Review Article

Ali Al-Bakri* and Mohammed Hefni

A review of some nonexplosive alternative methods to conventional rock blasting

https://doi.org/10.1515/geo-2020-0245 received November 28, 2020; accepted March 15, 2021

Abstract: The conventional blasting rock excavation method is the main means of rock breakage because of its high productivity, and it is relatively inexpensive compared to other methods. However, it raises safety concerns and can negatively impact the environment. The major disturbances that may be induced by this method include flyrock, gas emissions, and vibrations. This review discusses some nonexplosive rock breakage methods, particularly the hydraulic splitter and expansive chemical agents, that can be employed instead of the conventional blasting method and analyzes their potential effectiveness in rock breakage. Hydraulic splitting machines and expansive chemical agents were studied in the context of the literature. This review showed that hard rock breaking can be executed effectively and safely using alternative methods, which have a wide range of advantages, including safe operation, ease of use, and environmental friendliness, over conventional explosive methods. Moreover, as modern nonexplosive methods, hydraulic splitting machines and expansive chemical agents can generate pressure of up to 43 and 30-44 MPa to induce stresses in rocks, respectively. Owing to safety and environmental restrictions on conventional blasting, the application scope of the modern methods can be increased in the future.

Keywords: conventional blasting, hydraulic splitting machines, expansive chemical agents

Mohammed Hefni: Department of Mining Engineering, Faculty of Engineering, King Abdulaziz University (KAU), Jeddah, Saudi Arabia, e-mail: mhefni@kau.edu.sa

1 Introduction

Rock excavation is an essential phase in mining and civil engineering projects; it can be defined as the process of removing hard, compacted, or cemented material by using conventional or alternative blasting methods. Many methods have been used since the ancient times to break rocks for their use in subsequent processes. In the seventeenth century, black powder was used as a means of breaking rocks in mining and construction projects, while mechanical methods began to be employed in this field approximately 120 years ago [1]. Despite the accelerating progress in the mining industry as well as other related industries, conventional drilling and blasting remain the preferred options for rock breakage. Compared to other methods, conventional drilling and blasting provide more realistic solutions to the two most important mining issues, i.e., mining cost and production efficiency [2,3]. However, there are certain direct negative impacts that can arise when using these conventional methods for rock breakage. These impacts include flyrock, ground vibrations, air overpressure, back-break, and gas emissions [4–6]. Moreover, blasting can influence the stability and safety of the remaining rock mass and the surrounding structures in underground stopes, such as barrier pillars, backfills, and vertical sidewalls [7-9]. To minimize the aforementioned negative impacts, artificial neural network (ANN) and another artificial intelligence techniques have been applied recently for predicting the undesirable effects induced by blasting (Table 1) [10-14].

Against this background, this review investigates both conventional and unconventional rock breakage methods to highlight the potential negative effects of the conventional methods. In addition, we discuss the advantages of modern alternative rock breakage methods, including environmental protection and enhanced safety during the rock breakage process. The methods used in rock breakage date back to the beginnings of human civilization. Over time, many developments have been made. This chronology will be traced briefly as an introduction to this review article to understand the evolution of these

^{*} Corresponding author: Ali Al-Bakri, Department of Mining Engineering, Faculty of Engineering, King Abdulaziz University (KAU), Jeddah, Saudi Arabia, e-mail: abakri0008@stu.kau.edu.sa, tel: +96-6500-404-542

| Table 1: Artificial intelligence techniques and their model reliability in predicting blasting-induced impacts |
|---|
|---|

| Reference | Year | Data set | Technique | Environmental issue | Model reliability |
|------------------------------|------|----------|--|---------------------------|------------------------|
| Mohamed [10] | 2011 | 162 | Fuzzy logic and artificial neural network (ANN) | Ground and air vibrations | Accurate prediction |
| Ghasemi et al. [11] | 2014 | 385 | ANN | Flyrock | Efficient prediction |
| Nikafshan Rad et al. [12] | 2020 | 70 | Recurrent fuzzy neural network (RFNN) and genetic algorithm (GA) | Flyrock | Superior prediction |
| Monjezi et al. [13] | 2014 | _ | ANN | Backbreak | Well prediction |
| Murlidhar et al. [14] | 2018 | 111 | Hybrid imperialism competitive algorithm (ICA)–ANN | Rock fragmentation | Good prediction |

methods and their positive contributions to the mining and construction projects.

1.1 Evolution of rock breaking methods

Mining development dates back to the Stone Age, where stone tools were used [15]. Gradually, these primitive tools developed with the discovery of iron, copper, and bronze. Hammers and pickaxes became the main tools in mining production and directly contributed to the increased productivity. The invention of explosive black powder (also known as gunpowder) brought about a revolution in mining engineering and with it emerged a new period in mining engineering. The black powder used was a mixture of sulfur, charcoal, and potassium nitrate in various proportions [16,17]. Dynamite, patented by Alfred Nobel in 1867, marked a pivotal point in the development of mining engineering, and for 70 years, it remained known as the workhorse explosive of the world. Ammonium nitrate begun to be gradually used in the mid-twentieth century (Table 2 and Figure 1) [18]. Since then, this explosive material has played a significant role

Table 2: Consumption of explosives (kilotons) by the United States [18]

| Year | Black powder | Nitroglycerin dynamites | Ammonium nitrate |
|------|--------------|----------------------------|---------------------|
| 1800 | 0.2 | | |
| 1850 | 9.1 | | |
| 1900 | 100 | 100 | |
| 1925 | 115 | 200 | |
| 1950 | 10 | 310 | 10 |
| 1975 | 0.1 | 120 | 1,300 |
| 1985 | 0.1 | 80 | 1,700 |

in mining engineering, especially for hard rock that requires considerable blast energy for excavation. The consumed explosives by the United States have been increased to 3,590.9 kilotons in 2015 [19].

