International Journal of Rock Mechanics & Mining Sciences 147 (2021) 104915

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

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

Improving uniaxial compressive strength estimation of carbonate sedimentary rocks by combining minimally invasive and non-destructive techniques

David Benavente[a,*], Rafael Fort[b], Miguel Gomez-Heras[c]

[a] Universidad de Alicante. Dpto. Ciencias de la Tierra y del Medio Ambiente, 03690, Alicante, Spain
[b] Instituto de Geociencias (CSIC-UCM), 28040, Madrid, Spain
[c] Universidad Autónoma de Madrid, 28049, Madrid, Spain

ARTICLE INFO

Keywords:
Ultrasounds
Microdrilling
Leeb hardness
Limestone
Rock strength
Stone decay

ABSTRACT

Uniaxial compressive strength (UCS) is the most used parameter to measure rock strength. However, restrictions in sampling large volume of material, the need of very large set of results and onsite characterisation of UCS non-destructively are requirements in many scientific and engineering investigations. The estimation of UCS from a single non-destructive or minimally invasive technique (NDT) may result incomplete because each NDT is sensitive to different compositional and textural factors.

This paper combines open porosity, P-wave velocity, Leeb hardness and micro-drilling resistance force to estimate USC for a wide range of carbonate sedimentary rock types with different petrographic characteristics. Results reveal that mineralogical composition significatively affects micro-drilling resistance force profiles and P-wave velocity values, especially for quartz-bearing rocks. In addition, texture controls substantially the reproducibility of tests sensible to rock surface properties, such as Leeb hardness and micro-drilling resistance force.

Fifteen simple and multiple expressions for UCS are fitted. Linear expressions have shown better coefficients of determination (R^2) than non-linear equations because of the linearity shown by individual parameters. Curve fitting improves as the number of petrophysical parameters increase in the multiple linear regression analysis. The best correlation is found when the equation incorporates all the mechanical parameters obtained non-destructively as well as open porosity ($R^2 = 0.910$). Leeb hardness is always the most significant variable of the fitted regressions and its addition into multiple linear equations causes an increase of R^2. Open porosity also improves R^2 whereas drilling force and P-wave velocity have a lower statistical weight in the expressions. The UCS estimation from all NDT, without considering open porosity, shows a good correlation ($R^2 = 0.899$), which presents the advantage that they can be obtained non-destructively with portable equipment and can provide a numerous set of results at relatively low cost.

1. Introduction

Uniaxial compressive strength (UCS) is, arguably, the most relevant parameter in most fields of applied geosciences, engineering and material science, as it establishes the mechanical response of material under unconfined conditions. UCS tests are destructive and require a considerable volume of material, as rock sampling of both sound and weathered samples to prepare cores in different numbers and sizes depending on the standard test is necessary for performing measurements. However, the sampling of a large volume of material is not allowed or advisable in many studies in the field of rock mechanics, mining, civil and geological engineering, as well as building and heritage studies. In addition to this, the need for onsite characterisation or very large set of results limit the scope of UCS characterisation using standard tests and require the use of estimators from non-destructive measurements instead.

Recent investigations on physico-mechanical properties and durability of rocks are focusing on the use of onsite and non-destructive or minimally invasive techniques (NDT) for UCS estimation.[1–8] There is a wide range of portable NDTs used for these estimations: the most common and widely tested techniques include the measurement of the ultrasonic wave velocity, surface hardness using impact-based

---

* Corresponding author.
E-mail addresses: david.benavente@ua.es (D. Benavente), rafort@geo.ucm.es (R. Fort), miguel.gomezheras@uam.es (M. Gomez-Heras).

https://doi.org/10.1016/j.ijrmms.2021.104915
Received 3 July 2020; Received in revised form 19 May 2021; Accepted 8 September 2021

equipment (such as Schmidt hammer or Leeb hardness test) and the Drilling Resistance Measurement System (DRMS) test (so-called micro-drilling). These non-destructive portable techniques provide a larger amount of fast and low-cost measurements than UCS standard tests. Hence, research on the relationships between these techniques and UCS for a wide variety rock types is an increasingly hot topic.[9–11]

Methods based on elastic ultrasonic waves measurement are the most common properties used for estimating UCS non-destructively.[12–17] Among these, the compressional or primary (P) wave velocity, Vp, (also named ultrasonic pulse velocity) is the most frequently used because of its easy determination. Ultrasound penetrate deeply in the materials so it is suitable to characterise large volumes easily. Shear or secondary (S) elastic wave velocity, Vs measurement is usually performed in the lab in combination with P-waves for the calculation of the Young and Poisson dynamic elastic moduli. Wave propagation depends substantially on several material factors, such as mineralogy, texture, anisotropy, density, grain size and shape, porosity and pore and fissure size as well as the presence of water, precipitated salts, etc.[18–20] Although these factors also affect the mechanical strength of rocks, some of them do in a different way, which limits the use of Vp for UCS estimation. For example, the presence of water or precipitated salts in the pore space of rocks increase Vp values but diminish strength.[21–23] The mineralogical composition also influences the Vp values. For example elastic wave velocity values of rocks with quartz and feldspar are lower than those with calcite and dolomite,[22] which means that the occurrence of quartz in the rock will underestimate USC values obtained from Vp data.

Surface rock hardness or rebound hardness techniques measure the rebound or the deceleration of a spring-loaded mass impacting against the surface of a sample with a defined energy. The Schmidt hammer is probably the best-known and most widely used rebound method for the estimation of mechanical strength of materials.[24,25] Nevertheless, Schmidt hammer can leave impact marks and even destroy rock surfaces, which in some building and heritage studies would be unacceptable. Leeb rebound hardness test uses a much smaller impact body (3 mm diameter tip size) and applies a much lower impact energy (11.5 Nmm for a D-probe) so it can be considered as an almost non-destructive alternative to Schmidt Hammer to characterise surface rock hardness. Leeb rebound test is more accurate than Schmidt hammer and other non-destructive methods.[26–28] Likewise, existing research shows accurate correlations between Leeb hardness and UCS.[29–33] Therefore, Leeb hardness was selected as the surface rock hardness technique to estimate UCS. Rebound hardness techniques are sensitive to rock surface properties, including superficial alterations, superficial crusts, etc., which can interfere in the estimation of UCS of the whole sample.

DRMS test is a minimally invasive technique that measures drilling resistance (torque) on a material. This technique has been successfully applied to the onsite assessment of stone quality, in both at a quarry and on an existing structure, and in the determination of weathering extent in depth on buildings.[34,35] Changes in the drilling resistance or penetration force profiles are commonly related to rock alteration layers or to the presence of consolation products to a certain depth.[36–38] Surprisingly, Little research has been made to correlate DRMS with the mechanical properties of rocks.[10,35,38] Therefore, more research is needed to understand the influence of rock texture on micro-drilling force-depth profiles in terms of a better estimation of physico-mechanical properties of rocks. Mineral hardness and porosity affect substantially the drilling penetration force.[39] The downfall of this technique is that the drill causes a small hole in the material, typically with a penetration depth of 20–30 mm. Under this experimental condition, the drilling penetration force is sensitive to rock surface properties, as in the case of rebound hardness techniques.

Although all these non-destructive tests have a direct relation to UCS, they are sensitive to different rock parameters. Thus, the correlation between UCS and an individual NDT parameter is not completely accurate. To overcome this, there are in the literature numerous attempts to improve correlations with UCS through combining several non-destructive or minimally invasive techniques,[7,40–42] establishing straightforward correlations as well as other mathematical methods.[9,43] The SonReb method, combining Vp and Schmidt hammer is arguably one of the most widely used and standardised combined methods.[41,44,45]These attempts were based on the assumption that a variety of factors affects NDT measurements in competing ways, so their combined use might can improve the accuracy of the estimated UCS as a result of a “balancing effect”.[46] Hence, the combination several NDT will only provide more information than a single technique when the combined NDT are sensitive to different parameters.[44]

Table 1

Petrological classification, mean particle size and mineralogical composition of the studied carbonate sedimentary rocks. Reference includes information on the mean grain diameter: fine-grained, F (<0.5 mm); medium, M (0.5–2 mm); and coarse, C (>2 mm); and porosity: non-porous, nP (<10%); and porous, P (>10%) rocks.

