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Variation of Drilling Rate Index (DRI) with temperature and its relationship with thermal damage on ‘Prada’ limestone

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Abstract. This research evaluates the variation in the Drilling Rate Index (DRI) and its relationship with thermal damage on thermally treated rocks. Samples from ‘Prada’ limestone, a lower cretaceous formation in the southern Pyrenees (Lleida, Spain), were subjected to temperatures of 105, 300, 400 and 500 ºC and then cooled at a slow rate. Ultrasound P-wave velocity tests were performed before and after heating the samples to evaluate the thermal damage experienced by the rock. Sievers’ J miniature drill and brittleness tests were conducted on intact and thermally treated samples, and then resulting SJ and S₂₀ values were combined to determine DRI. The obtained results show that thermal treatment allowed an increase of 34% in the DRI of ‘Prada’ limestone at 500 ºC. DRI exhibited the same variation trend than S₂₀, so we can conclude that thermal variation in DRI is more influenced by S₂₀ than by SJ in ‘Prada’ limestone. We also report a strong relationship between DRI and P-wave velocity, confirming a tight dependence between the drilling performance and the thermally induced damage on the limestone. The observed substantial improvement in the drillability of the rock when heated, measured in terms of DRI value increase, could help in the advance on the development of thermally assisted mechanical excavation methods.

1. Introduction

Modern mechanical excavation strongly depends on the efficiency of the means involved to optimize investment costs. Rock properties influencing drillability have been discussed by different authors. Uniaxial Compression Strength, Brazilian Tensile Strength, Shore Scleroscope Hardness, Point Load Strength are among the most important parameters [1–6]. Additionally, physical and mechanical properties of rocks show dramatic variations with temperature that condition the drillability of the thermally treated rocks. The use of fire to ease rock excavability is an ancient art that was extensively employed during the Roman Empire [7], but few research exists on the effects of high temperatures in...
the drilling performance of rocks. Rossi et al. [8] explored the effects of using a flame jet to achieve high local heating rates, and determined a severe decay of 30% in the rock strength for temperatures up to 600 °C. Rossi et al. [9] studied a combined thermo-mechanical drilling (CTMD) and stated that thermal treatment of rocks causes extensive thermally induced cracks in the rocks, which significantly enhance the penetration performance of the cutting tool. Jamali et al. [10] used high powered laser technology to reduce the rock strength, drilling resistance and fracture toughness. Existing research is still scarce in the drilling performance of thermally treated rocks, even when that would help improve the efficiency of mechanical excavation means. In this study, thermal variation in the drillability of rocks will be studied through Drilling Rate Index (DRI).

2. Methodology

Rock samples were taken from two horizontal boreholes drilled during the design stage of the Tres Ponts Tunnel in Prada limestone, a lower Cretaceous limestone formation in the southern Pyrenees (Lleida, Spain) previously described by different authors [11–14]. A temperature of 105 °C was applied to a total of 20 samples to remove moisture content. Limestones were then separated into groups of 5 samples and heated in an electrical furnace at a slow rate (a gradient of 5 °C was applied) to target temperatures of 300, 400, and 500 °C and then maintained for one hour. Temperatures inside the furnace were monitored by means of PicoLog 6 data logger.

P-wave velocity was chosen since it is a parameter closely linked with the presence of micro-fissures and pores. Ultrasonic measurements were carried out over cylindrical samples before and after thermal treatment, according to the ISRM suggested method [15]. The transmission method consisted of two Olympus V1548 0.1 MHz piezoelectric sensors coupled to the sample at constant pressure. Compressive (P) waves were measured using polarised Olympus transducers videoscan V1548 (0.1 MHz). Emitting-receiving equipment (Proceq Pundit lab +) was used to acquire and digitalise the waveforms to be displayed, manipulated, and stored.