Owing to the dynamic increase in the world's production of mineral resources (Figure 2), 18,188.7 kilotons of explosives have been consumed in 2015 [19]. This value is expected to reach 22,400 kilotons in 2020 and 29,100 kilotons by 2027 [20]. Currently, mining projects are being carried out in 168 countries worldwide [15]. From underground mining only, the expected daily metal production in 2020 was estimated to be 480,000 tons per day [21]. According to economists' reports, this expansion of mining operations will have a direct impact on the size of the explosive materials market (Figure 3) [22].

2 Negative impact of blasting

Conventional blasting in open-pit mining and civil engineering projects has negative impacts on safety and the environment [23]. The accelerated exploitation of mineral resources and materials in recent years has led to an

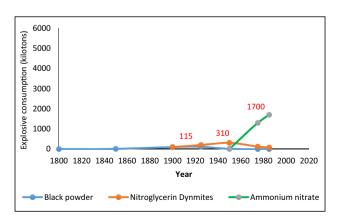


Figure 1: Trend of explosive consumption in the United States [18].

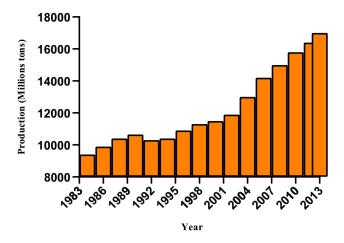


Figure 2: Mineral resource and material production 1984-2013 [16].

increase in the demand for explosive materials, and consequently, safety concerns and environmental accidents have increased. In the United States alone, 107 blasting-related injuries were reported from 1994 to 2004 [24].

2.1 Flyrock

Flyrock, which can be defined as fragmented rocks that are unexpectedly pushed out of the blasting area or moved by the force of the explosion, is considered the biggest concern during blasting (Figure 4) [25,26]. Propelled flyrock can travel a distance greater than 600 m



Figure 4: Flyrock poses a potential hazard [29].

at a speed that can reach 650 km/h [14]. According to several studies conducted in this field, flyrock caused 27% of explosive-related accidents in China [23], while it accounted for 20% of blasting accidents in India [27]. The main factors that can cause the generation of flyrock include geological structure discontinuity, poor layout and loading of the blast hole, insufficient burden, and inappropriate stemming and delay time [28].

2.2 Vibration

Environmental problems related to the blasting process can affect both businesses and residents [30]. Vibration

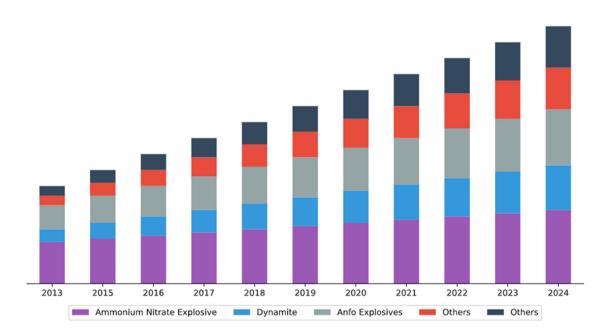


Figure 3: World industrial explosive market (USD million) [22].

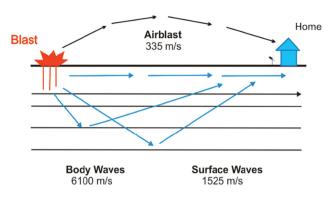


Figure 5: Types of blasting waves [31].

induced by blasting in mining and construction projects is a major environmental concern; it can cause damage to the neighboring structures and buildings. For example, ground vibrations affect the surrounding houses through basements and foundations, while airwaves enter buildings over walls and roofs (Figure 5) [31]. Humans feel and react to vibrations whose intensities are lower than that considered as the threshold for structural damage [32–34]. Vibration-induced damage is evaluated based on the frequency, magnitude, and duration of the vibration as well as the exposed building type. Damage based on the peak

particle velocity can be classified into four categories, which range from no damage to major damage (Table 3) [32].

Owing to the hazards associated with vibration, many countries have limited the permissible values of vibrations resulting from the blasting process. Determining these values is very significant and is subject to very strict standards. However, these values are affected by the reliability of the instrumentation and the analysis methods used [35].

2.3 Air overpressure

In the open-pit mine, air overpressure (air blast) induced by blasting operations is a major concern. It poses a risk to the surrounding buildings and structures. Air overpressure is creating due to the released energy from explosion. The study conducted in this field showed that 80–85% of explosive energy is wasted and generated a negative impact on the environment [6]. Air overpressure can be affected by spacing, burden, hole depth, hole diameter, specific charge, stemming, delay times, geological conditions, and rock mass characteristics (Figure 6) [36,37].

