New testing equipment to study dynamic fracture of rock and cement-based materials subjected to the action of roadheaders

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ABSTRACT: New customized testing equipment specifically developed to address the dynamic fracture of material excavated by a roadheader at a laboratory scale is shown. Furthermore, limestone and cement-based material samples are tested to analyze the response of both the material and the cutting head when the number of acting picks is increased as a consequence of the translation of the whole roadheader during the excavation process. Results prove that the new equipment allows to identify the initial and end points of the contact between the sample and each of the picks, as well as the relation between the material strength and the mechanical specifications of the excavating machine. Thus, the new equipment can be used to tailor cutting head designs and to optimize the cutting parameters for a particular mechanical removal operation.

Keywords: dynamic fracture, roadheader, excavation, rock cutting.

1 INTRODUCTION

Mining and civil engineering projects usually require to remove huge quantities of rock material in order to build galleries or tunnels. Main methods used to achieve such challenge are blasting and mechanical excavation. Using explosives is a complex and expensive technique, as its transport, storage and use have to be carefully executed under different law requirements (Deshmukh et al. 2020). Consequently, mechanical excavation is consistently becoming commonplace nowadays, as it involves less risk to the surrounding buildings, slopes and structures such as damns or mines themselves. The vast majority of these mechanical removal methods are based on the action of several picks, arranged on a cutter head, that crash against the rock material producing its breakage in form of chips. Literature on the physical phenomenon involved in this mentioned interaction between the pick and the material is mainly based on the theory proposed by Evans (I. Evans 1962; Ivor Evans 1984a, 1984b). His contribution lead to many improvements on the cutting techniques over the years, allowing the development of the state of the art in related fields as: weathering and damaging of picks (Fan et al. 2023), efficient design and safety requirements (Li et al. 2012), or even models to estimate the performance of roadheaders depending on the geological characteristics of the rock mass (Wang et al. 2021).

Nevertheless, better understanding of the interaction phenomenon between the pick and the rock material would lead to improved excavations techniques and optimized designed machinery (Cheluszka et al. 2022). However, the excavation process at a laboratory scale is complex and expensive. For this reason, there is a lack of versatile testing devices to address the excavation phenomenon using roadheaders at a laboratory scale in a control and safe environment. Nonetheless, there exists bibliography in which the interaction phenomenon between the pick and the material is carefully examined (Cheluszka et al. 2022; Fan et al. 2023; Guerrero-Miguel et al. 2023; Prendes-Gero, et al. 2021) and it has been proved that not only the characteristics of the cutting tool but also the mechanical properties of the material play a key role in the viability of using mechanical removing techniques in mining and civil projects (X Li et al., 2012; Li et al. 2013, Wang et al. 2022).

In this contribution a new testing equipment that allows to reproduce the interaction of several picks in good agreement which the experimental reality on in situ projects is shown and carefully explained. Afterwards, different tests on limestone and cement-based materials are carried out in order to explore the possibilities of the new design, proving that it allows to stablish the initial and end contact points of the actuating pick and analysing how different materials affect the performance of the cutting head.

2 METHODOLOGY

There exist some previous devices in order to address the interaction between the pick and the excavated material under certain circumstances (Fan et al. 2023). However, when it comes to the interaction of more than one pick, interaction between the different picks and the material requires of new customized testing equipment. For that reason, improvement of excavation techniques is up to date among the scientific community (Jeong et al. 2020; Peng et al. 2021). Cutting heads used on roadheaders are usually made by two symmetric drums; however, to carefully analyzed the excavation process at a laboratory scale is enough to employ just one of its halves (Figure 1). Therefore, the tailored designed cutting machine present in this contribution consist on a drum mounted on a rotating shaft. This latter one is connected to an electric engine of 11kW (Figure 1c) using a belt transmission which objective is to multiply the torque at the output of the electric motor. Both the shaft and the motor are fixed to the outer frame, which is made up of five steel plates stiffened by several U-profiles in its inner surface. The motor is controlled by an electrical panel that allows to vary the cutting speed using a frequency inverter (Figure 1a).

Inside the frame (Figure 1b), there is a trolley on which the sample is placed with the help of a crane. Subsequently, an oil-hydraulic circuit activates a double-acting cylinder that moves the trolley in both directions; either moving it towards the cutting head to perform the test or moving it away to gain as much space as possible during the sample placement process. Additionally, an ambient light is available to facilitate the work of the operators in reduced light conditions.

