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Experimental Analysis of Flake Formation Under Roadheader's Pick Impact

D. J. Guerrero-Miguel, M. I. Álvarez-Fernández, M. B. Prendes-Gero & C. González-Nicieza

DinRock Research Group, Universidad de Oviedo, Mieres, Asturias 33600, Spain.
inma@dinrock-uniovi.com

0000-0002-9125-4860
0000-0002-5681-6530
0000-0001-9125-4863
0000-0002-2575-9676

Abstract

The removal of rock material is a fundamental requirement to successful execution of most mining and civil engineering projects. Depending on the properties of the material to be excavated, roadheaders are frequently used as primary excavation tools. These machines employ an array of picks to fragment the rock, producing small portions -flakes. Consequently, the efficiency of this process significantly influences the economic revenue and the viability of such projects.

To gain a deeper understanding into the physical mechanisms underlying flake formation, the phenomenon was replicated at a laboratory mid-scale to examine the influence of most relevant involved variables. Specifically, a previously designed pendulum testing apparatus was used to conduct an experimental campaign in concrete specimens subjected to dynamic impact. The experimental campaign involved variations of the impact angle and the distance from the impact point to the free edge of the specimens. The tests were recorded using a high-speed camera to reveal the strong dependency of flake formation on both the angle of impact and proximity to the free edge. Additionally, the resulting fracture surfaces were characterized using three-dimensional scanning techniques to evaluate the effective damage produced depending on the transmitted energy.

For small angles and elevated distances from the free face, impacts produced minimal surface damage, mainly generating powder without flakes. Conversely, higher angles and closer proximity to the edge favored the formation of distinct flakes, which may also involve internal grain rupture. The fractured surfaces often resembled Gaussian bell shapes, suggesting a potential predictive model for flake volume and propagation based on impact parameters. Some tests exhibited multiple and sequential flake detachments, proving that pick action may be performed in different interactions rather than with a simultaneous failure in the affected area. These insights contribute to a better understanding of dynamic fragmentation in brittle and heterogeneous materials.

Keywords

Dynamic behaviour, Excavation, High-speed video, Rock surface.

1 Introduction

The performance of roadheaders is an essential operating parameter to ensure the execution of ground-related engineering projects within acceptable economic and operational constraints. Many variables influence the excavation process. In this sense, the overall material removal performance results from the interaction between the operational limitations of the machine and the mechanical properties of the excavated material. Hence, a thorough understanding of this interaction between the excavating device and the rock mass is essential to optimize mechanical rock excavation of rock masses and to advance knowledge of the real physical phenomena that arise during the excavation process itself. In the case of roadheaders, material removal is produced by successive impacts of cutting picks against the rock mass. Therefore, conical picks are among the most widely used tools in the field of mechanical rock excavation, with applications ranging from mining to civil engineering works, such as opening underground spaces or the renovation of road surfaces(Cheluszka et al. 2022).

To optimize the excavation process mainly translates as the best manner to increase its efficiency, although this may be achieved through several approaches. In this regard, previous literature pursued to reduce the wear of the conical picks, thus reducing the need for replacements and stops for maintenance operations. While the dominant research directions on pick wear aim to mitigate degradation during excavation (Wang 2024; Youlu et al. 2026), new approaches include the enhancement of pick geometry through topological optimization (Cao et al. 2025) and the incorporation of reinforcing sleeves to improve their performance (Cheluszka et al. 2022). In parallel, and aligned with the increasing automation tendency in mining and civil engineering fields, recent studies addressed the use of real-time sensor data collected during the excavation process to simultaneously optimize the cutting parameters(Kim et al. 2024).

Additionally, it is worth noting that alternative proposals focused on the role of the rock mass were evalauted. These includes disrupting techniques such as pre-slotting of the excavation face (Zhang et al. 2024), the generation of previous cracks in the rock masses to ease the excavation process (Dong et al. 2025)or the application of laser-beams to damage the prior to the impact of the pick (Xu et al. 2025). The results of these studies encourage a promising future when combined with roadheaders, although the available literature regarding these topics is still reduced.

As an initial step towards improving the efficiency, durability and energy consumption during the excavation process, a bespoke impact pendulum was employed to bring the accurate interaction of conical picks with the rock mass during the excavation process to light. The analysis of high-speed imaging data, combined with digital reconstruction of the failure surface, provides valuable insight into the complex mechanisms governing pick-rock interaction and enables to rethink the energy transmission processes between the pick and the material.

2 Methodology

The testing device (Fig. 1) was based on an impact pendulum specifically designed to conduct similar experimental campaigns within the research group (Guerrero-Miguel et al., 2023; Prendes-Gero et al., 2021).



Fig.1Impact pendulum used in the experimental campaign.

