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EVALUATION OF MARBLE THERMAL-INDUCED DECAY BY ULTRASONIC PULSE VELOCITY AND LEEB HARDNESS

Abstract - G. Pedrini, S. Pagnotta, M. Lezzerini, *Evaluation of marble thermal-induced decay by ultrasonic pulse velocity and Leeb hardness.*

Marble has a great importance in the field of cultural heritage and, therefore, it is important to quantify the decay level of the marble to implement at the right time restoration plans aimed at safeguarding as much as possible cultural heritages. The degradation of the marbles with consequent loss of mechanical properties is correlated to an increase in porosity; this increase in porosity is the result of the loss of cohesion among the grains and the formation of micro-cracks. When it is not possible to remove samples to be analysed in the laboratory or when are needed instant check, the role of non-destructive and operable in situ methods is fundamental. In this study, by using portable instruments, correlations were obtained between the variation in the ultrasonic pulse velocity (UPV), the variation in surface hardness Leeb (HL) in relation to the variation in porosity open to water. This porosity was obtained by subjecting two varieties of marble (from Apuan Alps, in Italy, and from Paros Island, in Greece) to artificial thermal degradation of varying intensity from 100°C up to 500°C, at ambient pressure. As the intensity of degradation increases, more and more porosities open to water are generated.

Key words - Apuan Alps, marble, decay, Paros Island, porosity, ultrasonic velocity, Leeb hardness

Riassunto - G. Pedrini, S. Pagnotta, M. Lezzerini, *Valutazione di marmi degradati termicamente mediante la misurazione della velocità di propagazione degli impulsi ultrasonici e della durezza superficiale Leeb.*

Il marmo ha una grande rilevanza nell'ambito dei beni culturali, e quindi è importante monitorarne il livello di degrado in modo da poter avviare tempestive pratiche di tutela e restauro. Il degrado dei marmi con conseguente perdita di proprietà meccaniche è correlato ad un aumento di porosità, tale aumento di porosità è il risultato della perdita di coesione tra i grani e della formazione di microfessure. Quando non è possibile asportare campioni da analizzare in laboratorio oppure quando si vuole fare una verifica istantanea il ruolo dei metodi non distruttivi e operabili in situ è fondamentale. In questo studio mediante l'utilizzo di strumenti portatili sono state ottenute correlazioni fra la variazione della velocità di impulsi ultrasonici (UPV), la variazione di durezza superficiale Leeb (HL) in relazione con la variazione di porosità aperta all'acqua. Questa porosità è stata ottenuta sottoponendo due varietà di marmo bianco (provenienti dalle Alpi Apuane, in Italia, e dall'isola di Paros, in Grecia), a degrado termico artificiale di varia intensità da 100 °C fino a 500 °C a pressione ambientale, con l'aumentare dell'intensità di degrado si sono cosi generate porosità aperte all'acqua sempre maggiori.

Parole chiave - Alpi Apuane, marmo, degrado, Isola di Paros, porosità, velocità impulso ultrasonico, durezza Leeb

Introduction

Since ancient times, marble has always been used as a building material for the most important buildings and monuments. Nowadays, several churches (Lezzerini, 2005; Ramacciotti *et al.*, 2015), theatres (Columbu *et al.*, 2018) (Taelman *et al.*, 2019), temples (Williams *et al.*, 1992) (Koralay & Kilinçarslan, 2016), other structures (Columbu *et al.*, 2014) (Skaggs *et al.*, 2019), and especially sculptures (Antonelli *et al.*, 2014; Pensabene *et al.*, 2012; Lezzerini *et al.*, 2017; Ouazaa *et al.*, 2013; Lezzerini *et al.*, 2012; Miriello *et al.*, 2012) of considerable historical value are made of marble. Since these man-made works are subject to processes of environmental and anthropic degradation, it is important to quantify the decay level of the marble to implement at the right time restoration plans aimed at safeguarding as much as possible cultural heritages. Generally, methods for analysing rocks are divided into destructive and non-destructive methods. In several recent papers marbles, stones and other building materials were analysed by using destructive methods such as OM, XRF, XRD, SEM-EDS (Franzini & Lezzerini, 2002, 2003b; Lezzerini *et al.*, 2018; Lezzerini *et al.*, 2013; Fratini *et al.*, 2015; Franzini *et al.*, 2010), but also some researches have made use of non-destructive methods such as light beam and geophysical methods (Biricotti & Severi, 2004; Yalçıner *et al.*, 2019; Boudani *et al.*, 2015) or by both of them (Baracchini *et al.*, 2005; Siegesmund *et al.*, 2021; Vagnon *et al.*, 2019; Sena da Fonseca *et al.*, 2021). Ultrasonic pulse velocity (UPV) method and Leeb rebound hardness (HL) test are very promising methods in the study of marble, stones and their decay (Ur Rehman *et al.*, 2022; Vasconcelos *et al.*, 2008; Gomez-Heras *et al.*, 2020).