Ref.	Classification	Mean grain size	Mineralogical composition (%)		
			Calcite	Quartz	Dolomite
nPF-1	Fossiliferous limestone	Fine	100		
nPF-2	Fossiliferous limestone	Fine	100		
nPF-3	Microcrystalline limestone	Fine	100		
nPF-4	Fossiliferous limestone	Fine	100		
PF-5	Dolostone	Fine	20	5	75
PF-6	Biocalcarenite	Fine	90	10	
PF-7	Biocalcarenite	Fine	75	25	
PF-8	Biocalcarenite	Fine	90	10	
PF-9	Biocalcarenite	Fine	80	15	5
PF-10	Biocalcarenite	Fine	90	10	
PF-11	Calcarenite	Fine	70	20	10
PF-12	Calcarenite	Fine	60	20	10
PF-13	Biocalcarenite	Fine	85	15	
PF-14	Biocalcarenite	Fine	90	10	
PF-15	Biocalcarenite	Fine	90	10	
PF-16	Biocalcarenite	Fine	85	15	
nPM-17	Oolitic limestone	Medium	100		
nPM-18	Oolitic limestone	Medium	100		
nPM-19	Oolitic limestone	Medium	100		
PM-20	Oolitic limestone	Medium	100		
PC-21	Biocalcirrudite	Coarse	95	5	
PC-22	Biocalcirrudite	Coarse	95	5	
PC-23	Biocalcirrudite	Coarse	98	2	
PC-24	Biocalcirrudite	Coarse	95	5	

This paper aims to estimate the uniaxial compressive strength by combining non-destructive or minimally invasive techniques for a wide range of carbonate sedimentary rock types with different petrographic characteristics. Three well-established parameters that allow onsite mechanical characterisation using portable equipment were selected: P-wave velocity, surface hardness using Leeb hardness test, and DRMS. For this purpose, a statistical analysis was conducted to empirically establish correlations between these parameters. The improvement of these correlations by the addition of the open porosity as an index parameter of the rock was also evaluated. Results are discussed in the context of the influence of rock texture and mineralogical composition on mechanical properties, which affect differently mechanical parameters, and on the reproducibility of measurements. Some practical aspects of this study are highlighted so to use the most appropriate combinations of non-destructive tests to estimate uniaxial compressive strength depending on the context of the study and the petrological properties of rocks.

2. Materials and methods

2.1. Rocks

Twenty-four carbonate sedimentary rock were investigated including biocalcarenites, biocalcirrudites, dolostones and fossiliferous, oolitic and microcrystalline limestone (Table 1). These rock types were chosen among carbonate building stones quarried in Spain because of their different mineralogical petrographic and petrophysical and mechanical characteristics. Cubic samples with different size were prepared for testing accordingly to standard tests described in the next section.

We classified the studied rocks based on the following textural properties:

(i) rocks were divided into three textural groups depending on the particle size: fine-grained (F), where the mean particle diameter is smaller than 0.5 mm; medium-grained (M) with particle diameter 0.5–2 mm; and coarse-grained (C) for particle diameter larger than 2 mm.[20]

(ii) studied rock samples were also classified into non-porous or low porous (nP), with porosity values lower than 10%, and porous (P), in which porosity is greater than 10%. The 10% porosity threshold is set because of the reported influence of open porosity on rock properties, including fluid transport, mechanical and durability of rocks. Below 10% porosity, pore connectivity dramatically decreases because of the closure and elimination of pore throats. Conversely, in rocks of a porosity higher than 10% pore space is well-connected and pore size distribution becomes the most important microstructure parameter.[47,48]

For most of the studied rocks, the predominant rock-forming mineral is calcite, and quartz and dolomite as minor minerals. Mineralogy was established using X-ray diffraction (Table 1).

2.2. Petrophysical and mechanical properties

The effective porosity and bulk density were selected as the rock index parameters. The mechanical proprieties were characterised using (i) non-destructives tests (ultrasonic wave velocity and Leeb hardness); (ii) a minimal destructives test (micro-drilling resistance); and (iii) a destructive test (uniaxial compressive strength).

We selected effective porosity as an index property of rocks because it is considered as a key parameter related to rock strength, permeability and durability. Effective porosity, P (%), was determined using the vacuum water saturation test.[49] Dried samples were weighed and placed in a vacuum chamber at 20 ± 7 mbar in order to eliminate any trapped air from the pore system. Distilled water was slowly introduced until the samples were completely covered and, finally, atmospheric pressure was re-established. The saturated and immersed weight of each sample was recorded. Bulk (apparent) density, ρ_b (g/cm^3), was determined as the ratio of dry weight to the volume of 5 cm cubes according to standard.[49]

The ultrasonic measurements were carried out using the transmission method, which consists of two piezoelectric transducers coupled to the sample at constant pressure. Compressive or primary (P) wave velocity, Vp (m/s), also named ultrasonic pulse velocity, was measured using polarised Panametric transducers (1 MHz). An emitting-receiving equipment (Panametrics-NDT 5058 PR) and an oscilloscope (TDS 3012B-Tektronix) were used to acquire and determinate the manual picking of the onset time of P-waves. A visco-elastic couplant (eco-gel) was used to ensure a good coupling between the transducers and the sample. Every measurement of the P waves was repeated three times in order to test the reproducibility of the characterisation.

Table 2

Physico-mechanical properties of the studied rocks. Mean values and coefficient of variation (CV) of bulk density (ρ_b), open porosity (P), P-wave velocities (Vp), Leeb hardness (LHD), micro-drilling resistance force (F) and uniaxial compressive strength (UCS).