In order to measure all the variables involved in the process, the testing device is instrumented with different sensors. First, an encoder (Figure 1c) is mounted on the rotating shaft of the cutting head to record the angular speed during the whole test. In addition, a linear displacement sensor is fixed on the exterior frame and connected to the trolley to measure its displacement. Thus, it is possible to set the feed rate before initiating the test. The pressure required in the oil-hydraulic circuit for this movement over the test time is recorded using a pressure sensor.

Material response is recorded using an accelerometer at 200 mm closest face of the sample to the cutting head (Figure 1d). Thus, optimizing its distance to the impact area in order to be as close as possible to it while keeping safe conditions. All data are synchronized with a high-speed camera that can record up to 20,000 frames per second (fps) when the illumination is enhanced using the flicker-free spotlights (Figure 1c). It is worth highlighting that also auxiliary high definition cameras were used (Figure 1b and Figure 1d). Data logging has been performed using a data acquisition card and a computer (Figure 1c).

After placing the sample on the trolley with the help of the crane, it is necessary to fix it so it does not move during the test. There are two fixing systems, main and auxiliary, with the same operating principle. Both consist of two threaded rods fixed to the trolley and an IPE 80 (auxiliary) or IPE 100 (main) that connects them. These profiles are placed in contact with the upper face of the sample to guarantee that it remains stationery during the execution of the test.

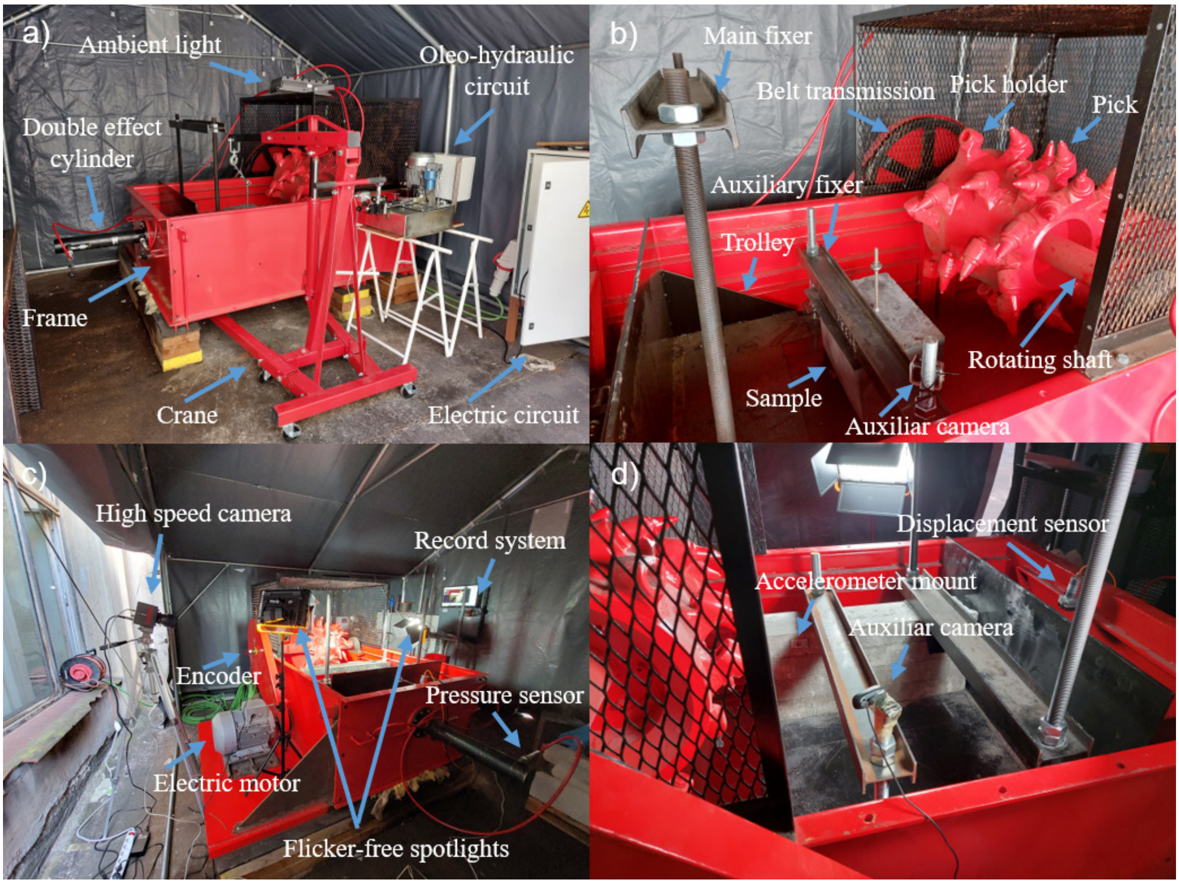

Figure 1. Exterior frame and auxiliary items of the testing machine (a); detail of the trolley, sample fixers and cutting head (b), instrumentation outside the frame of the machine (c); and detail of the instrumentation in the vicinities of the sample (d).

