Variation in the drilling rate in thermally treated limestones through penetration-time curves from Sievers' J-miniature drill tests

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ABSTRACT: In this research we subject Prada limestone samples to temperatures of 600 ºC, and then we perform Sievers' J-miniature drill tests to study the evolution of the penetration over time. We identify two characteristic intervals in the penetration–time plots: a superficial region with a variable penetration rate that includes an initial maximum value, and a deeper region in which the penetration rate stabilizes. Thermally treated samples exhibit an increase in the initial and final penetration rates, which indicates thermal damage both superficially and in-depth. We also observe that the time necessary to reach a stable drilling rate dramatically increases with temperature, involving an important part of the total test time. That has a clear influence on the final SJ value from Sievers' J-miniature drill tests and is a starting point to determine a corrected SJ value for thermally treated limestones.

Keywords: Rock drillability, Sievers' J-miniature drill tests, SJ value, Thermal treatment, Temperature, Limestone.

1 INTRODUCTION

The use of fire to facilitate the excavation of the rock mass is an art of tunnelling that began at the dawn of civilization. The mines excavated in Spain during the Roman Empire in search of gold are excellent examples of the use of this technique, due to the complex systems employed and the hundreds of millions of cubic meters of earth excavated. For example, the mining works at Las Médulas (Spain) were described in detail by Pliny the Elder in the 1st century A.D., including the firesetting technique, which was used to excavate more than 325 km of galleries (Juncá-Ubierna, 1998). The firesetting method involved setting fire to combustible material (mainly wood or a combination of wood and charcoal) in contact with the rock surface. Therefore, the combination of differential expansion of the minerals in the rock, and the increase in pore pressure because of water vapor, created large internal stresses that led to the fragmentation of the rock. Water was then used with the primary intention of cooling the hot rock before it was worked by hand. Historical reports describe a much more effective cracking and extraction when the rock was cooled by using water (Hooson, 1747). An evidence of the use of the firesetting technique is the existence of deep layers of ash, partially burnt wood and smoke-blackened roofs that are preserved in mines of all ages around the world, such as the Ai Bunar mine in Bulgaria, the oldest known mine in the world dating back to the fifth millennium B.C. Firesetting could maintain temperatures of the order of 700 °C for considerable periods and reach maximum values of 800 °C in carefully constructed fires (Weisgerber & Willies, 2000). The decline of this technique in the 18th and 19th centuries coincided with the introduction of the use of explosives and steel drills (Craddock, 1992).

Thermal-assisted drilling techniques are a topic of growing interest to make mining and civil engineering more efficient and cost-effective (Jamali et al., 2019; Rossi et al., 2020). Existing research demonstrates that the drillability of rocks is dominated by their mechanical and physical properties (Capik et al., 2017; Saeidi et al., 2014; Yarali & Soyer, 2011; Yenice, 2019; Yetkin et al., 2016), and high temperatures cause severe damage that alters these properties (Andriani & Germinario, 2014; Garrido et al., 2021; Martínez-Ibáñez et al., 2021; Sengun, 2014; Yavuz et al., 2010; Zhang et al., 2017), facilitating drillability (Martínez-Ibáñez et al., 2021).

The SJ value from Sievers' J-miniature drill tests (Sievers, 1950) is mostly combined with S_{20} from brittleness tests (von Matern & Hjelmér, 1943) to determine the widely used Drilling Rate Index (DRI) (Selmer-Olsen & Blindheim, 1970). These values represent different aspects of a rotary-percussive drilling process, with S_{20} indicating the impact action of the drill bit and SJ indicating the thrust and rotation (Su et al., 2016). Penetration-time curves obtained from Sievers' J-miniature drill tests can be registered and used as an indication of the drilling rate on rock samples (Dahl et al., 2007). However, few research exists on the use of such curves as a complementary method for studying rock drillability (O'Connor et al., 2020; Yetkín, 2021). Moreover, the shape of such curves and their defining characteristics remain unstudied for thermally treated rocks.

In this research we study penetration – time curves and its derivative, the penetration rate – time series from Sievers' J-miniature miniature drill tests on samples heated to 105 and 600 ºC to observe differences. These curves can provide valuable information on the effects of temperature on the drillability of Prada limestone.