Ref.	ρ_b (g/cm^3)	P (%)	Vp (m/s)	LHD	F (N)	UCS (MPa)
nPF-1	2.67 ± 0.01	1.30 ± 0.05	5948 ± 241	647 ± 18	69.91 ± 3.86	128.10 ± 13.72
nPF-2	2.66 ± 0.01	1.37 ± 0.03	5962 ± 201	625 ± 42	62.57 ± 5.69	135.70 ± 14.49
nPF-3	2.67 ± 0.04	0.85 ± 0.21	5916 ± 210	635 ± 37	77.17 ± 4.11	137.00 ± 11.80
nPF-4	2.66 ± 0.06	0.74 ± 0.09	6033 ± 190	695 ± 15	70.7 ± 8.03	98.10 ± 14.05
PF-5	2.30 ± 0.02	17.13 ± 0.41	3896 ± 193	419 ± 19	5.33 ± 0.32	57.00 ± 8.31
PF-6	2.26 ± 0.02	16.29 ± 0.30	3656 ± 135	454 ± 20	12.25 ± 0.87	35.50 ± 5.75
PF-7	2.17 ± 0.02	20.61 ± 0.31	3702 ± 105	408 ± 32	16.25 ± 1.89	27.90 ± 6.29
PF-8	2.26 ± 0.01	16.70 ± 0.24	3653 ± 139	428 ± 25	13.43 ± 1.54	34.30 ± 5.94
PF-9	2.22 ± 0.01	13.51 ± 0.77	3725 ± 104	398 ± 22	10.35 ± 0.57	74.00 ± 6.46
PF-10	2.19 ± 0.01	18.79 ± 0.80	3727 ± 143	434 ± 43	23.61 ± 2.91	61.9 ± 8.30
PF-11	2.37 ± 0.01	13.21 ± 0.50	4121 ± 189	477 ± 28	19.57 ± 2.13	85.1 ± 9.10
PF-12	2.20 ± 0.02	17.15 ± 0.70	3584 ± 109	407 ± 25	24.74 ± 3.69	46.29 ± 4.05
PF-13	2.1 ± 0.02	21.78 ± 0.03	3509 ± 121	320 ± 32	7.59 ± 0.75	38.20 ± 5.04
PF-14	2.26 ± 0.02	15.99 ± 0.61	3829 ± 150	460 ± 38	47.30 ± 9.06	72.07 ± 6.32
PF-15	2.20 ± 0.03	20.06 ± 0.30	3875 ± 137	392 ± 33	17.99 ± 1.95	63.2 ± 7.14
PF-16	2.11 ± 0.02	21.68 ± 0.93	3440 ± 187	364 ± 28	4.90 ± 0.66	39.93 ± 2.82
nPM-17	2.47 ± 0.2	8.62 ± 0.33	5621 ± 113	540 ± 65	42.38 ± 3.78	86.00 ± 5.42
nPM-18	2.56 ± 0.03	5.44 ± 0.31	5853 ± 192	599 ± 32	60.17 ± 3.11	116.4 ± 16.30
nPM-19	2.54 ± 0.02	1.14 ± 0.06	6406 ± 189	688 ± 23	56.14 ± 3.36	131.42 ± 14.20
PM-20	2.35 ± 0.01	14.53 ± 0.90	5002 ± 152	533 ± 48	25.64 ± 1.85	89.06 ± 10.60
PC-21	2.11 ± 0.03	20.35 ± 0.92	4880 ± 224	326 ± 115	20.73 ± 5.02	19.90 ± 7.08
PC-22	2.12 ± 0.04	19.01 ± 0.84	4905 ± 215	327 ± 46	29.54 ± 5.13	20.90 ± 6.38
PC-23	2.16 ± 0.05	11.94 ± 0.38	4168 ± 301	369 ± 117	15.00 ± 20.02	33.00 ± 5.42
PC-24	1.97 ± 0.01	24.72 ± 0.41	4186 ± 212	379 ± 153	18.87 ± 7.84	25.4 ± 2.31

For each rock type, three dried cubic samples were measured along three orthogonal directions and the anisotropy coefficient, ΔM(%), was calculated as follows:

$$\Delta M(\%) = \left(1 - \frac{2Vp, min}{Vp, int + Vp, max}\right) \cdot 100 \tag{1}$$

Where Vp,min, Vp,int and Vp,max are respectively the minimum, intermediate and maximum P-wave velocity values for the studied samples.[50] The anisotropy coefficient was also less than 5%, which can be considered as isotropic materials from the mechanical point of view.[51]

Leeb hardness, LHD, was measured using an Equotip 3 (Proceq) with a D-type impactor. Three dried samples were tested and six impacts were randomly made in each sample, half on the base and half on the opposite edge of the cube. Consequently, eighteen measurements were recorded for each type of rock. High and low outliers (upper 10% percent and lower 10% values) were discarded for calculating average values and standard deviation.

The determination of drilling resistance was carried out using a Drilling Resistance Measurement System (DRMS, SINT Technology). DRMS measures drill depth and penetration force for a given rotational

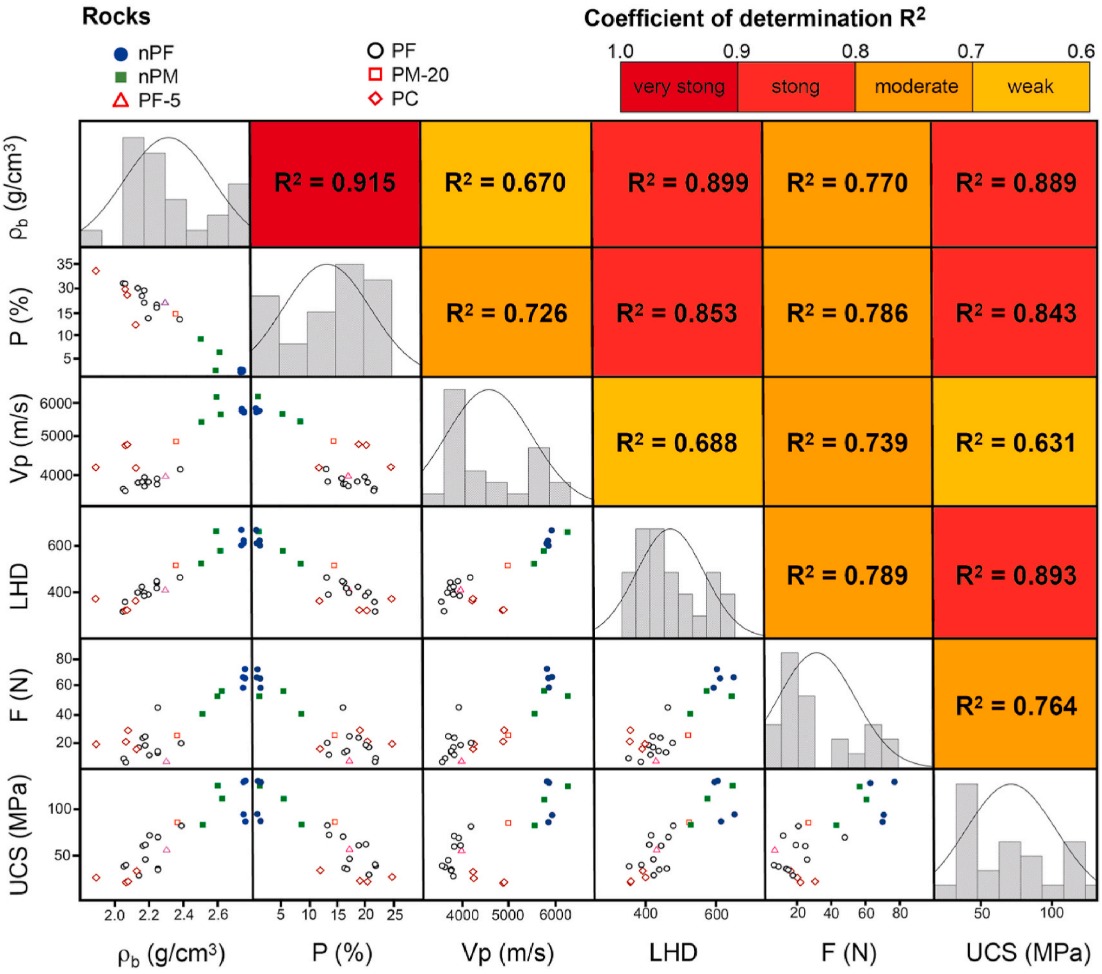

Fig. 1. Correlation matrix of the variables. Scatter plots below and on the left of the diagonal (lower triangle) show the relationships between bulk density (ρ_b), open porosity (P), P-wave velocities (Vp), Leeb hardness (LHD), micro-drilling resistance force (F) and uniaxial compressive strength (UCS). Closed symbols represent non-porous rocks whereas open symbols correspond to porous rocks. Values above and on the right of the diagonal (upper triangle) show the coefficient of determination (R^2) between variables. R^2 intervals are based on Evans.[58] The diagonal graphs show the frequency histograms of the corresponding variable.

and penetration speed. The operating conditions during the tests were ω = 600 rpm and 10 mm/min for the penetration rate as reported in previous investigations with similar rocks.[10,37,52,53]

The diamond drill bit (Diaber) has a 5 mm diameter flat edge. The total depth of penetration was 25 mm and the micro-drilling resistance force, F, was calculated as the average force value in the depth range from 0.5 to 25 mm. Five drills were performed in each dried sample. To reduce the drill bit wear effect, each drill bit was used for a maximum of 200 times, establishing a safety factor in relation to the observed drill bit wear effect, which is only noticeable after 250 drills.[37,52,54]

Uniaxial compressive strength, UCS (MPa), was performed following standard test EN 1926[55] using an Ibertest MEH-2000H/FIB-50 press. For each type of rock, ten 7-cm dried samples were tested.