It is worth mentioning that some pick holders are empty on Figure 1. This has been made on purpose, so it is possible to analyse within the same machine the effect of just one acting pick if the sample size and location are correctly chosen.

Cement-based and limestone samples have been used to show the possibilities of the new testing equipment. Thus, covering the spectrum of materials usually found in underground excavation projects. Cutting speed has been selected within the common working range employed in roadheaders. Particularly, it has been set to 30 rpm (revolutions per minute), which means that the acting picks will reach a maximum lineal speed of approximately 1.60 m/s. Meanwhile, the trolley is moving towards the cutting head at 0.5 mm/s. Samples have been placed so only picks 25 and 27 impact against it. Chosen picks are diametrically opposed, so an impact is expected each half revolution. In addition, due to the tapered design of the cutting head, pick 25 describes a circular with a radius 5 mm lower than pick 27.

3 RESULTS AND DISCUSSION

During the excavation process, two phenomena occur consecutively. First, the pick comes into contact with the material to be excavated at a single point, that evolves in a small contact area in the subsequent moments. This causes the impact energy to be transmitted through a small portion of the material in the initial stage, thus causing it to be pulverized during the first penetration phase. This phenomenon is known as crushing. In Figure 1a powder material is expulsed as a consequence of interaction between the pick and the material. It should be noted that not all the material released in the form of powder is projected outwards, some of it is trapped between the pick and the rest of the sample leading to wearing effects clearly visible on the curved surface of the picks (Figure 2). After crushing, there is a second phase of grinding of the trapped powder. Finally, the interaction between the pick and the material evolves towards the creation of a chip (Figure 2b) or the creation of a groove, depending on the properties of the material and/or the proximity to a free face.

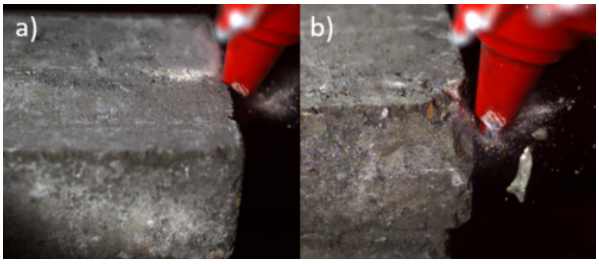

Figure 2. Different physical phenomena observed during excavation process: powder material (a) and chip formation (b).

Data registered during testing shows that oil pressure sensor had a significance delay before any disturbance is registered after the impact. In this sense, both the encoder and the accelerometer respond much quicker to any external disturbance and thus, become more suitable to address the performance of the cutting head in real time.

Based on the aforementioned, and considering that it is more suitable to track the evolution variations in the cutting head than obtaining real time information from the excavated material during in situ operations, a detailed analysis of the speed is done over the three last test impacts in limestone and cement-based material before the machine is unable to continue excavation due to the large amount of material to remove. Figure 3 proves how the variations in cutting speed can be used to detect and distinguish impacts between picks, thanks to points: A (initial deceleration point), B (final deceleration and initial acceleration point simultaneously) and C (final deceleration point).