In addition to the mechanical setup, a Photron Fastcam Mini AX100 high-speed camera was employed to record the impact tests at frame rates up to 5000 frames per second (fps), which allows a qualitative analysis of the flake formation process. This frame rate was set to optimize both the number of images and their resolution, as due to the limitations of the camera and increase in the acquisition speed will imply lowering image resolution.

To analyse the mechanisms of flake formation as a function of the transmitted energy and the distance to a free boundary within the specimen -its top surface-, commercial concrete blocks were employed (Fig. 2a). Previous mechanical characterization using the Schmidt Hammer test determined that the uniaxial compressive strength (UCS) of this material is 59.0 MPa, with acceptably low variability among specimens. Furthermore, it is worth noting that the heterogeneity of the material used is not only caused by its internal composition but is not only associated with its internal composition, but is also evident in the differing surface quality of the front (Fig. 2b) and back (Fig. 2c) surfaces of the tested specimen.

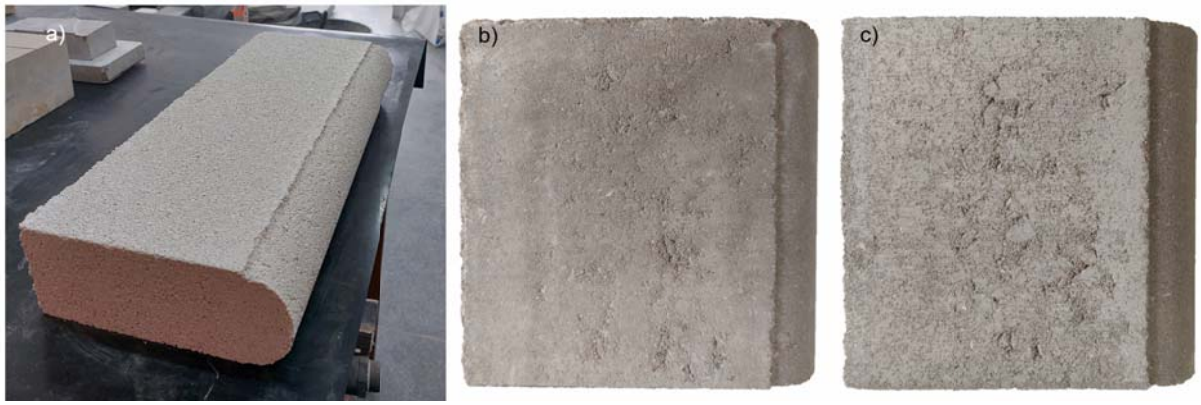


Fig. 2 Figures must be referred to in the text. Try to place the figures close to were they are referred to in the text.

Regarding the basket to place the specimen, it should be observed that the basket was designed to break its motion within predefined angular ranges controlled by a chain transmission connected to two gear. These gears allow the movement of the basket when deviating from the lowest point of the pendulum trajectory but impede its swing towards the pick. Hence, it is guaranteed that all the contact between the pick and the specimen is produced during the impact event and never after several collisions due to swinging movements.

The impact pendulum was instrumented employing an encoder that allows to accurately determined the inclination angle as a function of time. Consequently, the angular position, as well as the corresponding linear and rotational velocities and accelerations, were known throughout the entire pendulum trajectory.

Employing the aforementioned equipment, the experimental campaign consisted of a total of 12 impacts tests in which both the distance to the free surface *h* -defined as distance between the impact point and the top of the specimen- and the initial inclination angle of the pendulum were varied to evaluate their influence on the flake formation mechanism as well as in the overall amount of removed material. Specifically, distances of 5 mm, 10 mm and 15 mm were analysed in combination with angles of 10°, 30°, 50° and 70°. For these inclination angles, the linear speed of the pick is summarized in Table 1, widely covering the spectrum of usual operating speeds, which tend to be around 1.5 to 3.5 m/s.

Table 1. Maximum linear speed for picks under different initial angles.

Pendulum original inclination (°)	**Maximum linear speed of the pick (m/s)**
10°	0.57
30°	1.68
50°	2.75
70°	3.73

After completing the tests for the selected combinations of pendulum inclination and distance to the free surface, the specimens were scanned using a Roland Picza Pix-30 mechanical contact scanner. The scanning needle had semi-spherical head of 80 µm in diameter, enabling highly accurate reproduction of the failure surface. The impact area was scanned by generating a regular grid with a spacing of 0.5 mm between points, allowing the acquisition of the three-dimensional surface coordinates (x, y, z) at the predefined grid nodes. Subsequently, the surface was digitally reconstructed using the Delaunay triangulation technique. Based on this reconstruction, the volume of material removed -thus the volume of the overall flake- for each impact test was determined using a customized code developed ad hoc in the Matlab® environment.