UPV is a measurement of the speed of ultrasonic waves passing through a body. It is an economic, fast, and non-destructive (which is not irrelevant in the studies of cultural heritage) test to determine the properties of natural rocks and other materials, like concrete and bricks either in situ or laboratory conditions. The method was inspired by the relationships

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between sonic and mechanical properties found in oil exploration; ultrasonic methods start developing in 1940's for the assessment of concrete strength (Jones, 1949) and later it was used for evaluations of rocks physical proprieties. P-wave propagation in materials is affected by bulk properties of the stone such as mineral composition, texture, density, and porosity. In monomineralic rocks, like marble, elastic wave propagation is mostly affected by texture, grains proprieties and porosity (Luque *et al.*, 2011; Åkesson *et al.*, 2006; Royer-Carfagni, 1999; Malaga-Starzec *et al.*, 2006; Shushakova *et al.*, 2011; Weiss *et al.*, 2002). UPV method is widely used in the field of cultural heritage, i.e. to evaluate the degradation of building materials used in historical architecture, such as mortars, brick and natural stones. Some studies shows that physical properties, such as water absorption and porosity have established good correlations with P-wave velocity for some carbonate rocks (Kahraman & Yeken, 2008), granites (Vasconcelos *et al.*, 2008), calcarenites (Rahmouni *et al.*, 2013) and sandstones (Gomez-Heras *et al.*, 2020). Another important direct application of ultrasonic pulse velocity measurements is on the assessment of the quality of marble (Weiss *et al.*, 2002). Several authors studied variation of porosity and UPV vs induced and natural thermal degradation, on porous calcarenite (Vasanelli *et al.*, 2021), carbonate rocks (Ur Rehman *et al.*, 2022, Yavuz *et al.*, 2010, Ugur *et al.*, 2014), and granites (Tomás *et al.*, 2021). The basic assumption for the quality assessment of a natural building stone based on ultrasonic measurements is that a decrease of UPV is correlated with a certain degree of degradation. Marble's quality is susceptible to be damage by heating, the entity of this damage is influenced by some relevant parameters as mineralogical composition, grain size, grain boundaries linearity, grain shape preferred orientation, lattice preferred orientation, number of adjacent grains and initial number of micro-cracks (Yavuz *et al.*, 2010; Luque *et al.*, 2011) and, due to it, every type of marble has its own "starting UPV", which is UPV measured on non-degraded samples and that "starting UPV" decrease according to the degree of degradation, therefore, to investigate the degree of degradation of marble it's important to know UPV values in advance. A verifiable and repeatable way of preparing degraded samples is to subject them to induced thermal degradation. Various authors studied variation of porosity and UPV vs inducted and natural thermal degradation, on carbonate rocks (Yavuz *et al.*, 2010, Ugur *et al.*, 2014, Tomás *et al.*, 2021) findings some correlations between UPV and porosity vs thermal degradation. However, porosity is an important factor in determining the effectiveness weathering due to thermal induced degradation (Franzoni *et al.*, 2013).

HL is another non-destructive method developed in 1975 to provide a portable hardness test, originally for metals and polymers. This test uses energy measurement principles in determining the hardness of material (Leeb, 1979; Boogaard & Van Dijk, 1989). Later its use was expanded to measure the surface hardness of rocks (Aoki & Matsukura, 2008). In previews studies LRH was usually correlated with UCS (Corkum *et al.*, 2018; Gomez-Heras *et al.*, 2020), HL and Smith hammer vs UCS (Çelik & Çobanoğlu, 2019; Aoki & Matsukura 2008), but only few studies correlates HL, UPV and porosity (Gomez-Heras *et al.*, 2020).