Sievers' J-miniature drill test constitutes a measure of the rock surface hardness or resistance to indentation. According to Bruland [16], it is defined as the measured drillhole depths, after 200 revolutions of the 8.5 mm miniature drillbit acting with a vertical load of 20 kg (figure 1). The test was repeated five times on each sample previously heated to the target temperatures, and the Sievers' J-value was calculated as the mean value of the depth of the miniature drill holes, measured in 1/10 mm. The brittleness test gives a good measure of the rock brittleness or the ability of the rock to resist crushing by repeated impacts. It was conducted according to Bruland [16] to a total of 500 g of aggregate in the fraction 11.2 - 16.0 mm from each sample. Then, the aggregate was crushed by 20 impacts in the mortar and then the value $S_{20}$ was expressed as the percentage of material passing the 11.2 mm. The test was conducted on samples previously heated to the target temperatures and the brittleness $S_{20}$ value for each temperature was taken as the mean value of the samples tested. Finally, values of SJ and $S_{20}$ were combined to obtain a final DRI value for each temperature, allowing the classification of the drillability of Prada limestone according to Bruland [16].
3. Results
Variation in P-wave velocity with temperature was studied using normalised values (i.e., results after heating were divided by those of the same samples obtained at the reference temperature of 105 °C). The ultrasound P-wave velocity decreased with temperature (figure 2) and at 500 °C an abrupt decrease was observed.

SJ exhibited little variation up to 300 °C, and then a sudden increase at 400 °C was observed (figure 3). Total increase in SJ at 500 °C was of 44%. Additionally, values of S20 were almost constant up to 300 °C, and then abruptly increased at 400 °C (figure 4). Total variation in S20 was of 31% at 500 °C. Finally, DRI increased with temperature and trend was similar as that for S20 (figure 4). Total increase in DRI at 500 °C was of 34% (figure 5) and that implied a change in the drillability category at 500 °C (from medium to high) according to chartered values established by Bruland [16]. Different correlation functions were proposed in this research between DRI and P-wave velocity, and linear function showed best results (R² = 0.90).
Figure 2. P-wave velocity variation with temperature (normalised values).

Figure 3. SJ variation with temperature.
**Figure 4.** $S_{20}$ variation with temperature.

**Figure 5.** DRI variation with temperature.
4. Discussion
Thermal treatment resulted in a total increase of 34% in the DRI of Prada limestone at 500°C. An excellent linear correlation was determined between DRI and P-wave velocity. Thus, such increase in DRI must be related to the increase in the thermal damage in the rock, expressed by P-wave velocity variation.

SJ and S20 represent different effects in a rotary-percussive drilling process, since the impact action of the bit is expressed by S20, whereas thrust and rotation match with the SJ value [17]. Temperature influence is remarkable as total variation at 500°C in SJ and S20 was of 44% and 31%, respectively. The category of brittleness, or the ability to be crushed by repeated impacts (measured by S20), varied with temperature from medium to high, and rock surface hardness or resistance to indentation (represented by SJ) varied from medium to low, both in the scale of Dahl et al. [18]. We attribute this effect to the increase in porosity and to the propagation and coalescence of microfissures due to thermal treatment, what is expressed by a decrease on P-wave velocity, specially between 400 °C and 500 °C.

5. Conclusions
In this research, samples from Prada limestone were heated at temperatures of 105, 300, 400, and 500 °C and then cooled at a slow rate. We observed an increase in SJ and S20 that, combined through DRI, point to an increase in Prada limestone drillability. The derived conclusions of our study are listed below:

1. DRI increased with temperature, implying a change in the drillability category at 500 °C (from medium to high) and a total increase of 34%.
2. Variation in P-wave velocity with temperature is related to thermal damage and that represents the growth and coalescence of microfissures in the rock.
3. Total variation at 500°C in SJ and S20 was of 44% and 31%, respectively. An increase in microfissures (represented by P-wave velocity decrease) leads to an increase in the ability to indentation represented by SJ, and a drop in the resistance of rock to resist crushing represented by S20.
4. DRI exhibited the same variation trend than S20, so we can conclude that thermal variation in DRI is more influenced by S20 than by SJ.

A substantial improvement in the drillability of the rock when heated, measured through DRI index, can help improve efficiency of mechanical excavation means. The effects on the drillability of Prada limestone need to be explored at higher temperatures than those used in this study, and in rocks cooled at a rapid rate.

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