Table 3: Classification of vibration-induced damage [32]

| Classification | Damage description |
|-----------------|--|
| Threshold limit | No visually evident cracks or deformation in the wall of the structure due to blasting |
| Cosmetic damage | Loosening of paint; small plaster cracks at joints between construction elements; initiation of hair line cracks; lengthening of old cracks |
| Minor damage | Loosening and falling of plaster; cracks in the masonry around openings near partitions; hair line to 3 mm cracks; falling of loose mortar/plaster |
| Major damage | Cracks of several millimeters in walls; rupture of opening vaults; structural weakening; fall of masonry; detachment of bricks from walls, etc. |

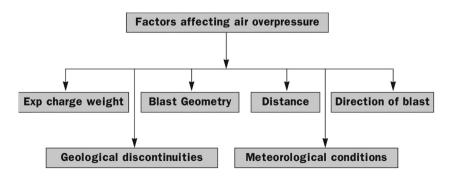


Figure 6: Parameters affecting air overpressure [37].

2.4 Air dust

A lot of dust is generated from open-pit mines processes, starting from mine development until operation. This dust can be a source of significant damage to the surrounding atmosphere and create an unsafe condition for work [38]. Investigated studies showed that drilling and blasting are most harmful due to the total amount of emitted dust while conducting these operations. Around 90% of the dust in the atmosphere is generated from drilling and blasting, while 10% from other mining operations [39].

2.5 Gas emissions

The regulations governing the mining industry are becoming stricter owing to the environmental impact of mining, particularly the impact of gases such as nitrogen oxides (NO_x) emitted during blasting operations to the atmosphere [40]. Based on the available literature, the middle range of annual NO_x emissions from mining blasting is 195.1 t. Blasting is the second-largest source of gas emissions after haul trucks (Figure 7) [40]. Studies conducted to analyze NO_x emissions have showed that the detonation reaction and blasting performance influence the quantity and attributes of the emitted gas [32]. For example, finer ammonium nitrate/fuel oil (ANFO) produces more NO_x fumes than coarser-grained fuel oil. This is because finegrained ANFO reacts faster than coarser-grained fuel oil, and more oxygen is available to drive more NO_x formation [41].

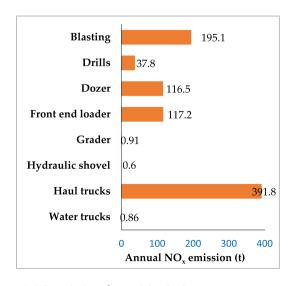


Figure 7: NO_x emissions from mining [40].

| Level | Description | Typical Apperance |
|---------|--|-------------------|
| Level 0 | No NO _x gas | |
| Level 1 | Slight orange fume of NO _x gas | |
| Level 2 | Yellow / Orange fume of NO _x gas | |
| Level 3 | Orange fume of NO _x gas | |
| Level 4 | Orange / Red fume of NO _x gas | |
| Level 5 | Red/ Brown fume of NO _x gas | |

Figure 8: Levels of NO_x fumes [42].

To monitor the blasting process and control NO_x emissions, a blasting register must be provided and filled by the site superintendent. The blasting register includes detailed fume information for every fired shot. The registered fume information can be used to determine the fume rating, which is scaled based on the color and intensity of the fume cloud (Figure 8) [42].

3 Nonexplosive rock breaking methods

Conventional explosive blasting has several drawbacks. The drilling, blasting, and scaling processes are complex; people and equipment need to be evacuated before blasting; safety is compromised; and the environment is negatively impacted [43]. Furthermore, the use of explosive blasting methods close to residential and populated areas requires strict procedures and precautions, which mainly affect the continuity of the rock excavation process. To overcome the drawbacks of conventional blasting and ensure the continuity of the rock excavation process,

several modern approaches have been developed as practical solutions for rock breaking under safe and environment-friendly operating standards [44,45].

The modern techniques developed have been introduced as unconventional methods for hard rock and concrete excavation and alternatives to the explosive blasting method. The application of these modern methods in the field of mining also contributes to continuity in the excavation process, reduces ore dilution and mineral losses, decreases the number of laborers required, and ensures safe conditions for mining operations [46]. Some modern methods such as water iet and high-pressure gas systems have been reviewed and compared [47]. Hydraulic fluid was patented to be used for hard rock breakage, and its effectiveness has been proven [48]. In addition, expansive chemical agents have been identified for the same purposes [49]. Herein, the hydraulic splitting method and expansive chemical agents are reviewed, highlighting their work process, applications, and potential effectiveness.

3.1 Hydraulic splitting method

Hydraulic splitting is a widely used method that has many advantages, such as ease of work, safe operation, and environmental protection [50]. This technique was designed and introduced based on the tensile strength concept, which can be explained by the fact that the compressive strength in rocks is much greater than the tensile strength [51–53]. Tensile strength is the stress at which a rock specimen fails under uniaxial tension [54]. The stress required to break a rock in tension is only 6–15% of the stress required to break the same rock in compression [50,55]. The ratio between the tensile and compressive splitting strengths of concrete has been studied, and the results have revealed that the ratio ranges from 5 to 10% [56].

According to the principle of the work, orientation, and type of the generated force, several hydraulic splitters have been manufactured [45]. Generally, a hydraulic splitting machine comprises two parts: a splitter and a power station (Figure 9). The splitter consists of a power cylinder with multiple pistons or wedges (based on a machine model) that apply pressure into a drilled hole, pushing the rock toward the free face. The power station consists of a hydraulic pump, hydraulic pipe, and control panel.

As for the work process, a hole with a rather large diameter is first drilled, for example, a 80 mm hole can be



Figure 9: Hydraulic splitting (the Powerking model).

drilled to a depth of 1–3 m; then, the power cylinder or wedge is inserted into the drilled hole. A pressure up to 43 MPa can be generated through pistons or feathers to induce a stress that pushes the rock toward the free-face side (Figures 10 and 11) [50,57,58].