The statistical analysis of the results, including descriptive statistics, dispersion plots and the step wise multiple regressions, were carried out using R code (R foundation).

3. Results and discussion

3.1. Influence of rock texture and porosity on mechanical and petrophysical properties

3.1.1. Uniaxial compressive strength

Table 2 summarises the mechanical and petrophysical properties of the tested rocks while Fig. 1 shows the relation between properties. Open porosity and bulk density show a large dispersion, which influences their mechanical properties. The studied rocks range from very low to high resistance according to Deere and Miller classification,[56] Their mean values vary from 20 to 90 MPa for porous rocks and 86–146 MPa for non-porous rocks. In porous rocks, texture considers the medium size of both grains and pores whereas, in non-porous rocks, texture only takes into account grain size. In non-porous rocks, pore space is defined by fissures, that includes mainly intercrystalline porosity and also stylolite, calcite veins and microfractures but in a small quantity. Strength and porosity show a negative relationship instead of the usual exponential trend. Porosity, on the one hand, contributes to a surface reduction of the loaded sample section. On the other hand, an increase in pore and fissure size drops the mechanical strength due to the strengthening the stress concentration at the pore and fractures tips.[57]

3.1.2. P-wave velocity

P-wave velocity and porosity show a negative linear relationship because propagation of ultrasonic waves is more difficult in rocks with a high pore space. The mineralogical composition also affects Vp. For example, quartz and feldspar lead to lower Vp values than calcite and dolomite.[22] Most of the studied porous rocks (calcarenites PF-6 to PF-16, and biocalcirrudites PC-21 to PC-24) contain quartz (Table 1). Vp decreases as quartz content increases for rocks with similar porosity, (Table 2). For example, PF-7 and PC-21 have similar porosity (~20%) but differ in their quartz content: 25% in PF-7 and 5% in PC-21. The

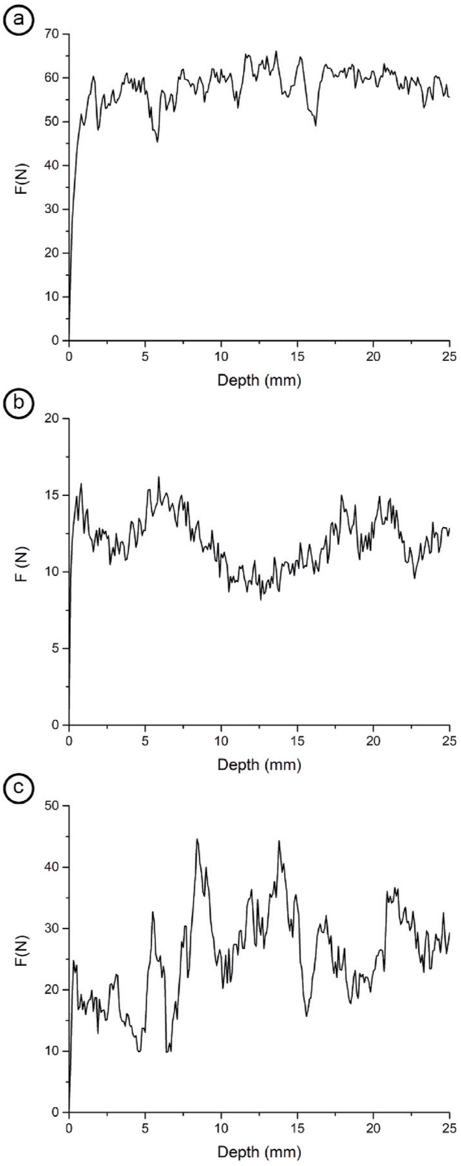

Fig. 2. Types of micro-drilling force-depth profiles: (a) normal, (b) fluctuating, and (c) randomly fluctuating. The selected examples correspond to nPM-18, PF-6 and PC-21, respectively.

different quartz content causes the difference in Vp observed: 3702 m/s in PF-7 and 4889 m/s in PC-21. If mineral content is not taken into account the interpretation of Vp could be misleading, as the presence of quartz in carbonate rocks can increase significantly their mechanical strength. This apparent contradiction between Vp values and UCS explains the cluster of points corresponding to calcarenites and calcirrudites that clearly are out of the linear trend between Vp and UCS (Fig. 1).

3.1.3. *Leeb hardness*

Open porosity and Leeb hardness have a negative relationship (Fig. 1). An increase in the open porosity buffers the rebound of the impact tip on the rock surface. In porous rocks, a larger grain size is coupled with larger pores. Hence, Coarse-grain porous rocks (PC-21 to PC-24 rocks) have lower LHD values than fine-grain porous rocks. In non-porous rocks, there is not a clear relation between grain size an LHD and medium-grained rocks (oolitic limestone nPM-17 to nPM-19) have slightly lower LHD values than fine-grained rocks (fossiliferous and microcrystalline limestone nPF-1 to nPF-4).

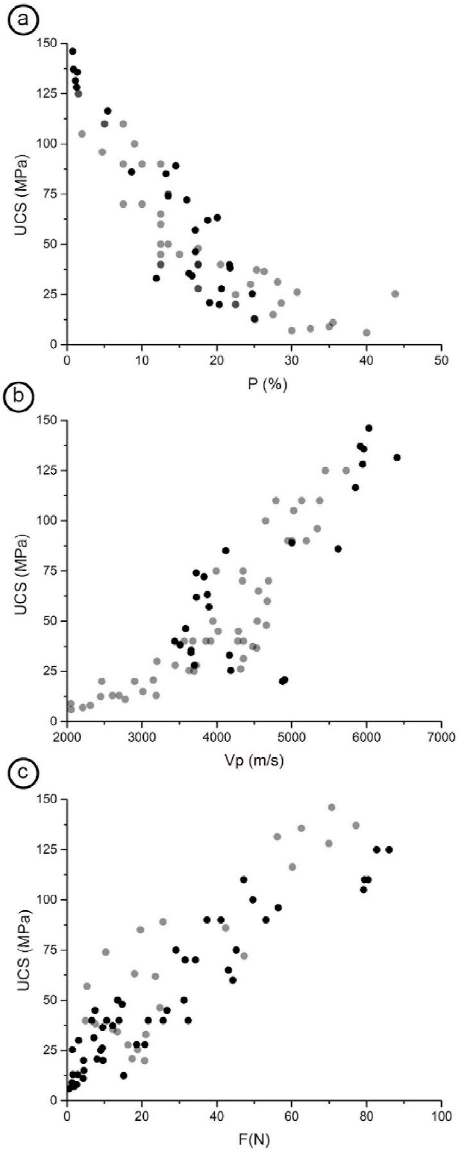

Fig. 3. Correlation between uniaxial compressive strength, UCS, with (a) open porosity (P), P-wave velocities (Vp) and micro-drilling resistance force (F) for the experimental data (black dots) and Theodoridou et al.[10] (grey dots).

3.1.4. *Micro-drilling resistance force*

Porosity influences substantially micro-drilling resistance force as porosity lowers penetration force significantly. Thus, porous rocks show lower values of F than non-porous rocks. Grain size and mineralogical composition do not significantly affect F of the studied carbonate rocks (Table 1). However, grain size and mineralogy cause a high dispersion in the F values (Table 2) as well as in the micro-drilling force-depth profiles (Fig. 2).