This study is aimed to investigate the porosity of marble induced by thermal decay evaluating it also by ultrasonic pulse velocity and Leeb rebound hardness test.

Material and methods

Two types of white marbles were analysed: 1) a fine grain-sized marble (MF), characterized by homeoblastic/granoblastic texture with straight boundaries and triple points at 120 degrees; 2) a coarse grain-sized marble (MC), characterized by heteroblastic/granoblastic texture with curve to lobate boundaries. MF and MC are from Apuan Alps (Italy) and from Paros Island (Greece), respectively. Six specimens for every selected marble, for a total of twelve samples, were measured before and after artificial treatments at 60 °C, 200 °C, 300 °C, 400 °C and 500 °C.

Real density, apparent density, porosity and water absorption at atmospheric pressure were determined according to the European Standards EN 13755 (EN 13755 2008; EN 1936 2006). The volumes of specimens were measured by using a hydrostatic balance on saturated samples (Franzini & Lezzerini, 2003a).

The ultrasonic pulse velocity (UPV) (Naik, Malhotra, Popovics, 2003) was measured by using a PROCEQ PUNDIT PL-200 instrument equipped with probes at frequency of 54 kHz. The measures were obtained for the three main directions of the cubic specimens and expressed as the mean of the three readings. UPV measurements were performed according to the European Standard EN 14579 (EN 14579 2004) on dry specimens at ambient temperature.

The measuring principle of Hardness Leeb (HL) is based on the dynamic rebound method. An impact body with a hard metal tip is projected by a preloaded spring against the surface of the samples. The impact causes a slight deformation of the surface, which leads to a loss of kinetic energy (Aoki & Matsukura, 2008). Speeds are measured by means of a permanent magnet in the impact body that generates an induced voltage in the firing pin probe. The identified voltage is proportional to the speed of the impact body. The HL values were obtained by using Proceq Equotip 550 with Type D device (HLD), the European Standard EN ISO 16859-1 (EN ISO 16859-1 2015) is specified for metal and not for rocks, so in this paper were follows recommendation for non-standardized test, averaging the hardness values taken at different points (Aoki & Matsukura, 2008).

Results and discussion

Table 1 shows for MF and MC Ultrasonic Pulse velocity UPV (m/s), Leeb Hardness measured with type D device (HLD) and type of thermal-induced degradation ordered by increasing open water porosity Ab_v (% by vol.). In MF samples an increasing of water open porosity from 0.27 to 3.84 (by fourteen time) leads to a decrease in the Ultrasonic Pulse Velocity UPV (m/s) up to 82% from 3865 to 696 and a decrease in Leeb Hardness HLD of 55% from 575 to 257. While, In MC samples an increasing of open water porosity Ab_v (% by vol.) from 0.20 to 3.37 (by sixteen time) leads to a decrease in the Ultrasonic Pulse Velocity UPV (m/s) up to 70% from 5011 to 1488 and a decrease in Leeb Hardness HLD of 65% from 347 to 121. For both marbles the increasement of porosity is correlated with increasement of intensity of thermally-induced decay as shown in other studies (Siegesmund, Menningen, Shushakova, 2021). The resistance to degradation change in function of the physical-mineralogical characteristics of the samples, such as: mineralogical composition, grain size, grain boundaries linearity, grain shape preferred orientation, lattice preferred orientation, number of adjacent grains and initial number of micro-cracks (Yavuz *et al.*, 2010; Luque *et al.*, 2011).
In the Figure 1, Ultrasonic Pulse Velocity UPV vs open water porosity Ab_v (% by vol.), MC and MF were well correlated by an exponential equations with coefficients of determination (R^2) respectively of: $R^2 = 0.9681$ for MF and $R^2 = 0.9494$ for MC, those equations confirms other what is shown in other studies (Siegesmund *et al.*, 2021; Gomez-Heras *et al.*, 2020). The correlation between open water porosity and HLD in marbles results less investigated from other studies (Çelik & Çobanoğlu, 2019). The Figure 2 shows an exponential correlation for both marbles with coefficients of determination (R^2) respectively of: $R^2 = 0.9613$ for MF and $R^2 = 0.9632$ for MC. The decrease of Ultrasonic Pulse Velocity and Leeb Hardness with the increase in porosity and, consequently, with thermal-induced decay are both significant and leaded by an exponential equation. Correlation between UPV and HLD shows a function that follows a linear trend for both marbles with high R^2: respectively 0.9367 for MF and 0.9579 for MC.

