Indirect test methods for the mechanical characterization of building stones

Giulia Forestieri

Facultad de Ingeniería, Universidad de la Sabana, Campus Universitario del Puente del Común, km 7 Autopista norte de Bogotá, Chía, Cundinamarca, Colombia

Abstract. The main objective of this study is to evaluate the usefulness of indirect methods to estimate the uniaxial compressive strength (UCS) of building stones. For this purpose, the results of the UCS test on five types of stones from southern Italy, one igneous and four sedimentary stones are firstly correlated with the corresponding results from Schmidt hammer, point load and UCS direct tests. Then, derived correlations are compared with the equations obtained by different researchers in the mechanical stone characterization.

1 Introduction

The uniaxial compressive strength (UCS) is widely employed in civil engineering to define mechanical resistance of building materials. Current testing procedures especially refer to the most employed worldwide standards of the International Society for Rock Mechanics (ISRM) and the American Society for Testing and Materials (ASTM). The advantage of performing direct tests consists in obtaining results very close to the mechanical behaviour of the tested materials but, on the contrary, these methods suppose large costs to the sample preparation according to the above standards. Thus, indirect methods are always more frequently preferred thanks to their less cost and to their ease, especially for in situ tests.

The aim of this research consists in predicting UCS using indirect tests, in particular Schmidt hammer test and Point load test and to compare results with direct UCS in order to establish correlations.

2 Methods and materials

2.1. Sampling

Five building stone types are sampled and tested in this study. Stone blocks are collected from active quarries and natural outcrops in the Calabria area of Italy (southern Italy). Each block sample is inspected for macroscopic defects so that it would provide test specimens free from fractures, partings or alteration zones. Selected stone types are:

1. San Giovanni in Fiore granite (GF) from San Giovanni in Fiore (39°15'N and 16°41'E), belonging to the Sila Batholith Unit of Upper Paleozoic and classified as granite [1];
2. Grisolia limestone (DG) from Grisolia (39°43'N and 15°51'E), from the Verbicaro Unit of the

Upper Triassic and classified as crystalline carbonate [2];

3. San Lucido calcarenite (CS) from San Lucido (39°18'N and 16°03'E), geologically belonging to the Miocene sedimentary Successions of the Tyrrhenian Coastal Range and petrographically known as biocalcarene [3];
4. Fuscaldo sandstone (AF) from Fuscaldo (39°24'N and 16°01'E), belonging to the same Miocene Succession of CS and known as graywacke [3];
5. Trebisacce limestone (TL) from Trebisacce (39°52'N and 16°32'E), belonging to the sedimentary successions of Holocene to Middle-Upper Pleistocene of the Albidona Formation and classified as limestone [4].

2.2 Experimental procedure

The Schmidt hammer test (SHT) provides a quick and inexpensive measure of surface hardness and it is widely used for estimating the mechanical properties of stone materials in the field [5]. L-type SHT are conducted in situ directly in blocks or outcrops surfaces. All tests are carried out with the hammer held vertically downwards and at right angles to horizontal faces of large stone blocks. 60 readings are obtained for each analyzed block. Readings are rejected if any individual impact test results in cracking or any other visible damage. The average value is recorded as the SHT rebound value according to the ASTM standards [6]. Equations correlating the compressive strength to SHT number are given in Table 1.

The point load test (PLT) is often employed as an indirect test method in order to evaluate the compressive or tensile strength of rock [7]. Table 2 lists the equations correlating compressive strength to PLT employed in this study. According to the ISRM standards [8], the ratio

*Corresponding author: giulia.forestieri@unisabana.edu.co

between compressive strength and PLT varies between 20 and 25 [9]. 32 cubic specimens for each stone type of 100 ± 5 mm edge are tested through a portable PLT machine connected to a barometer to register the maximum pressure. Results are corrected to a specimen diameter of 50 mm and the average value is recorded as the PLT strength.

Table 1. Equations correlating the estimated compressive strength ($UCS_{(SHT)}$) to the Schmidt hammer rebound (SHT).

Authors	Equation
Katz et al. (2000)	$UCS_{(SHT)} = 2.208e^{0.067SHT}$
Yilmaz and Sendir (2002)	$UCS_{(SHT)} = 2.27e^{0.054SHT}$
Fener et al. (2005)	$UCS_{(SHT)} = 4.24e^{0.059SHT}$

The direct uniaxial compressive strength (UCS) is evaluated through the Maschinen fabric Liezen system (MFL) testing machine at a constant speed rate of 1 mm/min with a maximum load capacity of 3000 kg. The test is repeated 10 times for each cubic stone specimen (50 ± 5 mm edge) and the average value is recorded as the UCS mean value.

Table 2. Equations correlating the indirect compressive strength ($UCS_{(PLT)}$) to the point load index (PLT).

Authors	Equation
D'Andrea et al. (1964)	$UCS_{(PLT)} = 15.3 PLT + 16.3$
Deere and Miller (1966)	$UCS_{(PLT)} = 20.7 PLT + 29.6$
Singh (1981)	$UCS_{(PLT)} = 18.7 PLT - 13.2$
Gunsallus and Kulhawy (1984)	$UCS_{(PLT)} = 16.5 PLT + 51.0$
Cargill and Shakoor (1990)	$UCS_{(PLT)} = 23.0 PLT + 13.0$

3 Results and discussion

Test results are given in Table 3 and are analysed using the method of least squares regression. Indirect tests values are correlated with the corresponding direct UCS values. The equation of the best-fit line, and the correlation coefficient are determined for each regression.

Table 3. Uniaxial compressive strength (UCS), Schmidt hammer rebound values (SHT) and point load strengths (PLT) for each investigated stone type.

