Point Load Strength Index of a limestone exposed to high temperatures and correlation with uniaxial compressive strength

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ABSTRACT: The most common procedure to obtain rock strength is the uniaxial compressive strength test (UCS). Extracting rock samples weakened by temperature can affect the estimation of the UCS values. Estimating UCS using the Point Load Test (PLT) is possible because both are linearly related. PLT needs smaller samples and is quicker and cheaper than the UCS test. This research determines UCS, Point Load Strength Index, and β-values (i.e., the ratio between UCS and Point Load Strength Index) of a limestone exposed to temperatures up to 900°C and then cooled on air or by immersion in water. Results show that strength and β-values decrease as temperature increases. There are two threshold temperatures in the relationship between point load strength and UCS in Pedra de Borriol samples: 600 ºC for samples subjected to slow cooling and 400 ºC for those subjected to quick cooling.

Keywords: UCS, PLT, limestone, high temperatures, Pedra de Borriol.

1 INTRODUCTION

Most historical heritage worldwide was built using rocks, and reported incidents demonstrate that fires seriously damage or destroy them (e.g., Windsor Castle 1992, National Museum of Brazil 2018; Notre Dame Cathedral 2019, and Plasencia Church 2020). These events cause major economic costs, social alarm and important heritage losses. Studying fire incidents in historic stone buildings helps us understand how high temperatures affect these structures (Ioannou et al. 2017; Zhang et al. 2009). To rehabilitate and rebuild historical monuments affected by fire it is essential to know the effects of thermal damage on rocks as well as the effects of the cooling methods used to extinguish the fire.

During a fire, thermal stresses create micro-cracks in rocks, leading to a progressive decay in rock integrity (Jansen et al. 1993, David et al. 1999; Keshavarz et al. 2010). This damage can be caused by differential thermal expansion and/or thermal oxidation processes (Martínez-Ibáñez et al. 2020). Every type of rock reacts differently to temperature changes based on properties such as mineralogical composition, water absorption, porosity, and density. Furthermore, it is known that mechanical properties of rocks are directly related to their physical properties, then it is obvious the effect of temperature on the mechanical behaviour of rocks.

One of the most crucial properties of rocks is their strength, which is typically measured using the uniaxial compressive strength (UCS) test. This test requires multiple samples to be accurately extracted, transported to the laboratory, and prepared according to established standards. However, the rocks strength can also be determined using other laboratory tests, such as the point load test (PLT), which is faster, cheaper, and provides sufficiently reliable results (Şahin et al. 2020; Galvan et al. 2014). The PLT is suitable for estimating rock strength on regular and irregular specimens and can be conducted both in the laboratory and in the field. Many studies have explored the prediction of UCS using the relationship with the Point Load Strength Index on intact rocks (Table 1). Still, few studies have investigated it on rocks exposed to high temperatures.

The relationship between UCS and Point Load Strength Index, $I_{s(50)}$, is expressed as follows:

$$UCS = \beta \cdot I_{S(50)} \quad (1)$$

Where β coefficients vary from 13.5 to 30.0, depending on the type of rock (Table 1).

Table 1. Values for β coefficient reported in previous studies.

Authors	Equation	R^2	Rocks type
Broch & Franklin (1972)	$UCS = 23.7I_{s(50)}$	NA	Different types of rock
Bieniawski (1975)	$UCS = 23.0I_{s(50)}$	NA	Different types of rock
O'Rourke (1988)	$UCS = 30.0I_{s(50)}$	NA	Sedimentary rocks
Singh & Singh (1993)	$UCS = 23.4I_{s(50)}$	0.64	Quartzite rocks
Tugrul & Zarif (1999)	$UCS = 15.3I_{s(50)}$	0.96	Granites
Sulukcu & Ulusay (2001)	$UCS = 15.3I_{s(50)}$	0.69	Different types of rock
Basu & Aydin (2006)	$UCS = 18.0I_{s(50)}$	0.97	Granites
Sabatakakis et al. (2008)	$UCS = 25.3I_{s(50)}$	0.71	Sedimentary rocks
Diamantis et al. (2009)	$UCS = 19.8I_{s(50)}$	0.74	Serpentinite
Galvan, M.A. (2011)	$UCS = 13.5I_{s(50)}$	0.87	Limestones
Kohno & Maeda (2012)	$UCS = 16.4I_{s(50)}$	0.85	Different types of rock
Rabat et al. (2020)	$UCS = 14.3I_{s(50)}$	0.98	Siltstones
Sadeghi et al. (2021)	$UCS = 14.3I_{s(50)}$	NA	Carbonated rocks

NA: Not available

The aim of this research is: a) to evaluate the influence of temperature on strength using both type tests UCS and PLT, and b) to obtain a correlation, which will enable a verification of the suitability of PLT to indirectly obtain the UCS of this limestone exposed to temperatures up to 900º C, to cover the range of temperatures that could develop during a fire (Brotóns et al. 2014).

