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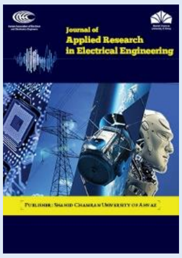

Research Article

New Approach in Minerals Cracking Using Electromechanical Breakdown Theory

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Abstract: One type of electrical breakdown in solid insulation is electromechanical failure. In mineral processing, crushing rocks is energy-intensive. Rock crushing using high voltage has many advantages, including high stone-breaking efficiency, and is a new and efficient way to break the stone. The shape of the electrode, the amount of applied voltage, and the selection of drilling process parameters are the main obstacles to using this method. In this study, based on the equivalent circuit of high voltage electro pulse failure, a mathematical model of high voltage electro pulse discharge in rock has been developed. Then, a high-voltage simulation model is developed based on the coaxial cylindrical electrode structure. This paper investigates the use of electromechanical failure phenomena for crushing minerals. High voltage pulses are used to crush the rock, then by simulating the relevant circuit, the necessary voltage for crushing three minerals is obtained and the feasibility of using this method is discussed. Finally, using the simulation and the obtained results, the possibility of using this method for crushing minerals has been investigated. This study provides a scientific basis for quantifying and predicting rock crushing using high-voltage technology to improve drilling efficiency and reduce energy loss.

Keywords: Electromechanical failure, crushing rocks, electrical breakdown in solids.

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1. Introduction

The mining industry is a major consumer of energy, accounting for 5-7% of global consumption. High mineral demand in the world has led many mining companies to process lower grade ores. Processing these ores requires a lot of energy to release minerals. With increasing energy consumption in the world and declining first-class ores, mining companies are forced to find alternative ways to reduce total energy consumption. Due to the phenomenon of electromechanical failure in solid insulation, if we can implement a mechanism that can be used to crush minerals, the needs of the mining industry can be met by reducing energy consumption. EPB is one of the new technologies of stone breaking [1, 2]. The advantages of this method compared to other methods of breaking the rock are controllable energy level, no pollution, no stone particles and its low cost. In the EPB process, short voltage pulses with high amplitude and current are required. There is a problem with the delay between the maximum voltage and current [3, 4]. The bumps and depressions in the rocks strongly affect the distribution of the electric field and reduce the efficiency of this method [5, 6]. A lot of work has been done by different people on breaking stones with electro pulse. Among them, Zhang developed a model of crushing rock by a plasma channel based on the principles of motion transfer. According to the classical blast theory, rock was considered as a homogeneous, isotropic and incompressible material in the model [7]. Due to the non-uniformity characteristics of rock, pores and electrical distortions, a failure model has been developed based on the theory of failure weaknesses and the cylindrical channel model. The proportional coefficient of electric field distribution is also included in the model. Breaking rock with electrical energy can be a cost-effective and better way to break up rock mass, in oil and gas extraction, tunnel construction and the like. Qiong Hu [8] has proposed plasma pulse discharge technology in order to achieve effective separation of ore and thin-layer bedrock and reduce the impact on the deep ocean environment. The energy transfer model is based on the equivalent circuit of the discharge channel to simulate the energy injection and energy consumption of the discharge channel. A pulsed power supply is designed and developed for experimental research. The breakdown voltage of artificial shells and artificial bedrock have been tested. The results show that the breakdown voltage is apparently different. The energy consumption is calculated and the results show that energy injection is useful for crushing. C. Li et al. [9] developed a complete high-pressure EPB damage model in granite, which includes a shock wave model and a high-pressure EPB damage model in granite. In this study, the use of the EPB damage model captures the complete process of high-voltage EPB, from discharge to shock wave generation, and thus the rock crushing through electric pulse can be simulated and calculated. The time-varying waveform of shock waves with different electrical parameters has been simulated and calculated based on the model. In the EPB granite damage geometry model, different shock wave forms are loaded to the surface and internal rock. Then the fracture process of the rock surface and inside and the rock fracture mechanism have been analyzed using EPB.

2. Pprinciples of Breaking Rock With High Voltage Pulse

Breaking a rock using a high voltage pulse is possible in two ways: 1- Hydroelectric 2- Electro-pulse, which is more effective in the latter case.

In breaking rock using high voltage pulse, heterogeneous and non-conductive feature of most ores is exploited. The ore is placed in a dielectric fluid, usually water, and high voltage pulses are applied to it. As shown in Fig. 1, when the high voltage pulse reaches its maximum in less than 500 ns, the breakdown voltage of the water is higher than most solids. Therefore, when the applied voltage is higher than the breakdown voltage, discharge occurs in the solids first. Thus, the rock is broken by the first voltage pulse and a plasma channel is created. Then, the energy stored in the power supply enters the plasma channel. As the plasma channel expands, tension is created. When this stress exceeds the strength of the rock, the rock breaks. The circuit schematic is shown in Fig. 2.