Samples	UCS (MPa)	SHT (rebound)	PLT (MPa)
GF	$104,1 \pm 30,5$	$51,0 \pm 2,1$	$2,1 \pm 0,1$
DG	$68,4 \pm 14,2$	$33,0 \pm 2,0$	$1,2 \pm 0,2$
CS	$33,8 \pm 5,9$	$17,0 \pm 0,9$	$0,8 \pm 0,2$
AF	$31,0 \pm 11,0$	$16,0 \pm 0,8$	$0,5 \pm 0,1$
TL	$82,8 \pm 7,8$	$49,0 \pm 3,0$	$1,6 \pm 0,3$

An exponential relation between SHT and UCS is found (Fig. 1) and the equation of the curve is:

$$UCS = 20.08e^{0.0316SHT} \quad r=0.95 \quad (1)$$

Fig. 1. Schmidt rebound value (SHT) vs. uniaxial compressive strength (UCS).

A linear relation between PLT and UCS is reported in Fig. 2. The equation of the line is:

$$UCS = 48.875PLT + 3.4154 \quad r=0.97 \quad (2)$$

To check the estimation capability of the derived equations (1) and (2), the estimated UCS values are plotted against the direct UCS values for each equation, respectively (Figs. 3–4).

Fig. 2. Point load strength (PLT) vs. uniaxial compressive strength (UCS).

The error in the estimated value is represented by the distance that each data point plots from the line. A point lying close to the line indicates a better estimation than those points that are far than the interpolation line. As it is shown in Figs. 3–4, the points are scattered uniformly about the diagonal line, suggesting that the obtained models are reasonable.

Fig. 3. Estimated UCS from Schmidt hammer rebound (SHT) vs. uniaxial compressive strength (UCS) using the derived equation 1.

Researchers used both linear and exponential equations to correlate SHT with UCS. Some researchers multiplied SHT by density to improve the correlation or by the porosity of the stone. In this study, exponential function gives the highest correlation coefficient. The relation found in this study is similar to the relations of Katz et al. (2000), Yilmaz and Sendir (2002), and Fener et al. (2005) [9].

As it is shown in the Fig. 1, the higher the stone strength the more scattered the data points are. The data points fall closer to the line at low strength values but become more scattered at higher strength values. This suggests that the ability to estimate the UCS of stones using SHT is better at low strength values, and is less reliable at higher strength values.

Fig. 4. Estimated UCS from point load strength (PLT) vs. uniaxial compressive strength (UCS) using the derived equation 2.

The comparison of the obtained equation between SHT and UCS and those derived from other researchers is shown in the Fig. 5. As shown in the graph, the derived equation is very similar to the equation developed by Fener et al. (2005) [9]. On the other hand, the most distant equation from the derived model of this study is represented by the equation of Yilmaz and Sendir (2002) at first, and by the equation of Katz et al. (2000) [9].

Fig. 5. Comparison to predict UCS from SHT of the derived equation from this study (1) with the equations [9] of: (2) Katz et al. (2000); (3) Yilmaz and Sendir (2002); (4) Fener et al. (2005).

Although, ISRM [8] stated that the ratio between UCS and PLT varies between 20 and 25, many researchers found different ratios, lower and higher than the above interval [9]. While some equations conform to $y=ax$ form, the others conform to $y=ax+b$ form as well as derived in this study. The derived equation of PLT vs. UCS is compared with the equations conforming to $y=ax+b$ form from literature. As shown in the Fig. 6, the obtained equation in this research shows a trend that is similar to some of the other equations. In particular it is similar to the equations of Deere and Miller (1966), Gunsallus and Kulhawy (1984) and Cargill and Shakoor (1990) [9] due to the proximity of the estimated values from this study to those obtained by the above researchers. Among them, the relationship of Cargill and Shakoor (1990) crosses the estimated equation and shows a more horizontal trend, quite parallel to the equation of this study. On the contrary, the equations of Grasso et al. (1992), Kahraman (2001) and Fener et al. (2005) [9] can be rejected because their trend does not respect the trend shown by the derived equation (in particular the lines are not parallel to the line of the estimated equation from this study) and values obtained by those researchers are very distant from those calculated experimentally in this study.

Fig. 6. Comparison to predict UCS from PLT of the derived equation from this study (1) with the equations [9] of: (2) D'Andrea et al. (1964); (3) Deere and Miller (1966); (4) Singh (1981); (5) Gunsallus and Kulhawy (1984); (6) Cargill and Shakoor (1990); (7) Grasso et al. (1992); (8) Kahraman (2001); (9) Fener et al. (2005).

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Conclusions

The uniaxial compression test, Schmidt hammer test and point load test are carried out on five Italian building stones (igneous and sedimentary) in order to develop predictive equations for uniaxial compressive strength. The usefulness of the indirect test methods is assured through test results. The obtained linear and exponential equations are compared to the relationships previously obtained by other researchers. It is found that there is no agreement between the equations suggested by different researchers. While some equations exhibit the same trend, the others differ. This is probably due to the differentiation of stone types and test conditions. Correlations show that the prediction of uniaxial compressive strength on the basis of different relationship gives in some cases inaccurate estimates and in others a good prediction. The most reliable results, especially in the case of the Schmidt hammer test, are obtained for stones with lower strength rather than for those that present higher uniaxial compressive strength. The most fitted relationship between other researches and this study is obtained by the equation of Fener et al. In the case of the point load test, the equation of Cargill and Shakoor shows the most similar trend to the estimated equation from this study. The application of the suggested equations must be practiced with care probably taking into account detailed stone features like the porosity or density.

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