The average tensile strength for hard rock, i.e., Laurentian granite, calculated by a dynamic Brazilian disc method is approximately 35 MPa [59]. The splitting process takes place within a few minutes. Many numerical and experimental investigations have been conducted to study the factors influencing rock breakage. From the highest to the lowest impact, these factors include the margin of the borehole, confining pressure, depth, and diameter of the hole [58]. In addition, factors affecting hydraulic splitting productivity include the hardness of the rock, the free face, and the direction of rock breakage. In the past, rock fragmentation by the splitting method was considered a secondary process. However, in recent years, researchers have considered splitting as the primary rock breakage method [60]. The hydraulic splitting method was successfully tested on limestone and granodiorite [61]. In addition, it is common and widely used in quarries in the United States, where effective related techniques have been developed based on this method. Furthermore, it is used in the mining of precious stones as well as rare mineral ores. In terms of hydraulic splitter machine manufacturers, China entered this field late but now has become a global leader [51].

3.2 Expansive chemical agents

Expansive chemical agents are nonexplosive agents that offer many advantages when used in mining and civil

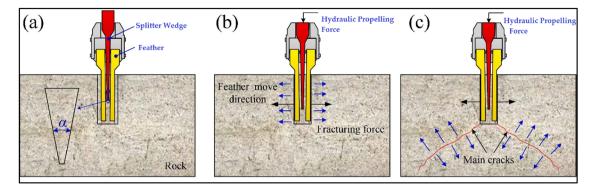


Figure 10: Rock breakage process using the hydraulic splitting method: (a) hydraulic splitter insertion, (b) hydraulic propelling force, and (c) induced fracture [58].

projects for rock breakage. Compared to conventional explosives, they are much safer, producing lower levels of noise, vibrations, and flyrock. Furthermore, expansive chemical agents can be applied without any restrictions, unlike explosives that are subject to strict regulations. Based on the rating issued by the environmental protection department of the Hong Kong government, this method has been ranked first among the methods that generate little to no noise in the field of rock and concrete breakage (Table 4) [62].

The work process commences when expansive chemical agents are mixed with water. The slurry mixture is then poured into a predrilled hole. Over a few hours, the injected slurry will expand, owing to a chemical interaction, and the rock will crack when the tensile stress exceeds the tensile strength (Figure 12). Typically, calcium oxide (CaO), also known as burnt lime, is an active ingredient. To release heat, a hydration reaction is used.

The expansion volume in the predrilled hole generates an expansion pressure that breaks the rock.

The compound temperature can be increased up to 150°C by a chemical reaction [4,63]. According to experiments, the generated expansion pressure reaches 30–44 MPa, while the pressure required to break the soft rock or concrete is 10–20 MPa [51].

Soundless chemical demolition agents (SCDAs) were introduced in the 1970s as an alternative rock breakage method but were not used in mining. Later, this method proved its effectiveness as a potential alternative method for rock breakage with clear advantages compared to others (Table 5) [66]. SCDAs can be used to induce fractures in water- and oil-saturated rocks for underwater applications [67]. Moreover, they can also be used in deep geological reservoirs [68]. However, the applications of SCDAs in underground and inundated conditions are still limited because of their dilution effect, washout mass loss, and delay in the generation of expansive pressure [69].

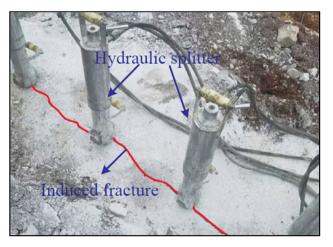


Figure 11: Rock breakage by the hydraulic splitting method [58].

Table 4: Sound pressure levels of the methods used for rock and concrete breakage [62]

| Equipment or method | Sound pressure level in dB(A) at 7 m from source |
|---|--|
| Excavator-mounted breaker | 95–105 |
| Handheld breaker | 85-104 |
| Chemical expansion agent | 60-65 |
| Hand-held concrete crusher | 67–69 |
| Quieter type wire saw or diamond wire saw | 76–81 |
| Quieter type blade saw | 76-81 |
| Hydraulic crusher for concrete breaking | 67–69 |
| High-pressure water jetting | 79 |

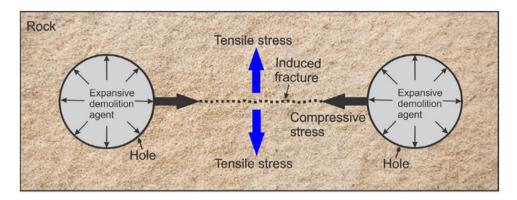


Figure 12: Mechanism of rock breakage by expansive chemical agents in tow drilled holes [64,65].

Although many variations of SCDAs exist, the chemical composition presented in Table 6 is the most common, with a high proportion of CaO.

Generally, the factors affecting SCDA performance are water content, ambient temperature, and borehole diameter (Figures 13–15) [4,70–73]. Because they have low efficiencies, require large volumes of water, and take a long time (>10 h) to induce rock cracking, expansive chemical agents are not widely applied. In addition,

Table 5: Comparison of rock breakage methods [66]

| | Explosives (dynamite) | Hydraulic splitter | SCDA |
|------------------|--------------------------|-----------------------|------|
| Breaking power | • | O | O |
| Noise | X | • | • |
| Ground vibration | X | • | • |
| Dust/gas | X | • | • |
| Flyrock | X | • | • |
| Safety | X | • | |
| Economy | • | X | O |

🔷: superior, 🔾: good, 🔀: inferior.

