (16)). High coefficients of determination were achieved for them (0.90–0.96). This allows the conversion of data that can be determinated in situ by means of non-destructive techniques, such as dynamic elastic modulus or moisture content, into information about deformability (static elastic modulus) that can be used in the development of numerical models for structural analyses.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing

interests: Victor Compan reports financial support was provided by Consejería de Economía, Conocimiento, Empresas y Universidad of the Andalusian Regional Government.

Data Availability

Data will be made available on request.

Acknowledgments

This work has been financially supported by Research Project US-1381164, funded by the Andalusian Regional Government (Spain).

References

[1] R. Bustamante, P. Vazquez, N. Prendes, Properties of the ignimbrites in the architecture of the historical center of arequipa, peru, Appl. Sci. 11 (22) (2021) 10571, https://doi.org/10.3390/app112210571.
[2] E. Işık, A. Büyüksaraç, E. Avşar, M.F. Kuluöztürk, M. Günay, Characteristics and properties of bitlis ignimbrites and their environmental implications, Mater. De. Constr. 70 (338) (2020) 214, https://doi.org/10.3989/mc.2020.06519.
[3] E. Verstrynge, R. Adriaens, J. Elsen, K.V. Balen, Multi-scale analysis on the influence of moisture on the mechanical behavior of ferruginous sandstone, Constr. Build. Mater. 54 (2014) 78–90, https://doi.org/10.1016/j.conbuildmat.2013.12.024.
[4] I. Lombillo, C. Thomas, L. Villegas, J. Fernández-Álvarez, J. Norambuena-Contreras, Mechanical characterization of rubble stone masonry walls using non and minor destructive tests, Constr. Build. Mater. 43 (2013) 266–277, https://doi.org/10.1016/j.conbuildmat.2013.02.007.
[5] M.-G. Masciotta, J.C. Roque, L.F. Ramos, P.B. Lourenço, A multidisciplinary approach to assess the health state of heritage structures: The case study of the church of monastery of jerónimos in lisbon, Constr. Build. Mater. 116 (2016) 169–187, https://doi.org/10.1016/j.conbuildmat.2016.04.146.
[6] M. Cámara, M. Romero, P. Pachón, V. Compán, P.B. Lourenço, Integration of disciplines in the structural analysis of historical constructions. the monastery of san jerónimo de buenavista (seville-spain), Eng. Struct. 230 (2021), 111663, https://doi.org/10.1016/j.engstruct.2020.111663.
[7] O. Katz, Z. Reches, J.-C. Roegiers, Evaluation of mechanical rock properties using a schmidt hammer, Int. J. Rock. Mech. Min. Sci. 37 (4) (2000) 723–728, https://doi.org/10.1016/S1365-1609(00)00004-6.
[8] Z.A. Moradian, M. Behnia, Predicting the uniaxial compressive strength and static young's modulus of intact sedimentary rocks using the ultrasonic test, Int. J. Geomech. 9 (1) (2009) 14–19, https://doi.org/10.1061/(ASCE)1532-3641(2009)9:1(14).
[9] J. Sato, J. Itoh, O. Aydan, T. Akagy, Prediction of time-dependent behaviour of a tunnel in squeezing rocks, in: FMGM'95, 4th International Symposium, Bergamo, 1995, 47–54.
[10] A. Besharatinezhad, M.A. Khodabandeh, N. Rozgonyi-Boissinot, Á. Török, The effect of water saturation on the ultrasonic pulse velocities of different stones, Periodica Polytechnica (feb), Civ. Eng. (2022), https://doi.org/10.3311/PPci.18701 (feb).
[11] H. Karakul, R. Ulusay, Empirical correlations for predicting strength properties of rocks from p-wave velocity under different degrees of saturation, Rock. Mech. Rock. Eng. 46 (5) (2013) 981–999, https://doi.org/10.1007/s00603-012-0353-8.