2 MATERIALS AND METHODS

This research is focused on the Prada limestone, a lower Cretaceous formation located in the Serra de Prada, a range of mountains in the Catalan south Pyrenean zone (Spain). Rock samples were taken from two horizontal survey boreholes drilled during the design stage of the Tres Ponts Tunnel, that was open to service in autumn 2021.

A total of 10 samples were selected and a temperature of 105 ºC was initially applied to remove natural moisture. Then samples were separated into two groups of 5 samples: the first group was subjected to thermal treatment and the other group was used for the determination of the intact rock properties. Thermal treatment consisted of heating samples in a furnace at temperatures of 600 ºC. A gradient of 5 ºC/min was applied and, once the furnace reached the target temperature, it was maintained for one hour. Samples were then cooled at a slow rate to room temperature.

Sievers' J-value represents the rock surface hardness or resistance to indentation. Tests were performed on both intact and thermally treated samples to observe the differences. More specifically, the performed test consisted in the measurement of the drillhole depths after 200 revolutions of an 8.5 mm miniature drillbit acting with a vertical load of 20 kg. The test was repeated five times on each rock sample, and the Sievers' J-value was calculated as the mean value of the depth of the miniature drill holes, measured in tenths of millimeters (Bruland, 2000). In this research the penetration of the drillbit was real-time monitored during the test, and the depth-time curves were represented every 0.5 s.

3 RESULTS AND DISCUSSION

Figure 1 represents Sievers' J-values (SJ) for samples heated to 105 and 600 ºC. Due to the reduced number of samples available, mean values may not be representative and, therefore, box-whisker plots with indication of the median values are plotted.

Prada limestone exhibited a significant decrease in resistance to indentation when heated to 600 ºC. Thus, SJ values for intact Prada samples are in the range of "Medium" to "High" resistance to indentation in the scale of Dahl et al.(2012). In contrast, drillability in Prada limestone sharply increased after thermal treatment: samples exhibited SJ values in the range of "Low" resistance to indentation. The causes for such a dramatic decay in the resistance to indentation at 600 ºC are linked with severe thermal damage in this rock in terms of increased porosity and growth and coalescence of microcracks (Martínez-Ibáñez et al., 2021). Although the intact Prada limestone has a homogeneous appearance, it is a natural material with small variations in its composition and texture, including microcracking, and this explains the dispersion in the results obtained at 105 ºC. We attribute a larger scattering in SJ at 600 ºC to the referred thermal damage suffered by the rock.