Table 6: Chemical composition of SCDA [4,66]

| s (%) |
|-------|
| |
| 8.5 |
| 5.0 |
| 3.0 |
| 96 |
| 6 |
| 4.0 |
| |

despite the commercial availability of SCDAs, to date, research on their performance is limited [4].

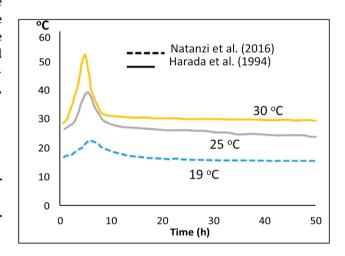


Figure 13: Effect of ambient temperature on SCDA temperature with time [4,72,73].

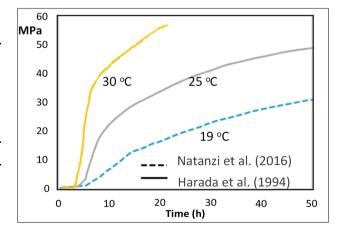


Figure 14: Effect of ambient temperature on SCDA pressure with time [4,72,73].

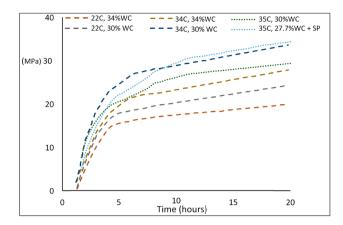


Figure 15: Effect of water content on SCDA pressure with time [4,70,73].

4 Conclusion

The hydraulic splitter and expansive chemical agents as alternative rock breakage methods have been discussed in this article based on their potential effectiveness in the field of rock breakage and their advantages highlighted. Both techniques have been developed based on the tensile strength of rock, which is much smaller than the compressive strength. The drilled hole diameter and drilling array significantly affect the effectiveness of the utilized method. Compared to the conventional explosive blasting, the examined methods can facilitate continuity of rock excavation, ensure a safe operation process, and eliminate the negative effects of rock excavation on the surrounding structure or environment. Nonexplosive methods can offer solutions for rock excavation in a confined or populated area without restrictions. The flexibility of these methods, in addition to their noncomplexity, will contribute to making them more widespread in the field of rock breakage. The challenges related to hydraulic splitter application are creating a second free face in underground mining to increase the splitting productivity and the quality of drilling that requires more time with some hazards. More research and extensive investigations on the performance of expansive chemical agents are recommended to increase the scope of their application.

Acknowledgments: The authors would like to thank all members of the Mining Engineering Department at King Abdulaziz University for their continuous support and cooperation during the period of preparing this review article.

Conflict of interest: Authors state no conflict of interest.

Data availability statement: The data presented in this review are available within the manuscript.

References

- Res J, Wladzielczyk K, Ghose A. Environment-friendly techniques of rock breaking. 1st edn. United States: CRC Press; 2003.
- [2] Babaeian M, Ataei M, Sereshki F, Sotoudeh F, Mohammadi S. A new framework for evaluation of rock fragmentation in open pit mines. J Rock Mech Geotech Eng. 2019;11(2):325–36. doi: 10.1016/j.jrmge.2018.11.006.
- [3] Kanchibotla SS, Morrell S, Valery W, Loughlin PO. Exploring the effect of blast design on SAG mill throughput at KCGM. Proc mine to mill conf, Brisbane; 1998. p. 1–16, [Online]. Available: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Exploring+the+effect+of+blast+design+on+SAG+mill+throughput+at+KCGM&btnG=
- [4] De Silva RV, Gamage RP, Anne Perera MS. An alternative to conventional rock fragmentation methods using SCDA: a review. Energies. 2016;9:11. doi: 10.3390/en9110958.
- [5] Caldwell T. A comparison of non-explosive rock breaking techniques. Proceedings of materials science; 2005. p. 1–7, [Online]. Available: http://www.ats.org.au/wp-content/ uploads/2017/01/2005-Tina_Caldwell.pdf
- [6] Bui XN, Nguyen H, Le HA, Bui HB, Do NH. Prediction of blast-induced air over-pressure in open-pit mine: assessment of different artificial intelligence techniques. Nat Resour Res. 2020;29(2):571–91. doi: 10.1007/s11053-019-09461-0.
- [7] Huo X, Shi X, Qiu X, Zhou J, Gou Y, Yu Z, et al. Rock damage control for large-diameter-hole lateral blasting excavation based on charge structure optimization. Tunn Undergr Sp Technol. 2020;106(November 2019):103569. doi: 10.1016/ j.tust.2020.103569.
- [8] Chen X, Shi X, Zhou J, Yu Z, Huang P. Determination of mechanical, flowability, and microstructural properties of cemented tailings backfill containing rice straw. Constr Build Mater. 2020;246:118520. doi: 10.1016/ j.conbuildmat.2020.118520.
- [9] García Bastante F, Alejano L, González-Cao J. Predicting the extent of blast-induced damage in rock masses. Int J Rock Mech Min Sci. 2012;56:44-53. doi: 10.1016/ j.ijrmms.2012.07.023.
- [10] Mohamed MT. Performance of fuzzy logic and artificial neural network in prediction of ground and air vibrations. J Eng Sci. 2011;39(2):425–40.
- [11] Ghasemi E, Amini H, Ataei M, Khalokakaei R. Application of artificial intelligence techniques for predicting the flyrock distance caused by blasting operation. Arab J Geosci. 2014;7(1):193-202. doi: 10.1007/s12517-012-0703-6.
- [12] Nikafshan Rad H, Bakhshayeshi I, Wan Jusoh WA, Tahir MM, Foong LK. Prediction of flyrock in mine blasting: a new computational intelligence approach. Nat Resour Res. 2020;29(2):609-23. doi: 10.1007/s11053-019-09464-x
- [13] Monjezi M, Hashemi Rizi SM, Majd VJ, Khandelwal M. Artificial neural network as a tool for backbreak prediction. Geotech Geol Eng. 2014;32(1):21–30. doi: 10.1007/s10706-013-9686-7.