According to the recorded micro-drilling force-depth profiles, we can define three different profile patterns: normal, fluctuating and randomly fluctuating. Using the terminology of a semi-variogram in geostatistics as an analogy, a normal profile shows a stable sill. The range and the mean value of the micro-drilling force, barely fluctuates along depth (Fig. 2a). Monomineral rocks (e.g. nPF-4, nPM-17 and PM-20, Table 1) show this type of profile. Fluctuating profiles (Fig. 2b) are observed in polymineral rocks (Table 1), mostly in biocalcarenites (fine-grained porous rocks). The fluctuation in the drilling profile is therefore caused by a set of minerals with different hardness homogeneously distributed. Randomly fluctuating profiles exhibit a strong oscillation of the micro-drilling force around the mean value of the micro-drilling force

Table 3
Simple and multiple linear expressions linking uniaxial compressive strength, UCS (MPa), effective porosity, P (%), P-wave velocity, Vp (m/s), Leeb hardness, LHD and micro-drilling resistance force, F(N), for all the tested samples. R^2 is the coefficient of determination (R^2). Significant codes: p-value: 0 ‘***’; 0.001 ‘**’; 0.01 ‘*’; 0.05 ‘·’; >0.1 ‘-’.

Eq.	Linear expression	R^2	P	Vp	LHD	F
(1)	$UCS = 137.656–4.953\ P$	0.843	***			
(2)	$UCS = -78.588 + 3.276 \cdot 10^{-2}\ Vp$	0.631		***		
(3)	$UCS = -85.414 + 0.332 \cdot LHD$	0.893			***	
(4)	$UCS = 21.911 + 1.580\ F$	0.764				***
(5)	$UCS = 126.735\ \text{-}4.753\ P + 1.800 \cdot 10^{-3}\ Vp$	0.844	***	–		
(6)	$UCS = -15.690\ \text{-}1.668\ P + 0.231 \cdot LHD$	0.907	·		**	
(7)	$UCS = 103.907\ \text{-}3.614\ P + 0.506\ F$	0.860	**			–
(8)	$UCS = -87.202 + 0.001\ Vp + 0.321 \cdot LHD$	0.893		–	***	
(9)	$UCS = -1.200 + 6.807 \cdot 10^{-3}\ Vp + 1.323\ F$	0.771		.		**
(10)	$UCS = -70.496 + 0.280 \cdot LHD + 0.297\ F$	0.899			***	–
(11)	$UCS = -4.652\ \text{-}1.859\ P -2.479 \cdot 10^{-3}\ Vp + 0.237 \cdot LHD$	0.908	·	–	**	
(12)	$UCS = 118.685\ \text{-}3.789\ P -3.183 \cdot 10^{-3}\ Vp + 0.574\ F$	0.861	**	–		–
(13)	$UCS = -16.525\ \text{-}1.478\ P + 0.218 \cdot LHD + 0.142\ F$	0.908	–		**	–
(14)	$UCS = -66.486\ \text{-}1.589 \cdot 10^{-3}\ Vp + 0.285 \cdot LHD + 0.337\ F$	0.899		–	***	–
(15)	$UCS = 1.411\ \text{-}1.683\ P -4.140 \cdot 10^{-3}\ Vp + 0.221 \cdot LHD + 0.226\ F$	0.910	–	–	**	–

(Fig. 2c). This profile type occurs in the studied biocalcirrudites (coarse-grained porous rocks) that present large pores. The shape of this profile type is caused by the sharp change of the penetration force when the drilling bit goes from a pore to a grain, and vice versa. The occurrence of minerals with different hardness also enhances fluctuations, as can be observed in the case of the studied calcarenites.

3.2. Statistical analysis

Fig. 1 shows the good linear relation between uniaxial compressive strength and the mechanical parameters obtained using non-destructive tests (Vp, LHD and F) as well as open porosity and bulk density. These linear relations allow performing a stepwise multiple regression analysis without any logarithmic, exponential or inverse transformation. The use of linear expression has practical advantages: they are easy to use and their parametrization consumes less computing time. Moreover, as discussed below, the goodness of fit in linear equations is slightly better than non-linear relations, which support statistically the use of linear expressions in the present research. In the literature, non-linear expressions are widely found for sedimentary rocks that relate uniaxial compressive strength with porosity, P-wave velocity, Leeb hardness and drilling resistance.[43,59–64] The results in this paper were compared to data from Theodoridou et al.,[10] which characterised fifty limestone used as building and decorative stones. These authors tested uniaxial compressive strength, micro-drilling resistance force, effective porosity, bulk density and dynamic Young’s modulus. The later was calculated using ultrasonic wave velocity and a Poisson ratio equal to 0.2 following the procedure described in EN 14579.[65] According to this procedure, we calculated Vp from dynamic Young’s modulus and bulk density from Theodoridou et al.[10] These authors also found a linear relation between UCS and F with a $R^2 = 0.871$. Petrophysical data from Theodoridou et al.[10] and the ones obtained in our research show comparable results on a wide range of mechanical and petrophysical values (Fig. 3). The similarity between our results and others obtained from different rocks suggests that the estimative equations obtained in the present research can be extrapolated for the estimation of uniaxial compressive strength in a broad variety of carbonate sedimentary rocks.

Uniaxial compressive strength, UCS (MPa) is taken as a dependent variable, while open porosity, P(%), P-wave velocity, Vp (m/s), Leeb hardness, LHD, and micro-drilling resistance force, F(N), are considered as independent variables. Bulk density was characterised because it is an index parameter that depends on the porosity and mineralogical

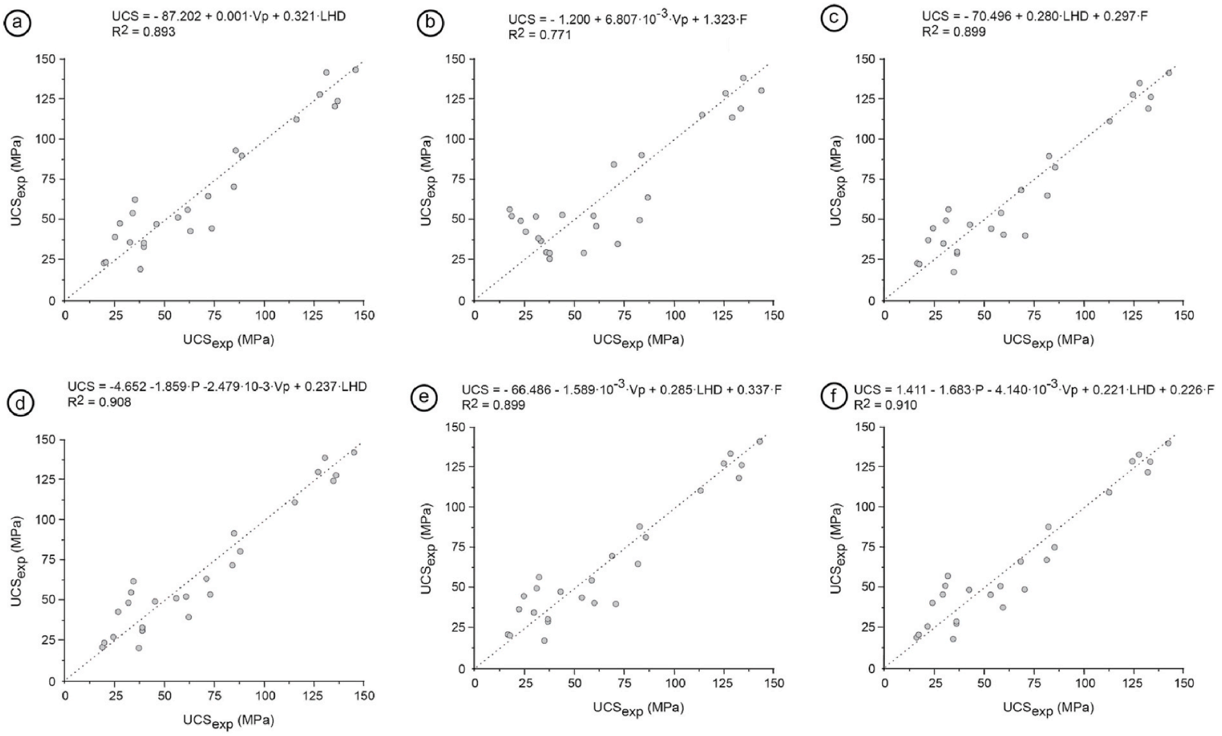

Fig. 4. Comparison of experimental, UCS_{exp}, and calculated, UCS_{cal}, uniaxial compressive strength using the multilineal equations from Table 3: (a) Eq. (8), (b) Eq. (9), (c) Eq. (10), (d) Eq. (11), (e) Eq. (14) and (f) Eq. (15). The dotted line is the one-to-one correspondence line.

composition. Fig. 1 displays the strong (negative) linear correlation between open porosity and bulk density because the mineralogical composition of the studied rocks is similar. Consequently, we only use porosity values for the regression equations to avoid redundant information.