2 MATERIALS AND METHODS

2.1 Rock description and samples preparation

A limestone named 'Pedra de Borriol' was used in this study. It is widely used in the cultural heritage buildings in Eastern Spain. Samples were extracted from a quarry in Borriol (Castellon, Eastern Spain). It is a Cretaceous rock mainly composed of calcite (75-85 %) and dolomite (15-20 %) (Garrido et al, 2022). Specimens tested were obtained from blocks measuring 300×140×100 mm.
Cylindrical and prismatic samples (85 of each of them) were drilled perpendicular to the stratification. Five cylindrical and five prismatic samples were dried at 105 ºC and then UCS and PLT tests were performed according ISRM suggested methods (Bieniawski 1975; ISRM 1977). The obtained results were considered as standardised reference values.

2.2 Heating and cooling process

Samples were divided into groups of ten units and heated at temperatures of 200, 300, 400, 500, 600, 700, 800, and 900 ºC (Figure 1). Heat treatments were performed with a gradient of 5 ºC/min. After having reached the target temperature, it was maintained for 1 h. Subsequently, two different cooling methods were then applied (Figure 1): slowly (i.e., air-cooled until reaching room temperature); or quickly (i.e., immersed in water for 10 min and then dried in an oven at 70 °C). Finally, UCS and PLT were carried out 24 hours later at room temperature (25 ºC) (Figure 1). The tests were developed according to ISRM Suggested Methods. The prismatic samples were loaded until failure and the Point Load Strength Index, I_s, was calculated and a size correction applied to obtain the $I_{s(50)}$ value because the samples sizes were different from the 50 mm standard diameter.

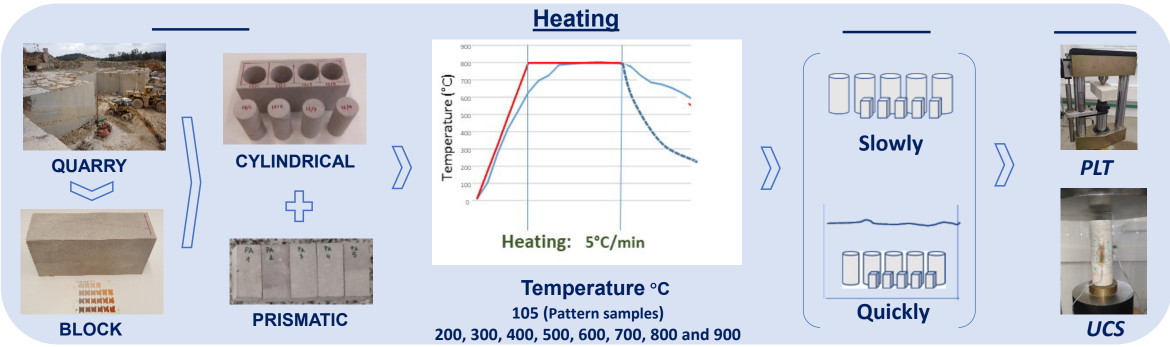

Figure 1. Scheme of the process of preparation, heating and testing of samples.

3 RESULTS AND DISCUSSION

3.1 Effects of temperature

The results of pattern samples (Garrido et al. 2021) show UCS is 176.8 ± 6.7 MPa, which is classified as a 'very strong' rock according to Bieniawski (1974), and the average Point Load Strength Index is 5.86 ± 0.38 MPa, which corresponds to 'very high' value according to Barton (1979).