Table 1. UPV, LEEB and open porosity.

Samples		TD-A	TD-B	TD-C	TD-D	TD-E
MF	UPV	3865	1971	1233	978	696
	Std. dev.	*241*	*178*	*232*	*101*	*111*
	HLD	575	478	425	390	335
	Std. dev.	*20*	*21*	*16*	*14*	*11.1*
	Ab_v (% by vol.)	0.27	1.05	2.04	2.5	3.84
	Std. dev.	0.04	0.04	0.04	0.04	0.04
MC	UPV	5011	4153	3050	2629	1488
	Std. dev.	*347*	*322*	*242*	*147*	*121*
	HLD	487	458	416	356	318
	Std. dev.	*27*	*49*	*31*	*19*	*24*
	Ab_v (% by vol.)	0.2	0.98	1.04	1.92	3.37
	Std. dev.	*0.01*	*0.01*	*0.01*	*0.01*	*0.01*

TD-(A-B-C-D-E): Thermal Induced Deacys A, B, C, D, E were obtained using a muffle furnace by leaving the samples for 2 hours at the following temperatures: A = 60 °C, B = 200 °C, C = 300 °C, D = 400 °C, E = 500 °C. Measurements were taken once the samples cooled to room temperature (25 °C).

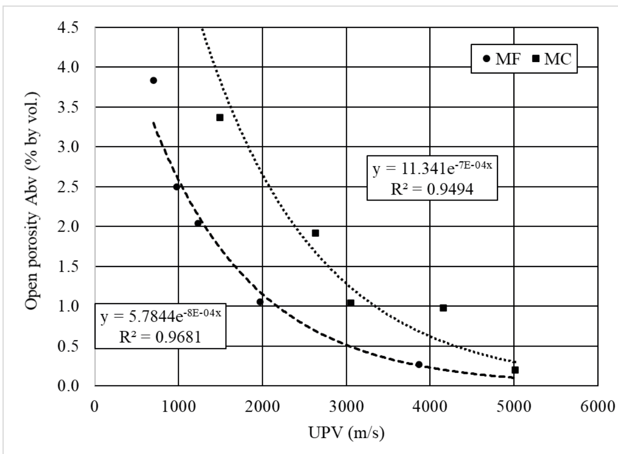

Figure 1. Ultrasonic Pulse Velocity UPV vs Open water porosity Ab_v (% by vol.).

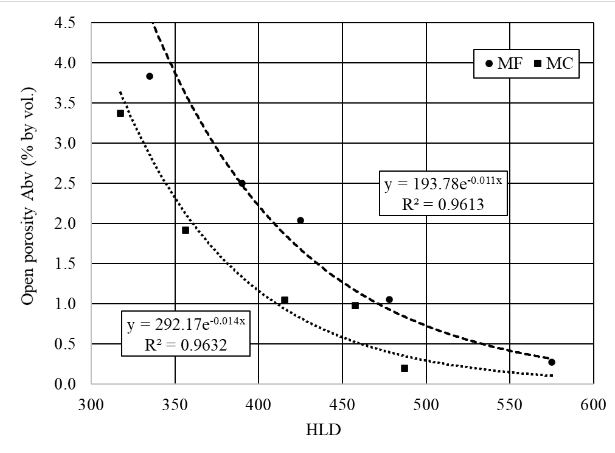

Figure 2. Leeb Hardness HLD vs Open water porosity Ab_v (% by vol.).