3 Results and discussion

Although a total of 12 different tests were conducted to investigate flake formation, an initial pendulum inclination of 10° did not transmit sufficient energy to generate a flake in any of the considered cases. This behaviour was reproduced for the cases of 30° and 10 mm, as well as for the cases of 30° and 50 ° with a distance of15 mm. These scenarios are therefore excluded from further discussion in the present work, as they are not associated with flake formation. Nevertheless, it should be noted that, in these cases, only fine powder was registered, accompanied by noticeable toolmarks for inclination angles above 30°.

In all tested scenarios that included flake formation, after the pick impacts the surface of the specimen (Fig. 3a), a busrt occurs ejecting material outward of the impact zone. This ejected material generally consists on fine-grained powder and small flakes (Fig. 3b). Despite the fact that that many flakes were detatched at this stage, they were all consistent in size. For higher pendulum inclination angles, however, a secondary flake formation event was observed following the first stage of material detachment (Fig. 3c).

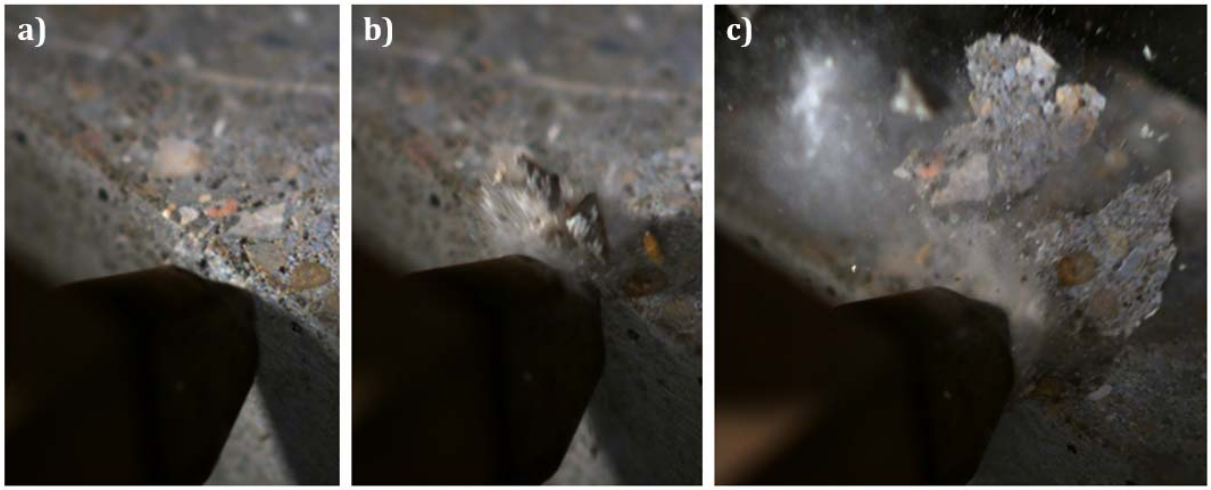


Fig. 3 Stages during the impact of large impact angles: a) initiation of contact, b) first stage of flake formation and c) second stage of flake formation.

This unexpected secondary flake formation mechanism can be successfully explained by a detailed examination of the failure surface generated within the specimen. In Fig. 4, the impact line at which the pick intiated contact with the specimen is indicated by a blue dashed line. This figure reveals that material was removed for distances greater than the predefined 5 mm from the free surface, which may appear contradictory at first glance. However, when the geometry of the pick is simultaneously considered, it becomes clear that although contact was initially established through the rounded tip of the pick, there is a subsequent stage where the frustoconical section reaches the specimen with sufficient speed to induce a larger-scale fracture. This mechanism highlights the existence of two distinct flake formation stages during the impact event.

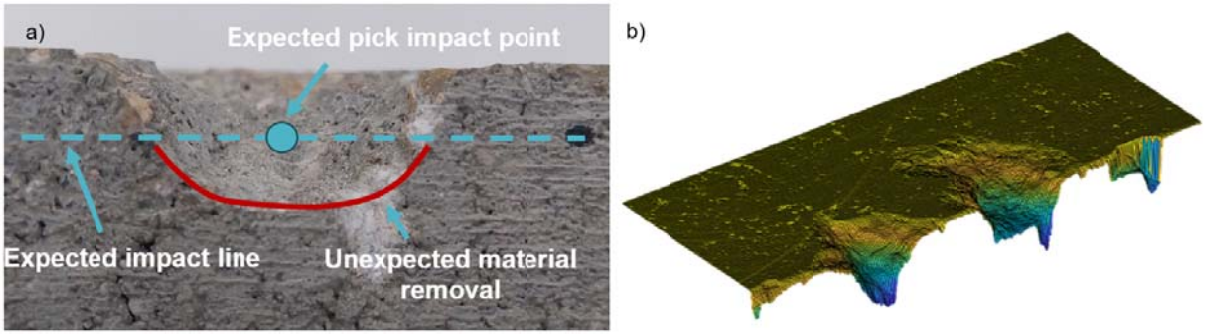


Fig. 4 Detailed analysis of the failure surface for the cases of 5 mm to the free boundary: a) real impact for 70° of inclination angle and b) 3D digital reconstruction of the failure surfaces related to impacts of 50°, 70° and 30°.