- [14] Murlidhar BR, Armaghani DJ, Mohamad ET, Changthan S. Rock fragmentation prediction through a new hybrid model based on imperial competitive algorithm and neural network. Smart Constr Res. 2018;2(3):1–12. doi: 10.18063/scr.v2i3.397.10.18063/scr.v2i3.397.
- [15] Gennadiy G, Volodymyr B, Yuliia H. Stone age and the world of primitive mining. Hist Sci. 2018;94(73):44-48. [Online]. Available: https://scholar.google.com/scholar?hl=en&as_ sdt=0%2C5&q=STONE+AGE+AND+THE+WORLD+OF +PRIMITIVE+MINING&btnG=.
- [16] Kirsanov AK, Vokhmin SA, Kurchin GS. A brief history of the development of blasting and the modern theory of rock breaking. J Degrad Min Lands Manag. 2016;3(4):617–23. doi: 10.15243/idmlm.2016.034.617.
- [17] Kutuzov BN. History of Mining and Blasting Engineering. Moscow: Moscow State Mining University Press, Mining Book Publishing House; 2008.
- [18] Meyers S, Shanley ES. Industrial explosives a brief history of their development and use. J Hazard Mater. 1990;23(2):183-201. doi: 10.1016/0304-3894(90)85027-Z
- [19] Grand View Research, Explosives & Pyrotechnics Market Size | Industry Report; 2024, 2016. https://www.grandviewresearch.com/industry-analysis/explosives-pyrotechnics-market (accessed Feb. 18, 2021).
- [20] Market Research, Global Explosives Industry; 2020. https:// www.reportlinker.com/p05443588/Global-Explosives-Industry.html (accessed Feb. 18, 2021).
- [21] Ramezanzadeh A, Hood M. A state-of-the-art review of mechanical rock excavation technologies. Int J Min Environ Issues. 2010;1(1):29-39. [Online]. Available: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:A+state-of-the-art+review+of+mechanical+rock+excavation+technologies#0.
- [22] Market Intellica, Global Industrial Explosives Market Study 2016-2026, by Segment (Ammonium Nitrate Explosive, Dynamite,), by Market (Coal Mine, Metallurgy,), by Company (Orica, IPL); 2019. https://www.marketintellica.com/report/MI7659-global-industrial-explosives-market-study-2016 (accessed Feb. 18, 2021).
- [23] Kricak L, Kecojevic V, Negovanovic M, Jankovic I, Zekovic D. Environmental and safety accidents related to blasting operation. Am J Env Sci. 2012;84:360-5. doi: 10.3844/ajessp.2012.360.365.
- [24] Verakis HC, Examination of mine blasting accidents over a quarter of a century; 2006. Accessed: Oct. 25, 2020. [Online]. Available: https://miningandblasting.files.wordpress.com/ 2009/09/an-examination-of-mine-blasting-accidents-over-aquarter-of-a-century.pdf
- [25] Shirani R, Jahed D, Monjezi M. Genetic programming and gene expression programming for fl yrock assessment due to mine blasting. Int J Rock Mech Min Sci. 2016;88:254–64. [Online]. Available: doi: 10.1016/j.ijrmms.2016.07.028.
- [26] Manoj K, Monjezi M. Prediction of flyrock in open pit blasting operation using machine learning method. Int J Min Sci Technol. May 2013;23(3):313-6. doi: 10.1016/j.ijmst.2013.05.005.
- [27] Akande JM, Aladejare AE, Lawal AI. Evaluation of the Environmental Impacts of Blasting in Okorusu Fluorspar Mine, Namibia. Int J Eng Technol. 2014;4(2):101–8. Accessed: Oct. 25, 2020. [Online]. Available: https://scholar.google.com/