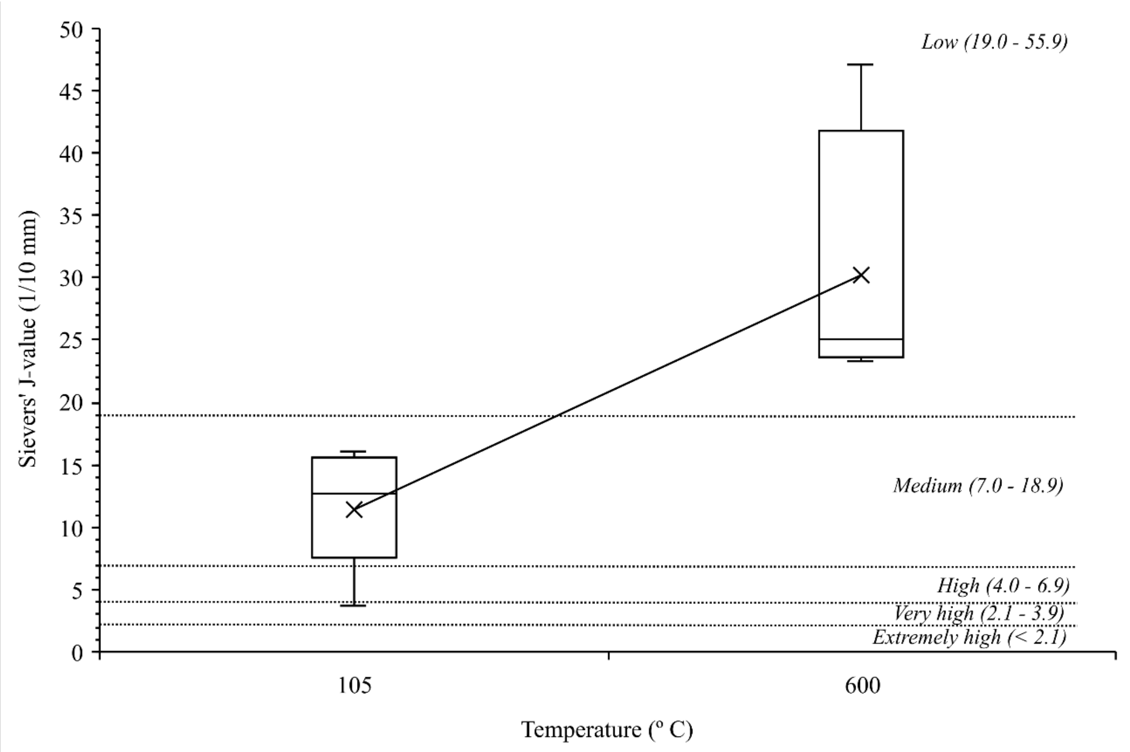

Figure 1. Variation of Sievers' J-value (SJ) with temperature. Categories of resistance to indentation according to Dahl et al. (2012).

Figure 2 represents penetration and drilling rate over time for both intact and thermally treated representative samples. We identify two distinct intervals: a surface area with a variable penetration rate that has a maximum value at the beginning, and a deeper area where the penetration rate becomes stable. When samples are heated to 600 ºC, the initial and final penetration rates increase, suggesting greater damage to both the surface and the depth of the sample.

Additionally, it takes much longer for the drilling rate to stabilize when samples are thermally treated, which takes up a significant portion of the total testing time. Thus, the penetration rate stabilizes in the first 3-4 seconds of the test in the intact samples, while in thermally treated samples the time is extended to around 7 - 8 seconds, the penetration rates being much higher. This implies that a significant part of the total SJ value is due to these first seconds of the test: a 20 % of the total penetration occurs in the first 7 seconds in the thermally treated sample.

All the above has a significant influence on the accuracy of the SJ value, as the initial penetration rate is not representative of the characteristic drillability of the overall thermally treated Prada limestone.

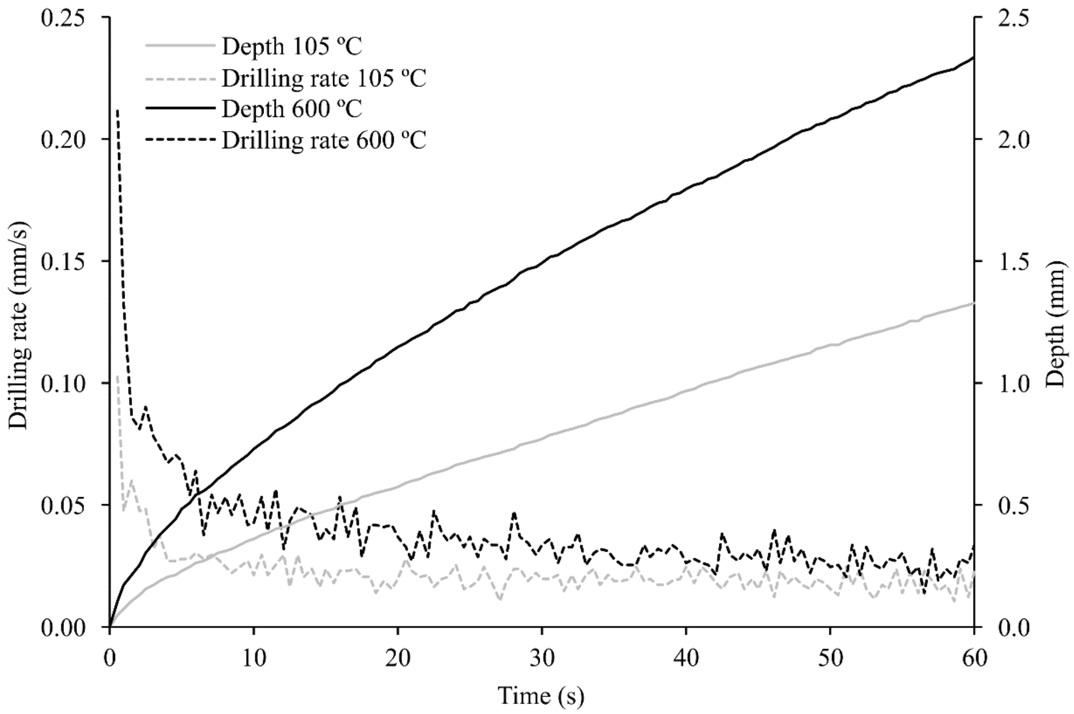

Figure 2. Depth – time and drilling rate – time plots for samples heated to 105 and 600 ºC.