Table 3 and Fig. 4 display the simple and multiple linear regressions for the estimation of UCS from non-destructive or minimally invasive techniques. Eqs. (1)-(4) (Table 3) represent simple lineal expressions that can be graphically observed in Fig. 1 which shows the relation of P, Vp, LHD and F individually with UCS for rocks tested in the present paper. As the number of independent variables (petrophysical parameters) increases in the multiple linear regressions, the goodness of the fits exhibits a general improvement. Importantly, Table 3 indicates whether the addition of each parameter (variable) to the multiple linear equations are significant, according to its p-value.

LHD shows a better correlation overall with UCS than Vp and F (Fig. 4). The addition of LHD to any multiple linear equation increase R^2 and it is always the most significant variable of the fitted regressions. For example, LHD increases the square coefficient of Vp and F (Eqs. (8) and (10), Table 3) around 26% and 14%, respectively, compared to when they are alone (Eqs. (2) and (4)). In general, P also improves R,[2] mainly in combination with F and Vp, although not always it a significant variable in the multiple equations (ej.: Eqs. (13) and (15)). F and Vp slightly enhance R^2 although they are not significant variables in the calculated regressions, except when they are in combination (Eq. (9)).

These results reveal that the accuracy in the assessment of UCS depends on the level of correlation each petrophysical parameter individually (Fig. 1), even when the combination of two or more estimators improves curve fitting for the multiple linear regressions. This explains the relatively poor results of regression by incorporation of F and, especially, Vp. As previously discussed, the dispersion of Vp values concerning UCS depends on the mineralogical composition. It is particularly high in the case of the studied biocalcarenites, which contains variable amounts of quartz. The measurement of ultrasonic wave velocities is an NDT commonly used in rock mechanics, engineering geology and stone conservation investigations that estimate the elastic characteristics of the tested rocks as well as their physico-mechanical and durability properties. Thus, a single Vp measurement is more representative of the mechanical property of the rock than a micro-drilling resistance force determination or an LHD impact. However, this limitation causes that in polymineral rocks Vp does not lead a significant improvement of the empirical equations of mechanical properties. Consequently, the application of the empirical equations to other rock types (e.g. siliceous rocks, such as sandstones, granites, gneiss and syenites) should be considered with some reservation.

Eqs. (14) (Table 3) contains all the mechanical parameters obtained with non-destructive or minimally invasive techniques (Fig. 4e). As discussed previously, the combination of open porosity with non-destructive parameters increases R^2 mainly with F and Vp. However, the measurement of LHD, F and Vp present the advantage that they can be obtained non-destructively with portable equipment as opposed to the porosity characterisation, commonly performed in the lab. Eqs. (14) (Table 3) do not include Vp but have the same R^2 value than Eq. (10), (Fig. 4e and c, respectively). Therefore, the measurement of Vp should not be necessary from a statistical point of view. Nevertheless, its use in the regression is highly recommended, if research or field conditions permit its measurement. Ultrasound measures a larger volume of rock than other techniques and the analysis of the recorded signal provide complementary information of the tested rock.[20] Eq. (8) is appropriate for the estimation of USC when the use of DRMS is not advisable. This minimally invasive technique causes a small hole in the material and it could be deemed as a destructive technique in some investigations conducted on heritage materials of high value such as statues, carvings or very visible stones in façades. The addition of LHD to any multiple linear equation increases R.[2] However, its use is not recommended for the estimation of mechanical properties of rocks with surface weathering. For example, LHD measurements on a rock surface with detachments, flaking and granular disaggregation will display lower values compared to the ones the unweathered rock beneath would show. Consequently, the bulk mechanical properties of the rock will be underestimated.

Eq. (15) shows the best fit, although R^2 is only slightly higher than R^2 of equations that include LHD (Fig. 4f). Eq. (15) incorporates all the mechanical parameters obtained non-destructively as well as open porosity. LHD has more statistical weight in Eq. (15) than the other NDT parameters. As discussed previously, multiple linear expressions provide more accurate estimations than the non-linear expression. For example, R^2 for Eq. (15) is equal to 0.910. However, the logarithmic expression of Eq. (15) ($\log \mathrm{UCS} = -2.750 - 0.083 \cdot \log \mathrm{P} - 0.502 \cdot \log \mathrm{Vp} + 2.439 \cdot \log \mathrm{LHD} - 0.043 \cdot \log \mathrm{F}$) has a $R^2 = 0.816$, lower than the linear expression, which statistically supports the use of linear combinations without any transformation in the stepwise multiple regression analysis.

4. Conclusions

This paper addresses the determination of the UCS by combining non-destructive or minimally invasive techniques. Results confirm that the assessment of UCS is improved if it is used in combination with other parameters, including open porosity. Although only carbonate sedimentary rocks were tested in this paper, the results highlight the need for considering both compositional and textural factors when establishing UCS-NDT correlations. Open porosity always presents a negative correlation with analysed parameters. However, the size of pores and grains and mineralogical composition of rock affect differently the mechanical parameters. Grain and pore size control substantially the reproducibility of NDT measurements, mostly in those techniques sensitive to rock surface properties (LHD and F). Mineralogical composition influences micro-drilling resistance force profile and Vp values, especially for quartz-bearing rocks. Consequently, the application of correlations between physico-mechanical parameters to all rock types should be used carefully unless there is a considerable database of tested parameters.

Fifteen simple and multiple expressions are fitted, with uniaxial compressive strength expressed as a generalized function of open porosity, P-wave velocity, Leeb hardness and micro-drilling resistance force. The best correlation is found when the estimative equation incorporates all the mechanical parameters obtained non-destructively and open porosity. LHD has more statistical weight in this equation than the other non-destructive parameters.

From the statistical point of view, LHD is always the most significant variable of the fitted regressions and its addition into multiple linear equations cause an increase of R.[2] P also improves R^2 of multiple equations mainly in combination with F and Vp, although not always is it a significant variable in the multiple equations. The use of Vp and F in multiple linear equations slightly increases curve fitting due to both their poor correlation with UCS and their strong dependence on mineralogical composition and texture. We also obtain an empirical equation that only contains only the mechanical parameters obtained with NDT without considering P. It displays has an acceptable goodness of fit and presents the advantage that they can be obtained non-destructively with portable equipment compared to the porosity characterisation, commonly performed in the lab.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Spanish Government [grant number

RTI2018-099052-B-I00] and Regional Government of Madrid (Spain) [Top Heritage, grant number S2018/NMT-4372].

References

1 Moropoulou A, Labropoulos KC, Delegou ET, Karoglou M, Bakolas A. Non-destructive techniques as a tool for the protection of built cultural Heritage. *Construct Build Mater*. 2013;48:1222–1239. https://doi.org/10.1016/j.conbuildmat.2013.03.044.

2 Vasanelli E, Calia A, Colangiuli D, Micelli F, Aiello MA. Assessing the reliability of non-destructive and moderately invasive techniques for the evaluation of uniaxial compressive strength of stone masonry units. *Constr Build Mater*. 2016;124:575–581. https://doi.org/10.1016/j.conbuildmat.2016.07.130.

3 Vasanelli E, Colangiuli D, Calia A, Sbartaï ZM, Breysse D. Combining non-invasive techniques for reliable prediction of soft stone strength in historic masonries. *Construct Build Mater*. 2017;146:744–754. https://doi.org/10.1016/j.conbuildmat.2017.04.146.