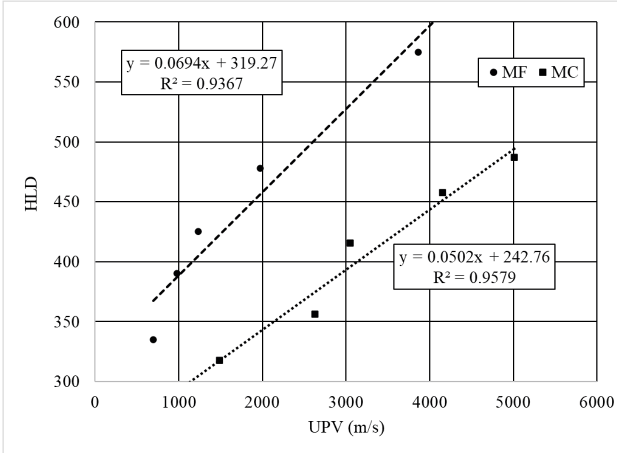

Figure 3. Ultrasonic Pulse Velocity UPV vs Leeb Hardness HLD.

Conclusions

The present study confirms that thermal treatments generate increasing porosity in marble. Porosity is confirmed to be an excellent parameter for evaluating the artificial marble decay. Each marble reacts differently to the thermally induced degradation, essentially due to the different petrographic characteristics, showing different porosity values for the same intensity of thermal degradation in different samples. UPV method is useful to determine the increase in porosity in a non-destructive way. A decrease in UPV speed is attributable to an increase in porosity. UPV measurements results a powerful and sensitive method for measuring degradation in marbles. Also, HLD method can be used for determining the increase in porosity in a non-destructive way, and the decreasing in hardness is strictly related to an increase in porosity. In conclusion NDT as UPV and HLD can be considered valid tools for the quick and in situ study of marbles decay.

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REFERENCES

Åkesson U., Lindqvist J.E., Schouenborg B., Grelk B., 2006. Relationship between Microstructure and Bowing Properties of Calcite Marble Claddings. *Bulletin of Engineering Geology and the Environment* 65(1): 73-79.

Antonelli F., Columbu S., Lezzerini M., Miriello D., 2014. Petrographic Characterization and Provenance Determination of the White Marbles Used in the Roman Sculptures of Forum Sempronii (Fossombrone, Marche, Italy). *Applied Physics A: Materials Science and Processing* 115(3): 1033-1040. doi:10.1007/s00339-013-7938-2

Aoki H., Matsukura Y., 2008. Estimating the Unconfined Compressive Strength of Intact Rocks from Equotip Hardness. *Bulletin of Engineering Geology and the Environment* 67(1): 23-29. doi:10.1007/s10064-007-0116-z

Baracchini C., Pini R., Fabiani F., Ciafaloni M., Siano S., Salimbeni R., Sabatini G. *et al.*, 2005. The Pilot Restoration Yard of the Church of San Frediano in Pisa: Results of a Multidisciplinary Study. *Springer Proceedings in Physics* 100 (Lasers in the Conservation of Artworks): 191-197.

Biricotti F., Severi M., 2004. A Non-Destructive Methodology for the Characterization of White Marble of Artistic and Archaeological Interest. *Journal of Cultural Heritage* 5(1): 49-61. doi:10.1016/j.culher.2003.09.006

Boogaard J., Van Dijk G.M., 1989. Non-Destructive Testing. Vol. 2, Elsevier, Amsterdam, 1091 pp.

El Boudani M., Wilkie-Chancellier N., Martinez L., Hébert R., Rolland O., Forst S., Vergès-Belmin V., Serfaty S., 2015. Marble Characterization by Ultrasonic Methods. *Procedia Earth and Planetary Science* 15: 249-256. doi:10.1016/j.proeps.2015.08.061

Çelik S.B., Çobanoğlu I., 2019. Comparative Investigation of Shore, Schmidt, and Leeb Hardness Tests in the Characterization of Rock Materials. *Environmental Earth Sciences* 78: 554. doi:10.1007/s12665-019-8567-7

Columbu S., Lisci C., Sitzia F., Lorenzetti G., Lezzerini M., Pagnotta S., Raneri S. *et al.*, 2018. Mineralogical, Petrographic and Physical-Mechanical Study of Roman Construction Materials from the Maritime Theatre of Hadrian's Villa (Rome, Italy). *Measurement: Journal of the International Measurement Confederation* 127: 264-276. doi:10.1016/j.measurement.2018.05.103