4 CONCLUSIONS

In this research we novelty study penetration – time and penetration rate – time curves from Sievers' J-miniature miniature drill tests in thermally treated samples. We devise conclusions about the drilling performance of limestones from Prada formation and the influence of temperature. To do so, we subjected samples to temperatures of 105 and 600 ºC and cooled them at a slow rate to observe differences. The following are the primary conclusions derived from this research:

- Two characteristic zones are identified here in view of penetration–time and penetration rate – time plots: a surface area with a variable penetration rate that has a maximum value at the beginning, and a deeper area where the penetration rate becomes stable.
- Samples heated to 600 ºC exhibited an increase in both the initial and final penetration rates due to thermal damage in the rock.
- The time necessary to reach a stable drilling rate increases with temperature, and that involves an important proportion of the final SJ value.

All the above has a clear influence on the final SJ value from Sievers' J-miniature drill tests and is a starting point to determine a corrected SJ value for thermally treated limestones. Future research should focus on this topic, using a larger number of samples, temperatures, and a wider number of limestone types.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Kreum SA, Ayesa SA, Infraestructures de la Generalitat de Catalunya, S.A.U., and the Lleida regional roads authority (Servei Territorial de Carreteres de Lleida, Generalitat de Catalunya) for providing rock samples. This work was supported by the Department of Geological and Geotechnical Engineering, Universitat Politècnica de València.

REFERENCES

Andriani, G. F., & Germinario, L. (2014). Thermal decay of carbonate dimension stones: fabric, physical and mechanical changes. *Environmental Earth Sciences*, *72*(7), 2523–2539. https://doi.org/10.1007/s12665-014-3160-6

Bruland, A. (2000). *Hard Rock Tunnel Boring Vol. 8 - Drillability - Test Methods. Doctoral thesis* (Nummer April) [Norwegian University of Science and Technology (NTNU Trondheim)]. https://doi.org/10.13140/RG.2.1.3363.4729

Capik, M., Yilmaz, A. O., & Yasar, S. (2017). Relationships between the drilling rate index and physicomechanical rock properties. *Bulletin of Engineering Geology and the Environment*, *76*(1), 253–261. https://doi.org/10.1007/s10064-016-0991-2

Craddock, P. T. (1992). A short history of firesetting. *Endeavour*, *16*(3), 145–150. https://doi.org/10.1016/0160-9327(92)90074-Y

Dahl, F., Bruland, A., Jakobsen, P. D., Nilsen, B., & Grøv, E. (2012). Classifications of properties influencing the drillability of rocks, based on the NTNU/SINTEF test method. *Tunnelling and Underground Space Technology*, *28*(1), 150–158. https://doi.org/10.1016/j.tust.2011.10.006

Dahl, F., Grøv, E., & Breivik, T. (2007). Development of a new direct test method for estimating cutter life, based on the Sievers' J miniature drill test. *Tunnelling and Underground Space Technology*, *22*(1), 106–116. https://doi.org/10.1016/j.tust.2006.03.001

Garrido, M. E., Petnga, F. B., Martínez-Ibáñez, V., Serón, J. B., Hidalgo-Signes, C., & Tomás, R. (2021). Predicting the Uniaxial Compressive Strength of a Limestone Exposed to High Temperatures by Point Load and Leeb Rebound Hardness Testing. *Rock Mechanics and Rock Engineering*, *0123456789*. https://doi.org/10.1007/s00603-021-02647-0

Hooson, W. (1747). The Miners Dictionary: Explaining Not Only the Terms Used by Miners, But Also Containing the Theory and Practice of that Most Useful Art of Mineing, More Especially of Lead-mines ... and T. Payne, in Wrexham. https://books.google.es/books?id=OtKuoQEACAAJ

Jamali, S., Wittig, V., Börner, J., Bracke, R., & Ostendorf, A. (2019). Application of high powered Laser Technology to alter hard rock properties towards lower strength materials for more efficient drilling, mining, and Geothermal Energy production. *Geomechanics for Energy and the Environment*, *20*, 100112. https://doi.org/10.1016/j.gete.2019.01.001

Juncá-Ubierna, J. A. (1998). Tunnel heritage in Spain: Roots of the underground. *Tunnelling and Underground Space Technology*, *13*(2), 131–141. https://doi.org/10.1016/S0886-7798(98)00040-6