[12] O. Sass, H. Viles, How wet are these walls? testing a novel technique for measuring moisture in ruined walls, J. Cult. Herit. 7 (4) (2006) 257–263, https://doi.org/10.1016/j.culher.2006.08.001.
[13] J.C. Rodríguez-Estévez, Cantera y obral.Las canteras de la Sierra de San Cristóbal y la Catedral de Sevilla, Ayuntamiento de El Puerto de Santa María, 1998.
[14] F. Pozo, R. Gil, E. Méndez, Intervención arquitectónica puntual en Monasterio de San Jerónimo de Buenavista (Sevilla), 2010.
[15] A. Barrios-Padura, J. Barrios-Sevilla, J. García-Navarro, Bearing capacity diagnosis of santiago church (jerez de la frontera, spain), Constr. Build. Mater. 25 (5) (2011) 2519–2527, https://doi.org/10.1016/j.conbuildmat.2010.11.090.
[16] M.E. Rodríguez-Mayorga, Rehabilitación del templo parroquial de santiago apóstol en jerez de la frontera: Anamnesis, diagnosis, terapia y control, Ph.D. thesis, Universidad de Sevilla , 2011.
[17] J.R. Baeza, V. Compán, G. Castillo, M. Cámara, P. Pachón, Determining static elastic modulus of weak sandstone in andalusian historical constructions from non-destructive tests: San cristóbalas stone, J. Build. Eng. 57 (2022), 104864, https://doi.org/10.1016/j.jobe.2022.104864.
[18] C.G. Dyke, L. Dobereiner, Evaluating the strength and deformability of sandstones, Q. J. Eng. Geol. 24 (1) (1991) 123–134, https://doi.org/10.1144/GSL.QJEG.1991.024.01.13.
[19] A.B. Hawkins, B.J. McConnell, Sensitivity of sandstone strength and deformability to changes in moisture content, Q. J. Eng. Geol. 25 (2) (1992) 115–130, https://doi.org/10.1144/GSL.QJEG.1992.025.02.05.
[20] A. Shakoor, E.H. Barefield, Relationship between unconfined compressive strength and degree of saturation for selected sandstones, Environ. Eng. Geosci. 15 (1) (2009) 29–40, https://doi.org/10.2113/gseegeosci.15.1.29.
[21] E. Kim, H. Changani, Effect of water saturation and loading rate on the mechanical properties of red and buff sandstones, Int. J. Rock. Mech. Min. Sci. 88 (2016) 23–28, https://doi.org/10.1016/j.ijrmms.2016.07.005.
[22] M.A. B. López, Caracterización y estado de alteración química de los materiales empleados en la construcción de la catedral de sevilla, Ph.D. thesis, Universidad de Sevilla 1988.
[23] J. Baeza, V. Compán, M. Cámara, P. Pachón, G. Castillo, Identificación de las propiedades mecánicas de la piedra de san critóbal mediante técnicas no destructivas, in: REHABEN 2018, Euro-American Congress: Construction Pathology, Rehabilitation, Technology and Heritage Management, 2018, 1098–1106.
[24] IFAPA, Instituto de Investigación y Formación Agraria y Pesquera. Estación meteorológica de Jerez de la Frontera. Junta de Andalucía.(2023). ⟨https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web/estacion/11/2⟩.
[25] EN1936:2006.Natural stone test methods - Determination of real density and apparent density, and of total and open porosity , 2006.
[26] EN 13755:2008.Natural stone test methods - Determination of water absorption at atmospheric pressure , 2008.
[27] EN 14146:2004.Natural stone test methods - Determination of the dynamic modulus of elasticity (by measuring the fundamental resonance frequency) , 2004.
[28] EN 14580:2005.Natural stone test methods - Determination of static elastic modulus , 2005.
[29] EN 1926:2006.Natural stone test methods - Determination of uniaxial compressive strength , 2007.
[30] M. Kwasniewski, P. Rodriguez-Oitabén, Effect of water on the deformability of rocks under uniaxial compression, in: ISRM Regional Symposium - EUROCK 2009, Cavtat, Croatia.2009.