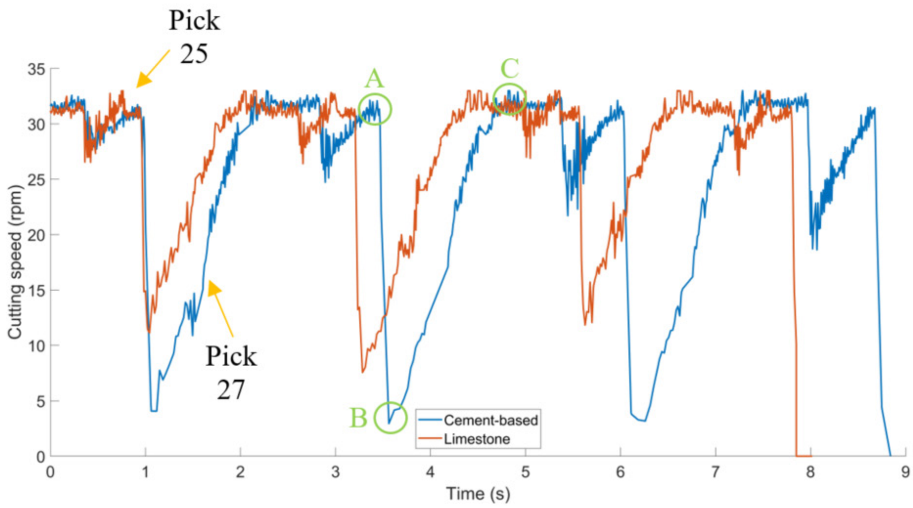

Figure 3. Acceleration and decelerations measured by the encoder in the cutting speed.

Each impact generates two different zones in the cutting-speed vs time plot that can be physically correlated with the excavation process itself:

- AB section: It is considered to be the contact time between the pick and the excavated material. This affirmation is based on the hypothesis that once the contact between the two is finished, the machine is free to start accelerating again until it reaches its regimen speed at point C. This section can be approximately defined by a downhill straight line,

the slope of which stores the information about the braking process. It is obvious that a less resistant material would have braked the machine much less, but it is also true that such a consequence would have been achieved if the machine were more powerful. Therefore, the downhill slope stores mixed information in which it is not possible, a priori, to separate the part due to the material from the part due to the machine.
- BC section: If it is only referred to the recovery of the electric motor, and the sample is not influencing it, then it follows that all data adjustments should respond to a similar fit. Although last part of the BC section is slightly nonlinear, linear regression has been elected to determine acceleration and deceleration rates. Results depicted below show that linear regression can successfully be used to treat recorded data.

To verify the previous hypothesis about the information included in the cutting speed plot shown in Figure 3, acceleration and deceleration rates have been compared (Figure 4). In both materials, acceleration rates related to pick 25 remains almost constant and around 10 rpm/s, whereas those related to pick 27 oscillate around 20 rpm/s. Regarding deceleration evolution during the test, both materials follow a linear law in the case of pick 25, related to smaller impacts. However, it is worth highlighting than, in this occasion, both have clearly different slopes, so as it was stated before the recorded behavior has been different. Regarding the approximately constant value on deceleration for both picks, it can be explained from the relative position of both the sample and the cutting head. Cutting depth increases in each cutting revolution till it reaches a maximum value, once it is reached, decelerations can be expected to slightly vary within a tight range.

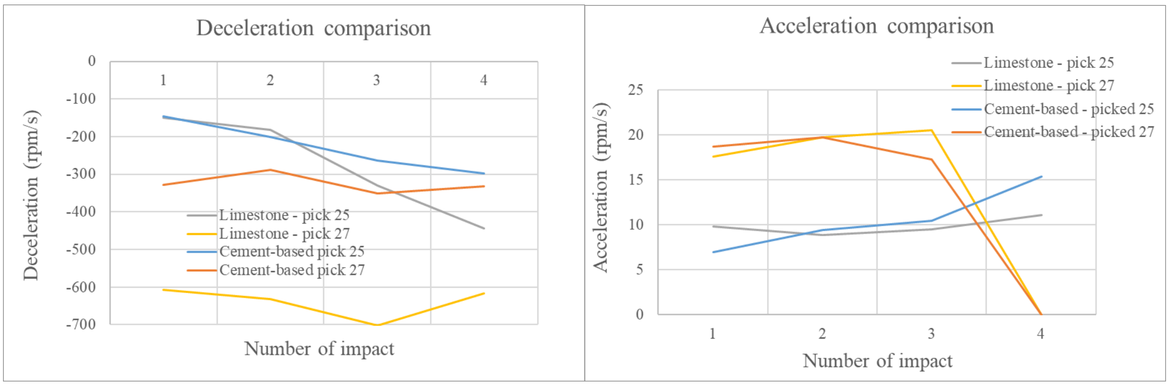

Figure 4. Deceleration and accelerations measured by the encoder in the cutting speed.

4 CONCLUSIONS

New equipment to address the physical interaction between roadheaders cutting tools and excavated material has been successfully designed and instrumented. Evolution of machine parameters during the execution of tests in both rock and cement-based materials prove that monitoring cutting speed in real time applications can lead to optimize the cutting process once basic characteristics of the machine are known as the average acceleration and deceleration rates. This contribution paves the way to reproduce the excavation process at a laboratory scale under safety conditions, triggering a cost reduction in tailored studies related to particular engineering projects or conditions.

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