Various authors have reported that the heating process has an adverse effect on UCS (Zhang et al. 2009; Wu et al. 2013; Brotóns et al. 2013; Martínez-Ibáñez et al. 2020). As the temperature increases, the strength decreases. At 900 ºC, the slow- and quick-cooled samples exhibited reductions of 92.7 and 95.0 %, respectively. The decrease rate of UCS was similar for both cooling methods, with slightly lower values for quickly cooled samples. The samples exposed to 800 ºC are an exception because the UCS values for slowly cooled samples were higher than those for quickly cooled ones. Both cooling methods showed a linear trend. Samples tested up to 400 ºC were identified as *very strong* rocks, while those tested from 400ºC to 800 ºC were identified as *strong* rocks. Samples exposed to 900 ºC became *weak* rocks (Figure 2a).

The Point Load Strength Index decreases with increasing temperature. Samples quickly cooled show a lower Point Load Strength Index than those cooled slowly. There were no differences between both cooling methods for samples exposed to 500 ºC and 600 ºC. Beyond the target temperature of 400 ºC, there was a substantial decrease in the Point Load Strength Index in air-cooled samples. The Point Load Strength Index shows a continuous and gradual strength reduction with increasing temperature. At 900 ºC, this value decreases by 54.5 and 69.4% for slow and quick cooling, respectively. It means the Point Load Strength Index had less variation than that observed for UCS values. Samples tested up to 400 ºC can be classified as *very high* Point Load Strength Index, while those tested from 400 ºC to 900 ºC can be classified as *high* Point Load Strength Index (Figure 2b).

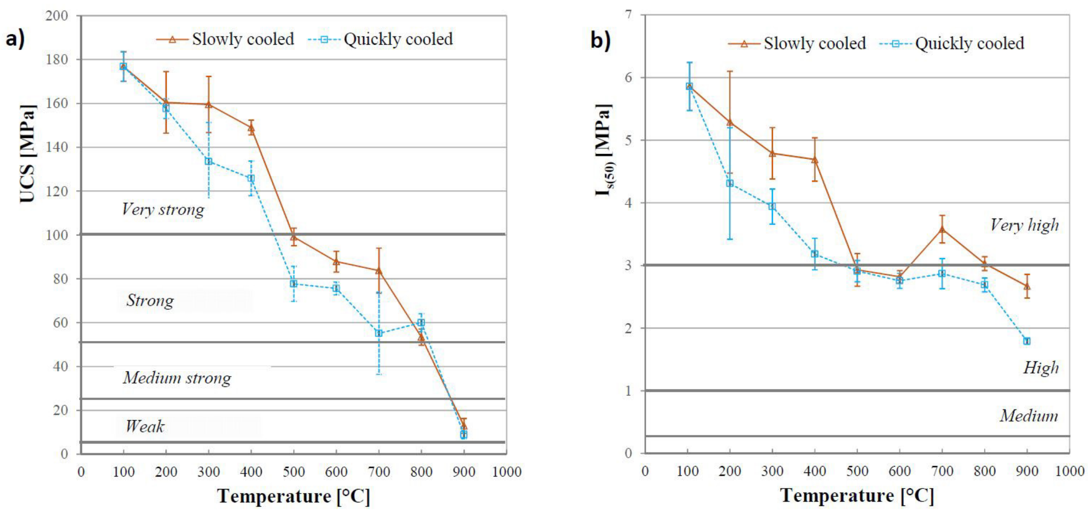

Figure 2. Effects of temperature on: a) Uniaxial Compressive Strength and b) Point Load Strength Index.

Jha et al. (2017) obtained the Point Load Strength Index on two types of schist exposed to high temperatures. The result shows the Point Load Strength Index presents a linear decrease. At 900 ºC reaches up to 70 %, both are slowly cooled. This value is somewhat higher than that obtained for Pedra de Borriol samples subjected to the same cooling conditions. Idris (2018) studied the temperature effect on the Point Load Strength Index on two carbonate rocks, limestone and marble. The results reveal that the strength of both rocks decreased with increasing temperature, up to 90 % at 900 ºC. Overall, the decrease is higher than that obtained in the current study and the research of Jha et al. (2017). The common characteristic for all studies is the result of PLT shows many fluctuations as temperature increases.

3.2 UCS and Point Load Strength Index correlation

The results obtained for the Pedra de Borriol samples subjected to thermal treatment show the best fit between UCS and Point Load Strength Index is a linear regression that passes through the origin (Equation 1), which is the most common in rock mechanics.