Columbu S., Antonelli F., Lezzerini M., Miriello D., Adembri B., Blanco A., 2014. Provenance of Marbles Used in the Heliocaminus Baths of Hadrian's Villa (Tivoli, Italy). *Journal of Archaeological Science*: 49: 332-342. doi:10.1016/j.jas.2014.05.026

Corkum A.G., Asiri Y., El Naggar H., Kinakin D., 2018. The Leeb Hardness Test for Rock: An Updated Methodology and UCS Correlation. *Rock Mechanics and Rock Engineering* 51(3): 665-675. doi:10.1007/s00603-017-1372-2

EN 13755, 2008. Natural Stone Test Methods - Determination of Water Absorption at Atmospheric Pressure.

EN 14579, 2004. Natural Stone Test Methods - Determination of Sound Speed Propagation.

EN 1936, 2006. Natural Stone Test Methods - Determination of Real Density and Apparent Density, and of Total and Open Porosity.

EN ISO 16859-1, 2015. Metallic Materials. Leeb Hardness Test Test Method.

Franzini M., Lezzerini M., 2002. The Triassic Marble from the Punta Bianca Promontory (La Spezia, Italy). Did Romen Quarrying Of 'lunensis Marble' begin Here? *Periodico di Mineralogia* 71: 137-144.

Franzini M., Lezzerini M., 2003a. A Mercury-Displacement Method for Stone Bulk-Density Determinations. *European Journal of Mineralogy* 15(1): 225-229. doi:10.1127/0935-1221/2003/0015-0225

Franzini M., Lezzerini M., 2003b. The Stones of Medieval Buildings in Pisa and Lucca Provinces (Western Tuscany, Italy); 1, The Monte Pisano Marble. *European Journal of Mineralogy* 15(1): 217-224. doi:10.1127/0935-1221/2003/0015-0217

Franzini M., Lezzerini M., Origlia F., 2010. Marbles from the Campiglia Marittima Area (Tuscany, Italy). *European Journal of Mineralogy* 22(6): 881-893. doi:10.1127/0935-1221/2010/0022-2056

Franzoni E., Sassoni E., Scherer G.W., Naidu S., 2013. Artificial Weathering of Stone by Heating. *Journal of Cultural Heritage* 14(3): e85-e93. doi:10.1016/j.culher.2012.11.026

Fratini F., Pecchioni E., Cantisani E., Antonelli F., Giamello M., Lezzerini M., Canova R., 2015. Portoro, the Black and Gold Italian 'marble.' *Rendiconti Lincei* 26(4): 415-423. doi:10.1007/s12210-015-0420-7

Gomez-Heras M., Benavente D., Pla C., Martinez-Martinez J., Fort R., Brotons V., 2020. Ultrasonic Pulse Velocity as a Way of Improving Uniaxial Compressive Strength Estimations from Leeb Hardness Measurements. *Construction and Building Materials* 261: 119996.

Jones R., 1949. The Non-Destructive Testing of Concrete. *Magazine of Concrete Research* 1(2): 67-78.

Kahraman S., Yeken T., 2008. Determination of Physical Properties of Carbonate Rocks from P-Wave Velocity. *Bulletin of Engineering Geology and the Environment* 67 (2): 277-281.

Koralay T., Kilinçarslan S., 2016. A Multi-Analytical Approach for Determining the Origin of the Marbles in Temple-A from Laodicea Ad Lycum (Denizli-Western Anatolia, Turkey). *Journal of Cultural Heritage* 17: 42-52. doi:10.1016/j.culher.2015.05.005

Leeb D., 1979. Dynamic Hardness Testing of Metallic Materials. *NDT International* 12(6): 274-278.

Lezzerini M., 2005. Mapping of Building Stones Used in the Façade of St. Frediano Church (Pisa, Italy). *Atti della Società Toscana di Scienze Naturali, Memorie, Serie A* 110: 43-50.