4 Capozzoli L, Rizzo E. Combined NDT techniques in civil engineering applications: laboratory and real test. *Constr Build Mater*. 2017;15:1139–1150. https://doi.org/10.1016/j.conbuildmat.2017.07.147.

5 Hussain A, Akhtar S. Review of non-destructive tests for evaluation of historic masonry and concrete structures. *Arab J Sci Eng*. 2017;42:925–940. https://doi.org/10.1007/s13369-017-2437-y.

6 Sari M. Investigating relationships between engineering properties of various rock types. *Global Journal of Earth Science and Engineering*. 2018;5:1–25. https://doi.org/10.15377/2409-5710.2018.05.1.

7 Yilmaz NG, Goktan RM. Comparison and combination of two NDT methods with implications for compressive strength evaluation of selected masonry and building stones. *Bull Eng Geol Environ*. 2019;78:4493–4503.

8 Sykora M, Diamantidis D, Holicky M, Markova J, Rozsas J. Assessment of compressive strength of historic masonry using non-destructive and destructive technique. *Construct Build Mater*. 2018;193:196–210. https://doi.org/10.1016/j.conbuildmat.2018.10.180.

9 Aldeeky H, Al Hattamleh O, Rababah S. Assessing the uniaxial compressive strength and tangent Young's modulus of basalt rock using the Leeb rebound hardness test. *Materiales de Construción*. 2020;70(340), e230. https://doi.org/10.3989/mc.2020.15119.

10 Theodoridou M, Dagrain F, Ioannou I. Micro-destructive cutting techniques for the characterization of natural limestone. *Int J Rock Mech Min Sci*. 2015;76:98–103. https://doi.org/10.1016/j.ijrmms.2015.02.012.

11 Corkum AG, Asiri Y, El Naggar H, Kinakin D. The Leeb hardness test for rock: an updated methodology and UCS correlation. *Rock Mech Rock Eng*. 2018;51:665–675. https://doi.org/10.1007/s00603-017-1372-2.

12 Kahraman S. Evaluation of simple methods for assessing the uniaxial compressive strength of rock. *Int J Rock Mech Min Sci*. 2001;38:981–994. https://doi.org/10.1016/S1365-1609(01)00039-9.

13 Benavente D, Martínez-Martínez J, Jáuregui P, Rodríguez MA, García-del-Cura MA. Assessment of the strength of building rocks using signal processing procedures. *Construct Build Mater*. 2006;20:562–568. https://doi.org/10.1016/j.conbuildmat.2005.01.043.

14 Martinez-Martinez J, Benavente D, Ordoñez S, Garcia-del-Cura MA. Multivariate statistical techniques for evaluating the effects of brecciated rock fabric on ultrasonic wave propagation. *Int J Rock Mech Min Sci*. 2008;45:609–620. https://doi.org/10.1007/s11204-016-9352-1.

15 Martinez-Martinez J, Benavente D, Gomez-Heras M, Marco-Castano L, Garcia-del-Cura MA. Non-linear decay of building stones during freeze-thaw weathering processes. *Constr. Build. Mater*. 2013;38:443–454. https://doi.org/10.1016/j.conbuildmat.2012.07.059.

16 Fort R, Alvarez de Buergo M, Perez-Monserrat E. Non-destructive testing for the assessment of granite decay in heritage structures compared to quarry stone. *Int J Rock Mech Min Sci*. 2013;61:296–305. https://doi.org/10.1016/j.ijrmms.2012.12.048.

17 Vasconcelos G, Lourenco PB, Alves CAS, Pamplona J. Ultrasonic evaluation of the physical and mechanical properties of granites. *Ultrasonics*. 2008;48:453–466. https://doi.org/10.1016/j.ultras.2008.03.008.

18 Hamdi E, Lathaj Z. Microcracking based rock classification using ultrasonic and porosity parameters and multivariate analysis methods. *Eng Geol*. 2013;167:27–36. https://doi.org/10.1016/j.enggeo.2013.10.008.

19 Brotons V, Tomas R, Ivorra S, et al. Improved correlation between the static and dynamic elastic modulus of different types of rocks. *Mater Struct*. 2016;49:3021–3037. https://doi.org/10.1617/s11527-015-0702-7.

20 Benavente D, Galiana-Merino JJ, Pla C, Martinez-Martinez J, Crespo-Jimenez D. Automatic detection and characterisation of the first P- and S-wave pulse in rocks using ultrasonic transmission method. *Eng Geol*. 2020;266:105474. https://doi.org/10.1016/j.enggeo.2020.105474.

21 Kahraman S. The correlations between the saturated and dry P-wave velocity of rocks. *Ultrasonics*. 2007;46:341–348. https://doi.org/10.1016/j.ultras.2007.05.003.

22 Schön JH. *Physical Properties of Rocks: Fundamentals and Principles of Petrophysics. Handbook of Geophysical Exploration*. second ed. Oxford: Elsevier; 2011.

23 Benavente D, Martínez-Martínez J, Cueto N, Ordóñez S, García-del-Cura MA. Impact of salt and frost weathering on the physical and durability properties of travertines and carbonate tufas used as building material. *Environmental Earth Sciences*. 2018;77:147–160. https://doi.org/10.1007/s12665-018-7339-0.

24 Katz O, Reches Z, Roegiers JC. Evaluation of mechanical rock properties using a Schmidt Hammer. *Int J Rock Mech Min Sci*. 2000;37:723–728. https://doi.org/10.1016/S1365-1609(00)00004-6.

25 Wang M, Wan W. A new empirical formula for evaluating uniaxial compressive strength using the Schmidt hammer test. *Int J Rock Mech Min Sci*. 2019;123:104094. https://doi.org/10.1016/j.ijrmms.2019.104094.

26 Aoki H, Matsukura Y. A new technique for non-destructive field measurement of rock-surface strength: an application of the Equotip hardness tester to weathering studies. *Earth Surf Process Landforms*. 2007;32:1759–1769. https://doi.org/10.1002/esp.1492.

27 Viles H, Goudie A, Grab S, Lalley J. The use of the Schmidt Hammer and Equotip for rock hardness assessment in geomorphology and heritage science: a comparative analysis. *Earth Surf Process Landforms*. 2011;36:320–333. https://doi.org/10.1002/esp.2040.

28 Perez-Alberti A, Gomes A, Trenhaile AS, Oliveira M, Horacio J. Correlating river terrace remnants using an Equotip hardness tester: an example from the Miño River, northwestern Iberian Peninsula. *Geomorphology*. 2013;192:59–70. https://doi.org/10.1016/j.geomorph.2013.03.017.

29 Verwaal W, Mulder A. Estimating rock strength with the Equotip hardness tester. *International Journal of Rock Mechanics Mining Sciences and Geomechanics Abstracts*. 1993;30:659–662. https://doi.org/10.1016/0148-9062(93)91226-9.

30 Meulenkamp F, Alvarez Grima M. Application of neural networks for the prediction of the unconfined compressive strength (UCS) from Equotip hardness. *Int J Rock Mech Min Sci*. 1999;36:29–39. https://doi.org/10.1016/S0148-9062(98)00173-9.

31 Aoki H, Matsukura Y. Estimating the unconfined compressive strength of intact rocks from Equotip hardness. *Bull Eng Geol Environ*. 2008;67:23–29. https://doi.org/10.1007/s10064-007-0116-z.

32 Yilmaz NG. The influence of testing procedures on Uniaxial compressive strength prediction of carbonate rocks from Equotip hardness tester (EHT) and proposal of a new testing methodology: hybrid dynamic hardness (HDH). *Rock Mech Rock Eng*. 2013;46:95–106. https://doi.org/10.1007/s00603-012-0261-y.