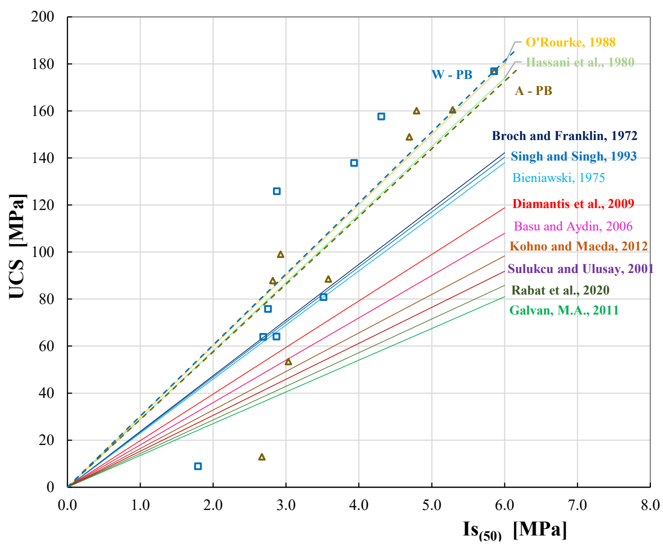

Figure 3. Correlations between UCS and $I_{s(50)}$ to different authors and the results of current study. A-PB is Pedra de Borriol slowly cooled and W-PB is Pedra de Borriol quickly cooled.

The parameter that defines this relationship is β, which is 28.4 and 30.2 in samples slowly and quickly cooled, respectively. Previous research has shown that this coefficient varies over a wide range on intact rocks (Figure 3), but there are no published results of β-values on rocks exposed to high temperatures. The highest β-values were proposed by Hassani et al. (1980) and O'Rourke (1988), obtained for sedimentary rocks (Table 1). Most of the studies, such as Broch & Franklin (1972), Bieniawski (1975), Galván et al. (2011) and Rabat et al. (2020), submit smaller β-values.

Figure 3 shows that the values whose prediction is less accurate correspond to the samples exposed to 800 and 900 ºC. For this reason, the value of the β coefficient has been calculated for each tested temperature (Table 2). These values are of the same order of magnitude up to 600 ºC in Pedra de Borriol samples subjected to slow cooling and decrease from this temperature. The same can be observed on quickly cooled samples after 400 ºC. Based on the data in Table 2, it could be stated that 600 ºC is a threshold temperature in the relationship between point load strength and uniaxial compression strength in Pedra de Borriol samples subjected to slow cooling. In contrast, the threshold temperature for samples subjected to quick cooling is 400 ºC.

Table 2. β-Values obtained from each target temperature and cooling method.

	Temperature [°C]	105	200	300	400	500	600	700	800	900
Slowly cooled	UCS [MPa]	176.8	160.5	160.1	149.0	99.1	87.8	88.5	53.4	12.9
	$I_{s(50)}$ [MPa]	5.86	5.29	4.79	4.69	2.93	2.82	3.58	3.03	2.67
	β	30.2	30.3	33.4	31.8	33.8	31.1	24.7	17.6	4.8
Quickly cooled	UCS [MPa]	176.8	157.6	137.9	125.8	80.8	75.7	64.0	63.9	8.9
	$I_{s(50)}$ [MPa]	5.86	4.31	3.94	3.18	2.91	2.75	2.87	2.69	1.79
	β	30.2	36.6	35.0	39.6	27.8	27.5	22.3	23.8	5.0

4 CONCLUSIONS

The effect of exposure to high temperatures on strength has been studied using UCS and Point Load Strength Test in Pedra de Borriol. The main conclusions of the current study are:

1. The samples exposed to temperatures up to 900 ºC show a significant strength reduction compared with the pattern samples.
2. The rate of decrease is similar for both cooling methods tested, although quick-cooling results are always slightly lower than those obtained for slow cooling.
3. The linear regression between UCS and $I_{s(50)}$ of Pedra de Borriol exposed to high temperatures is similar to those previously obtained by other authors on intact rocks. However, the β-values that relate both parameters are higher than most previously published ones.
4. Two threshold temperatures have been identified for β-values: 600 ºC on samples subjected to slow cooling and 400 ºC for those subjected to quick cooling.

In any case, the results suggest that PLT is a suitable test to estimate UCS in Pedra de Borriol exposed to high temperatures.

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