Lezzerini M., Di Battistini G., Zucchi D., Miriello D., 2012. Provenance and Compositional Analysis of Marbles from the Medieval Abbey of San Caprasio, Aulla (Tuscany, Italy). *Applied Physics A: Materials Science and Processing* 108(2): 475-485. doi:10.1007/s00339-012-6917-3

Lezzerini M., Tamponi M., Bertoli M., 2013. Reproducibility, Precision and Trueness of X-Ray Fluorescence Data for Mineralogical And/or Petrographic Purposes. *Atti della Società Toscana di Scienze Naturali, Memorie, Serie A* 120: 67-73. doi:10.2424/ASTSN.M.2013.15

Lezzerini M., Antonelli F., Gallello G., Ramacciotti M., Parodi L., Alberti A., Pagnotta S., Legnaioli S., Palleschi V., 2017. Provenance of Marbles Used for Building the Internal Spiral Staircase of the Bell Tower of St. Nicholas Church (Pisa, Italy). *Applied Physics A: Materials Science and Processing* 123: 385. doi:10.1007/s00339-017-0998-y

Lezzerini M., Raneri S., Pagnotta S., Columbu S., Gallello G., 2018. Archaeometric Study of Mortars from the Pisa's Cathedral Square (Italy). *Measurement: Journal of the International Measurement Confederation* 126: 322-331. doi:10.1016/j.measurement.2018.05.057

Luque A., Ruiz-Agudo E., Cultrone G., Sebastián E., Siegesmund S., 2011. Direct Observation of Microcrack Development in Marble Caused by Thermal Weathering. *Environmental Earth Sciences* 62(7): 1375-1386.

Malaga-Starzec K., Åkesson U., Lindqvist J.-E., Schouenborg B., 2006. Microscopic and Macroscopic Characterization of the Porosity of Marble as a Function of Temperature and Impregnation. *Construction and Building Materials* 20(10): 939-947.

Miriello D., Alfano I., Miceli C., Ruffolo S.A., Pingitore V., Bloise A., Barca D. *et al.*, 2012. Analysis of Marble Statues from the San Bruno Church (Serra San Bruno, Southern Italy): Provenance and Degradation. *Applied Physics A: Materials Science and Processing* 106(1): 171-179. doi:10.1007/s00339-011-6671-y

Naik T.R., Mohan Malhotra V., Popovics J.S., 2003. *The Ultrasonic Pulse Velocity Method.* In: Handbook on Nondestructive Testing of Concrete: 1-8. 2nd ed., CRC Press, Civil and Environmental Engineering Grainger College of Engineering.

Ouazaa N.L., Casas L., Álvarez A., Fouzai B., Moreno-Vide M., Vidal L., Sihem R., Sonzogni C., Borschneck D., 2013. Provenance of Marble Sculptures from the National Museum of Carthage (Tunisia). *Journal of Archaeological Science* 40(3): 1602-1610. doi:10.1016/jjas.2012.10.035

Pensabene P., Antonelli F., Lazzarini L., Cancelliere S., 2012. Provenance of Marble Sculptures and Artifacts from the so-Called Canopus and Other Buildings of 'Villa Adriana' (Hadrian's Villa - Tivoli, Italy). *Journal of Archaeological Science* 39(5): 1331-1337. doi:10.1016/j.jas.2012.01.015

Rahmouni A., Boulanouar A., Boukalouch M., Géraud Y., Samaouali A., Harnafi M., Sebbani J., 2013. Prediction of Porosity and Density of Calcarenite Rocks from P-Wave Velocity Measurements. *International Journal of Geosciences* 4(9): 1292-1299. doi:10.4236/ijg.2013.49124

Ramacciotti M, Spampinato M., Lezzerini M., 2015. The Building Stones of the Apsidal Walls of the Pisa's Cathedral. *Atti della Società Toscana di Scienze Naturali, Memorie, Serie A* 122: 55-62. doi:10.2424/ASTSN.M.2015.20

Royer-Carfagni G., 1999. Some Considerations on the Warping of Marble Facades: The Example of Alvar Aalto's Finland Hall in Helsinki. *Construction and Building Materials* 13(8): 449-457.