- scholar?hl=en&as_sdt=0%2C5&q=Evaluation+of+the +Environmental+Impacts+of+Blasting+in+Okorusu+Fluorspar +Mine%2C+Namibia&btnG=
- [28] Adhikari GR. Studies on flyrock at limestone quarries. Rock Mech Rock Eng. 1999;32(4):291–301. doi: 10.1007/ s006030050049.
- [29] Yesko D, Weber C, Lobb T, Report of investigation, fatal explosives accident, Pennsylvania; 1999. Accessed: Nov. 01, 2020. [Online]. Available: https://arlweb.msha.gov/FATALS/ 1999/FAB99M53.HTM.
- [30] Ozer U. Environmental impacts of ground vibration induced by blasting at different rock units on the Kadikoy-Kartal metro tunnel. Eng Geol. 2008;100(1-2):82-90. doi: 10.1016/j.enggeo.2008.03.006.
- [31] Malbašić V, Stojanović L. Determination of seismic safety zones during the surface mining operation development in the case of the 'buvač' open pit. Minerals. 2018;8(2):1–13. doi: 10.3390/min8020071.
- [32] Singh PK, Roy MP. Damage to surface structures due to blast vibration. Int J Rock Mech Min Sci. Sep. 2010;47(6):949-61. doi: 10.1016/j.ijrmms.2010.06.010.
- [33] Siskind DE, Stagg MS, Kopp JW, Dowding CH, Structure response and damage produced by ground vibration from surface mine blasting; 1980. [Online]. Available: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Structure+Response+and+Damage+Produced+By+Ground+Vibration+From+Surface+Mine+Blasting.&btnG=
- [34] Siskind DE, Stachura VJ, Stagg MS, Kopp JW, Structure response and damage produced by airblast from surface mining; 1980.
- [35] Norén-Cosgriff KM, Ramstad N, Neby A, Madshus C. Building damage due to vibration from rock blasting. Soil Dyn Earthq Eng. August, 2020;138:106331. doi: 10.1016/ j.soildyn.2020.106331.
- [36] Singh TN, Dontha LK, Bhardwaj V. Study into blast vibration and frequency using ANFIS and MVRA. Trans Inst Min Metall Sect A Min Technol. 2008;117(3):116-21. doi: 10.1179/037178409X405741.
- [37] Khandelwal M, Singh TN. Prediction of blast induced air overpressure in opencast mine. Noise Vib Worldw. Feb. 2005;36(2):7-16. doi: 10.1260/0957456053499095.
- [38] Mihail M, Isheyskiy V, Vadim D. Drilling and blasting influence on the process of dust particles formation. Int J Mech Eng Technol (IJMET). 2018;9(12):97–103. Accessed: Feb. 19, 2021. [Online]. Available: http://www.iaeme.com/ijmet/issues.asp? JType=IJMET&VType=9&IType=12http://www.iaeme.com/IJMET/issues.asp?]Type=IJMET&VType=9&IType=12
- [39] Sairanen M, Selonen O. Dust formed during drilling in natural stone quarries. Bull Eng Geol Env. Aug. 2018;77(3):1249-62. doi: 10.1007/s10064-017-1016-5.
- [40] Lashgari A, Johnson C, Kecojevic V, Lusk B, Hoffman JM. NO_x emission of equipment and blasting agents in surface coal mining. Min Eng. 2013;65(10):34–41. [Online]. Available: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5& q=NOx+emission+of+equipment+and+blasting+agents+in +surface+coal+mining&btnG=
- [41] Bhattacharyya MM, Singh PK, Ram P, Paul RK. Some factors influencing toxic fume generation by NG-based semigel explosives in laboratory studies. Propell Explos Pyrotech. May 2001;26(2):69-74. Accessed: Oct. 25, 2020. [Online].

- Available: https://scholar.google.com/scholar?hl=en&as_ sdt=0%2C5&q=Some+factors+influencing+toxic+fume +generation+by+NG-based+semigel+explosives+in +laboratory+studies&btnG=
- [42] Onederra I, Bailey V, Cavanough G, Torrance A. Understanding main causes of nitrogen oxide fumes in surface blasting. Trans Inst Min Metall Sect A Min Technol. 2012;121(3):151-9. doi: 10.1179/1743286312Y.0000000019.
- [43] Genet M, Yan W, Tran-Cong T. Investigation of a hydraulic impact: A technology in rock breaking. Arch Appl Mech. 2009;79(9):825-41. doi: 10.1007/s00419-008-0256-z.
- [44] Murray C, Courtley S, Howlett PF. Developments in rockbreaking techniques. Tunn Undergr Sp Technol Inc Trenchless. Apr. 1994;9(2):225-31. doi: 10.1016/0886-7798(94)90034-5.
- [45] Singh SP. Non-explosive applications of the PCF concept for underground excavation. Tunn Undergr Sp Technol. 1998;13(3):305-11. doi: 10.1016/s0886-7798(98)00062-5.
- [46] Haase HH, Pickering RGB. Non-explosive mining: An untapped potential for the South African gold-mining industry. J S At Inst Min Met. 1991;91(11):381-8.
- [47] Young C. Controlled-foam injection for hard rock excavation, in Vail Rocks 1999, The 37th U.S. symposium on rock mechanics (USRMS), 7-9 June, Vail, Colorado; 1999, June. p. 115-21. [Online]. Available: https://scholar.google.com/scholar?hl= en&as_sdt=0%2C5&q=Controlled-foam+injection+for+hard +rock+excavation&btnG=
- [48] Denisart J-P, Barry E, Institut CS. Vaud SLB, Method of breaking a hard compact material, means for carrying out the method and application of the method, 3988037; 1976.
- [49] Kawano K, Shiro Z, Demolition agent for brittle materials, 4316583; 1982.
- [50] De Graaf WW, Spiteri W. A preliminary qualitative evaluation of a hydraulic splitting cylinder for breaking rock in deep-level mining. J South African Inst Min Metall. 2018;118(8):891-7. doi: 10.17159/2411-9717/2018/v118n8a13.
- [51] Zhou H, Xie X, Feng Y. Rock breaking methods to replace blasting, IOP Conf Ser Mater Sci Eng. 2018;322(2). doi: 10.1088/1757-899X/322/2/022014.
- [52] Luong MP. Tensile and shear strengths of concrete and rock. Eng Fract Mech. Jan. 1990;35(1-3):127-35. doi: 10.1016/0013-7944(90)90190-R.
- [53] Sarfarazi V, Ghazvinian A, Schubert W, Nejati HR, Hadei R. A new approach for measurement of tensile strength of concrete. Period Polytech Civ Eng. 2016;60(2):199-203. doi: 10.3311/PPci.8328.
- [54] Huang S, Chen R, Xia KW. Quantification of dynamic tensile parameters of rocks using a modified Kolsky tension bar apparatus. J Rock Mech Geotech Eng. May 2010;2(2):162-8. doi: 10.3724/sp.j.1235.2010.00162.
- [55] Steyn J, Gerber RJ, Harrison AT, Ferreira PH. Investigation of the characteristics of thin sprayed liners (TSL) and their use as an additional support medium in block cave mining. Narrow Vein and Reef 2008; 2008. p. 1-19. [Online]. Available: https:// scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q= Investigation+of+the+characteristics+of+thin+sprayed+liners +%28TSL%29+and+their+use+as+an+additional+support +medium+in+block+cave+mining&btnG=