Following the quantification of the material removed through flake formation, it can be stated that a linear relationship exists between this value and the original inclination of the pendulum (Fig. 5a). Nevertheless, for larger impact energies the tendency may deviate from this linearity, although, these cases are beyond the scope of this work as they would exceed the regular working conditions of roadheaders. Furthermore Fig. 5a can be schematically interpreted as illustrated in Fig. 5b, where the regression line corresponding to a ditance of 15 mm to the free surface was drawn for explanatory purposes and, as in the case of 10 mm, elongated to determine the intersection points among the different cases. In this schematic representation, the red circles indicate the key points for optimizing the excavation process, as they represent the precise switching moment in which is possible to remove more material for the same amount of transmitted energy, and thus enhacing the efficiency of the excavation proccess. It is worth noting that this evidence suggests potential new approaches in the design of picks for roadheaders. Furthermore, these tentative results encourage the development of a larger experimental campaign, considering more distances to the free face and initial angles, to determine the optimum pick speed for each case.

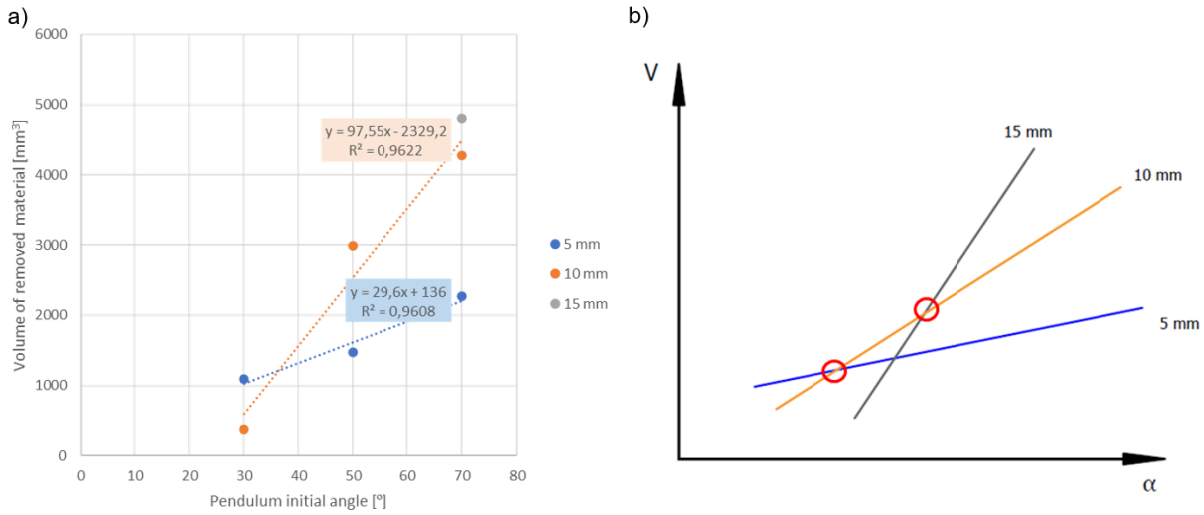


Fig. 5 Volume of removed material versus the pendulum initial angle: a) actual results of the conducted experimental campaign and b) schematic representation with elongated lines to determine the optimum points for increasing removal of material for a certain pendulum initial angle.

4 Conclusions

An experimental campaign was conducted employing a bespoke impact pendulum to evaluate the interaction phenomenon between the rock mass and the picks employed in roadheaders at a laboratory scale. The use of a high-speed camera and the digital recreation of the surface generated after the impact in the specimen allow to conclude that:

- The operational efficiency of the excavation process can be addressed from the combination of the impact energy and the volume of the flakes after identifying the threshold points that allow to remove the maximum amount of material for a given cutting speed.
- The failure surfaces resemble a Gaussian bell shape, which allows to develop predictive mathematical models to estimate the size of the flakes. Nevertheless, this finding should be

regarded as preliminary, and further experimental investigation is required to confirm its general validity and applicability.

- The failure mechanism for high impact speeds consists on a dual-stage fragmentation, transforming the interaction of the pick and the rock mass in a complex scenario with subsequent failures rather than an isolated single event. Hence, the design of conical picks may be tailored depending on their foreseen cutting speed even to the actual operating speeds.

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