Martínez-Ibáñez, V., Garrido, M. E., Hidalgo Signes, C., Basco, A., Miranda, T., & Tomás, R. (2021). Thermal Effects on the Drilling Performance of a Limestone: Relationships with Physical and Mechanical Properties. *Applied Sciences*, *11*(7), 3286. https://doi.org/10.3390/app11073286

Martínez-Ibáñez, V., Garrido, M. E., Hidalgo Signes, C., & Tomás, R. (2021). Micro and macro-structural effects of high temperatures in Prada limestone: Key factors for future fire-intervention protocols in Tres Ponts Tunnel (Spain). *Construction and Building Materials*, *286*, 122960. https://doi.org/10.1016/j.conbuildmat.2021.122960

O'Connor, E., Friedman, M., Dahl, F., Jakobsen, P. D., van Oosterhout, D., & Long, M. (2020). Assessing the abrasivity characteristics of the central Dublin fluvio-glacial gravels – A laboratory study. *Tunnelling and Underground Space Technology*, *96*(March 2019), 103209. https://doi.org/10.1016/j.tust.2019.103209

Rossi, E., Jamali, S., Saar, M. O., & Rudolf von Rohr, P. (2020). Field test of a Combined Thermo-Mechanical Drilling technology. Mode I: Thermal spallation drilling. *Journal of Petroleum Science and Engineering*, *190*(December 2019), 107005. https://doi.org/10.1016/j.petrol.2020.107005

Saeidi, O., Torabi, S. R., Ataei, M., & Rostami, J. (2014). A stochastic penetration rate model for rotary drilling in surface mines. *International Journal of Rock Mechanics and Mining Sciences*, *68*, 55–65. https://doi.org/10.1016/j.ijrmms.2014.02.007

Selmer-Olsen, R., & Blindheim, O. T. (1970). On the drillability of rock by percussive drilling. *2nd Congress of ISRM*.

Sengun, N. (2014). Influence of thermal damage on the physical and mechanical properties of carbonate rocks. *Arabian Journal of Geosciences*, *7*(12), 5543–5551. https://doi.org/10.1007/s12517-013-1177-x

Sievers, H. (1950). Die Bestimmung des Bohrwiderstandes von Gesteinen. *Glückauf*, *86*(37/38), 776–784.

Su, O., Sakız, U., & Akçın, N. A. (2016). Effect of elastic and strength properties of rocks during blasthole drilling. *ISRM International Symposium - EUROCK 2016*, *August*, 217–221. https://doi.org/10.1201/9781315388502-36
von Matern, N., & Hjelmér, A. (1943). Försök med pågrus ("Tests with Chippings"). I: *Meddelande 65*. Statens väginstitut. https://www.diva-portal.org/smash/get/diva2:867288/FULLTEXT01.pdf
Weisgerber, G., & Willies, L. (2000). The use of fire in prehistoric and ancient mining-firesetting. *Paléorient*, *26*(2), 131–149. https://doi.org/10.3406/paleo.2000.4715
Yarali, O., & Soyer, E. (2011). The effect of mechanical rock properties and brittleness on drillability. *Scientific Research and Essays*, *6*(5), 1077–1088. https://doi.org/10.5897/SRE10.1004
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. https://doi.org/10.1016/j.ijrmms.2009.09.014
Yenice, H. (2019). Determination of Drilling Rate Index Based on Rock Strength Using Regression Analysis. *Anais da Academia Brasileira de Ciências*, *91*(3), 1–10. https://doi.org/10.1590/0001-3765201920181095
Yetkín, M. E. (2021). Examining of rock drilling properties in underground metal mine excavation. *Anais da Academia Brasileira de Ciências*, *93*(1), 1–10. https://doi.org/10.1590/0001-3765202120191202
Yetkin, M. E., Özfırat, M. K., Yenice, H., Şimşir, F., & Kahraman, B. (2016). Examining the relation between rock mass cuttability index and rock drilling properties. *Journal of African Earth Sciences*, *124*, 151–158. https://doi.org/10.1016/j.jafrearsci.2016.09.025
Zhang, W., Sun, Q., Zhu, S., & Wang, B. (2017). Experimental study on mechanical and porous characteristics of limestone affected by high temperature. *Applied Thermal Engineering*, *110*, 356–362. https://doi.org/10.1016/j.applthermaleng.2016.08.194