- [56] Arioglu N, Canan Girgin Z, Arioglu E. Evaluation of ratio between splitting tensile strength and compressive strength for concretes up to 120 MPa and its application in strength criterion. ACI Mater J. 2006;103(1):18-24. doi: 10.14359/15123.
- Chollette D, Clark GB, Lehnhoff TF. Fracture stresses induced by rock splitters. Int J Rock Mech Min Sci. 1976 Oct;13(10):281-7. doi: 10.1016/0148-9062(76)90559-3.
- [58] Liu S, Li H, Cheng G. Numerical and experimental investigation on rock breaking performance with hydraulic splitter. Tunn Undergr Sp Technol. 2020;96:103181. November 2019. doi: 10.1016/j.tust.2019.103181.
- [59] Xia K, Yao W, Wu B. Dynamic rock tensile strengths of Laurentian granite: Experimental observation and micromechanical model. J Rock Mech Geotech Eng. Feb. 2017;9(1):116-24. doi: 10.1016/j.jrmge.2016.08.007.
- [60] Paraszczak J, Hadjigeorgiou J. Rock splitting as a primary excavation technique. Tunn Tunn. Jun. 1994;26(11):49-52. doi: 10.1016/0148-9062(95)97087-y.
- [61] Park J, Lee D-H. Development of hydraulic rock splitting technique for rock excavation. J Eng Geol. 2016;26(3):353-60. doi: 10.9720/kseg.2016.3.353.
- [62] E. protection department of the H. K. Government, Quieter Construction Methods; 2016. https://www.epd.gov.hk/epd/ misc/construction_noise/contents/index.php/en/concreteremoval/55-quieter-construction-methods.html (accessed Oct. 25, 2020).
- [63] Hinze J, Brown J. Properties of soundless chemical demolition agents. J Constr Eng Manag. 1994 Dec;120(4):816-27. doi: 10.1061/(ASCE)0733-9364(1994)120:4(816).
- [64] Shang J, Zhao Z, Aliyu MM. Stresses induced by a demolition agent in non-explosive rock fracturing. Int J Rock Mech Min Sci. 2018;107:172-80. March 2017. doi: 10.1016/ j.ijrmms.2018.04.049.
- [65] Natanazi AS, Laefer DF, Mullane S. Chemical demolition of unit masonry: a preparatory study. Structural analysis of historical constructions: anamnesis, diagnosis, therapy, controls -Proceedings of the 10th international conference on structural analysis of historical constructions, SAHC 2016; 2016. p. 88-95. doi: 10.1201/9781315616995-10.
- [66] Huynh M-P, Laefer DF, Huynh M-P. Expansive cements and soundless chemical demolition agents: state of technology review, 2009, Accessed: Oct. 25, 2020. [Online]. Available: http://hdl.handle.net/10197/2285
- [67] De Silva VRS, Ranjith PG, Perera MSA, Wu B. The effect of saturation conditions on fracture performance of different soundless cracking demolition agents (SCDAs) in geological reservoir rock formations. J Nat Gas Sci Eng. 2019;62:157-70. November 2018. doi: 10.1016/j.jngse.2018.11.013.
- [68] De Silva VRS, Ranjith PG, Perera MSA, Wu B, Rathnaweera TD. The influence of admixtures on the hydration process of soundless cracking demolition agents (SCDA) for fragmentation of saturated deep geological reservoir rock formations. Rock Mech Rock Eng. Feb. 2019;52(2):435-54. doi: 10.1007/ s00603-018-1596-9.
- [69] De Silva VRS, Ranjith PG, Perera MSA, Wu B, Rathnaweera TD. A modified, hydrophobic soundless cracking demolition agent for non-explosive demolition and fracturing applications. Process Saf Env Prot. Oct. 2018;119:1-13. doi: 10.1016/ j.psep.2018.07.010.

- [70] Hinze J, Nelson A. Enhancing performance of soundless chemical demolition agents. J Constr Eng Manag. Jun. 1996;122(2):193-5. doi: 10.1061/(asce)0733-9364(1996)122:2(193).
- [71] Gómez C, Mura T. Stresses caused by expansive cement in Borehole. J Eng Mech. Jun. 1984;1106:1001-5. doi: 10.1061/ (ASCE)0733-9399(1984)110:6(1001).
- [72] Harada T, Soeda K, Idemitsu T, Watanabe A. Characteristics of expansive pressure of an expansive demolitionagent and the
- development of new pressure transducers. Doboku Gakkai Ronbunshu. Nov. 1993;478:91-100. doi: 10.2208/ jscej.1993.478_91.
- [73] Natanzi AS, Laefer DF, Connolly L. Cold and moderate ambient temperatures effects on expansive pressure development in soundless chemical demolition agents. Constr Build Mater. 110(May), 2016. p. 117-27. doi: 10.1016/ j.conbuildmat.2016.02.016.