33 Hujer WH, Finkbeiner T, Persaud M. Estimating rock strength from nondestructive strength testing (EQUOTIP) and related benefits. *EAGE Workshop on Geomechanics in the Oil and Gas Industry*. 2014:1–3. https://doi.org/10.3997/2214-4609.20140444.

34 Exadaktylos G, Tiano P, Filareto C. Validation of a model of rotary drilling of rocks with the drilling force measurement system. *J Restor Build Monum*. 2000;3:307–340.

35 Modestou S, Theodoridou M, Ioannou I. Micro-destructive mapping of the salt crystallization front in limestone. *Eng Geol*. 2015;193:337–347. https://doi.org/10.1016/j.enggeo.2015.05.008.

36 Tiano P, Filareto C, Ponticelli S, Ferrari M, Valentini E. Drilling force measurement system, a new standardisable methodology to determine the stone cohesion: prototype design and validation. *Int Z Bauinstandsetzen Baudenkmalpflege, Geowissenschaften, Jahrgang, Heft*. 2000;6:115–132.

37 Delgado Rodrigues J, Ferreira Pinto AP, Costa D. Tracing of decay profiles and evaluation of stone treatments by means of microdrilling techniques. *J Cult Herit*. 2002;3:117–125. https://doi.org/10.1016/S1296-2074(02)01172-X.

38 Fratini F, Rescic S, Tiano P. A new portable system for determining the state of conservation of monumental stones. *Mater Struct*. 2006;39:139–147. https://doi.org/10.1617/s11527-005-9013-8.

39 Pamplona M, Kocher M, Snethlage R, Aires Barros L. Drilling resistance: overview and outlook. *Z Dtsch Ges Geowiss*. 2007;158:665–679. https://doi.org/10.1127/1860-1804/2007/0158-0665.

40 Aliabdo AAE, Elmoaty AEMA. Reliability of using nondestructive tests to estimate compressive strength of building stones and bricks. *Alexandria Engineering Journal*. 2012;51:193–203. https://doi.org/10.1016/j.aej.2012.05.004.

41 Gómez-Heras M, Benavente D, Pla C, Martínez-Martínez J, Fort R, Brotons V. Ultrasonic pulse velocity as a way of improving uniaxial compressive strength estimations from Leeb hardness measurements. *Construct Build Mater*. 2020;261:119996. https://doi.org/10.1016/j.conbuildmat.2020.119996.

42 Sbartaï ZM, Breysse D, Larget M, Balayssac JP. Combining NDT techniques for improved evaluation of concrete properties. *Cement Concr Compos*. 2012;34:725–733. https://doi.org/10.1016/j.cemconcomp.2012.03.005.

43 Al-Ameeri AS, Al-Hussain K, Essa M. Constructing a mathematical model to predict compressive strength of concrete from non-destructive testing. *Int J Civ Eng Technol*. 2013;4:1–20.

44 Breysse D, Klysz G, Dérobert X, Sirieix C, Lataste JF. How to combine several nondestructive techniques for a better assessment of concrete structures? *Cement Concr Res*. 2008;38:783–793. https://doi.org/10.1016/j.cemconres.2008.01.016.

45 Uva G, Porco F, Fiore A. The SonReb method: critical review and practical aspects. In: di Prisco M, Menegotto M, eds. *Proceedings of Italian Concrete Days 2016. ICD 2016. Lecture Notes in Civil Engineering*. 10. Springer; 2018. https://doi.org/10.1007/978-3-319-78936-1_12.

46 Masi A, Chiauzzi L. An experimental study on the within-member variability of in situ concrete strength in RC building structures. *Construct Build Mater*. 2013;47:951–961. https://doi.org/10.1016/j.conbuildmat.2013.05.102.

47 Benavente D, Cueto N, Martinez-Martinez J, Garcia del Cura MA, Canaveras JC. The influence of petrophysical properties on the salt weathering of porous building rocks. *Environ. Geol*. 2007;52:197–206. https://doi.org/10.1007/s00254-006-0475-y.

48 Benavente D, Pla C, Cueto N, et al. Predicting water permeability in sedimentary rocks from capillary imbibition and pore structure. *Eng Geol*. 2015;195:301–311. https://doi.org/10.1016/j.enggeo.2015.06.003.

49 UNE-EN 1936. *Natural Stone Test Methods. Determination of Real Density and Apparent Density, and of Total and Open Porosity*. Bruxelles: European Committee for Standardization; 2007.

50 Guyader J, Denis A. Propagation des ondes dans les roches anisotropes sous contrainte évaluation de la qualité des schistes ardoisiers. *Bull Int Assoc Eng Geol*. 1986;33:49–55. https://doi.org/10.1007/BF02594705.

51 Fort R, Varas MJ, Alvarez de Buergo M, Freire DM. Determination of anisotropy to enhance the durability of natural stone. *J Geophys Eng*. 2011;8:132–144. https://doi.org/10.1088/1742-2132/8/3/S13.

52 Delgado Rodrigues J, Costa D. A new method for data correction in drilling resistance. Tests for the effect of drill bit wear. *Int J Restoration Build Monuments*. 2004;10:1–18.

53 Theodoridou M, Torok A. In situ investigation of stone heritage sites for conservation purposes: a case study of the Székesfehérvár Ruin Garden in Hungary. *Progress in Earth and Planetary Science*. 2019;6:15. https://doi.org/10.1186/s40645-019-0268-z.

54 Dumitrescu TF, Pesce GLA, Ball RJ. Optimization of drilling resistance measurement (DRM) user-controlled variables. *Mater Struct*. 2017;50:243. https://doi.org/10.1617/s11527-017-1113-8.

55 UNE-EN 1926. *Natural Stone Tests Methods. Determination of Uniaxial Compressive Strength*. Bruxelles: European Committee for Standardization; 2007.

56 Deere DU, Miller RP. Engineering classification and index properties for intact rock. Air Force Weapons Laboratory Technical, Report AFWL-TR-65-116. 1966.

57 Griffith AA. The phenomena of rupture and flow in solids. *Philos Trans R Soc Lond A*. 1921;221:163–198.

58 Evans JD. *Straightforward Statistics for the Behavioral Sciences*. Thomson Brooks/Cole Publishing Co; 1996.

59 Yaşar E, Erdoğan Y. Estimation of rock physicomechanical properties using hardness methods. *Eng Geol*. 2004;71:281–288. https://doi.org/10.1016/S0013-7952(03)00141-8.

60 Cobanoglu I, Celik SB. Estimation of uniaxial compressive strength from point load strength, Schmidt hardness and P-wave velocity. *Bull Eng Geol Environ*. 2008;67:491–498.

61 Gokceoglu C, Sönmez H, Zorlu K. Estimating the uniaxial compressive strength of some clay bearing rocks selected from Turkey by nonlinear multivariable regression and rule-based fuzzy models. *Expet Syst*. 2009;26:176–190. https://doi.org/10.1111/j.1468-0394.2009.00475.x.

62 Garagon M, Can T. Predicting the strength anisotropy in uniaxial compression of some laminated sandstones using multivariate regression analysis. *Mater Struct*. 2010;43:509–517. https://doi.org/10.1617/s11527-009-9507-x.

63 Yesiloglu-Gultekin N, Gokceoglu C, Sezer EA. Prediction of uniaxial compressive strength of granitic rocks by various nonlinear tools and comparison of their performances International. *Journal of Rock Mechanics and Mining Sciences*. 2013;62:113–122. https://doi.org/10.1016/j.ijrmms.2013.05.005.

64 Celik SB, Cobanoglu I. Comparative investigation of Shore, Schmidt, and Leeb hardness tests in the characterization of rock Materials. *Environmental Earth Sciences*. 2019;78:554. https://doi.org/10.1007/s12665-019-8567-7.

65 UNE-EN 14579. *Natural Stone Test Methods. Determination of Sound Speed Propagation*. Bruxelles: European Committee for Standardization; 2004.