SENA DA FONSECA B., FERREIRA PINTO A.P., RODRIGUES A., PIÇARRA S., FONSECA D., MONTEMOR M.F., 2021. On the Estimation of Marbles Weathering by Thermal Action Using Drilling Resistance. *Journal of Building Engineering* 42 102494. doi:10.1016/j.jobe.2021.102494

SHUSHAKOVA V., FULLER E.R., SIEGESMUND S., 2011. Influence of Shape Fabric and Crystal Texture on Marble Degradation Phenomena: Simulations. *Environmental Earth Sciences* 63(7): 1587-1601.

SIEGESMUND S., MENNINGEN J., SHUSHAKOVA V., 2021. Marble Decay: Towards a Measure of Marble Degradation Based on Ultrasonic Wave Velocities and Thermal Expansion Data. *Environmental Earth Sciences* 80(11): 1-34.

SKAGGS S., TYKOT R.H., POWIS T.G., 2019. Isotopic Analysis of Newly Discovered Fragments of an Ulúa Valley Marble Vase at the Ancient Maya Site of Pacbitun, Belize. *Journal of Archaeological Science: Reports* 26 101896. doi:10.1016/j.jasrep.2019.101896

TAELMAN D., DELPINO C., ANTONELLI F., 2019. Marble Decoration of the Roman Theatre of Urvinum Mataurense (Urbino, Marche Region, Italy): An Archaeological and Archaeometric Multi-Method Provenance Study. *Journal of Cultural Heritage* 39: 238-250. doi:10.1016/j.culher.2019.03.009

TOMÁS R., CANO M., PULGARÍN L.F., BROTÓNS V., BENAVENTE D., MIRANDA T., VASCONCELOS G., 2021. Thermal Effect of High Temperatures on the Physical and Mechanical Properties of a Granite Used in UNESCO World Heritage Sites in North Portugal. *Journal of Building Engineering* 43 102823. doi:10.1016/j.jobe.2021.102823

UGUR I., SENGUN N., DEMIRDAG S., ALTINDAG R., 2014. Analysis of the Alterations in Porosity Features of Some Natural Stones due to Thermal Effect. *Ultrasonics* 54(5): 1332-1336.

UR REHMAN A., AHMED W., AZAM S., SAJID M., 2022. Characterization and Thermal Behavior of Marble from Northwestern Pakistan. *Innovative Infrastructure Solutions* 7(1): 1-8.

VAGNON F., COLOMBERO C., COLOMBO F., COMINA C., FERRERO A.M., MANDRONE G., VINCIGUERRA S.C., 2019. Effects of Thermal Treatment on Physical and Mechanical Properties of Valdieri Marble - NW Italy. *International Journal of Rock Mechanics and Mining Sciences* 116: 75-86. doi:10.1016/j.ijrmms.2019.03.006

VASANELLI E., QUARTA G., MICELLI F., CALIA A., 2021. The Effects of an Historical Fire on a Porous Calcarenite from an Industrial-Archaeological Building in the South of Italy. *Engineering Geology* 292 106270.

VASCONCELOS G., LOURENÇO P.B., ALVES C.A.S., PAMPLONA J., 2008. Ultrasonic Evaluation of the Physical and Mechanical Properties of Granites. *Ultrasonics* 48(5): 453-466.

WEISS T., RASOLOFOSAON P.N.J., SIEGESMUND S., 2002. Ultrasonic Wave Velocities as a Diagnostic Tool for the Quality Assessment of Marble. *Geological Society, London, Special Publications* 205(1): 149-164.

WILLIAMS W.S., TRAUTMAN B., FINDLEY S., SOBEL H., 1992. Materials Analysis of Marble from the Parthenon. *Materials Characterization* 29(2): 185-194. doi:https://doi.org/10.1016/1044-5803(92)90114-W

YALÇINER C.C., BÜYÜKSARAÇ A., KURBAN Y.C., 2019. Non-Destructive Damage Analysis in Kariye (Chora) Museum as a Cultural Heritage Building. *Journal of Applied Geophysics* 171 103874. doi:10.1016/j.jappgeo.2019.103874

YAVUZ H., DEMIRDAG S., CARAN S., 2010. Thermal Effect on the Physical Properties of Carbonate Rocks. *International Journal of Rock Mechanics and Mining Sciences* 47(1): 94-103. doi:10.1016/j.ijrmms.2009.09.014

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