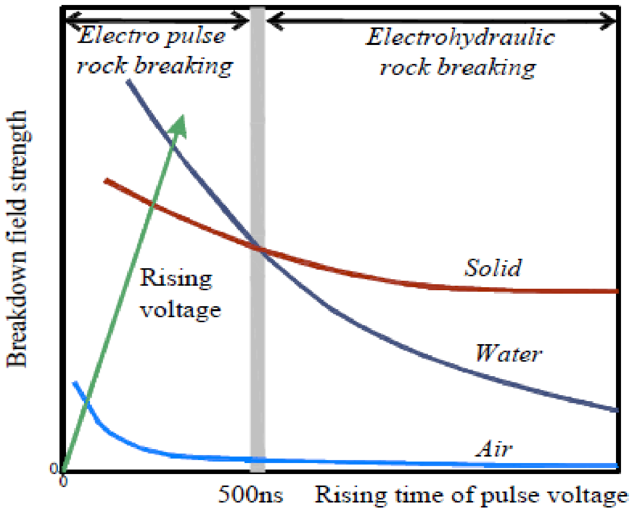

Fig. 1: The breakdown voltage of different materials relative to the pulse rise time [10].

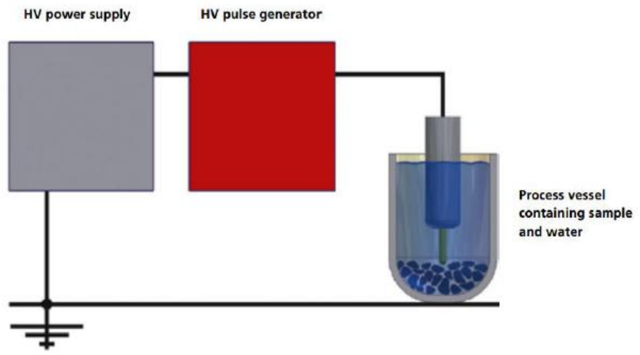

Fig. 2: The circuit schematic [10].

The process of breaking a rock with a voltage pulse can be divided into three parts: 1- Electromechanical failure 2- Injection of energy into the plasma channel 3-shock-wave fracturing [11, 12].

2.1. Eelectromechanical Breakdown Modelling

When an insulator with a dielectric constant $\mathcal{E}$ is placed in a strong electric field, the field of impact of the mechanical gravitational force is applied to the insulation and depending on its mechanical strength, the initial length of the insulation reaches from d0 to d. If d0 is the initial thicknesses of the part with Yang constant (Y) and the insulation thickness is reduced to d by applying voltage V, then if the electrostatic force is tolerated by the solid insulator, the compressive stress due to the electrostatic force will be in equilibrium with the mechanical strength:

$$\frac{1}{2}\mathcal{E}_0\mathcal{E}_r\frac{V^2}{d^2} = Y\ Ln\frac{d_0}{d} \quad (1)$$

$$V = \sqrt{\frac{2Yd^2}{\varepsilon}Ln\frac{d_0}{d}} \quad (2)$$

Derivative of equation (2) with respect to *d*, voltage that leads to mechanical instability insulation is achieved in the following conditions:

$$\frac{d}{d_0} = e^{-1/2} \quad (3)$$

Therefore, the maximum electric field strength that can be tolerated for insulation is equal to:

$$V_{max} = 0.6d_0\sqrt{\frac{Y}{\varepsilon}} \quad (4)$$

$$E_{max} = 0.6\sqrt{\frac{Y}{\varepsilon}} \quad (5)$$

It is observed that the electromechanical breakdown field of insulation depends on the electrical ($\mathcal{E}$) and mechanical (*Y*) characteristics of the insulation simultaneously. According to the theory that breakdown occurs at weak points [10], the breakdown of solid dielectrics begins at weak points such as cracks or holes. According to [11] for the plasma channel model in electromechanical failure, the Kratal cylindrical channel model is used. As shown in Fig. 3, *lch* is the length of the plasma channel, *Vch* is the volume of the plasma channel, and r is the radius of the plasma channel (=10μm). In the field of electrostatics, the plasma channel contains electrostatic and electromechanical energy [13]. Wes electrostatic energy can be expressed as follows:

$$W_{es} = \frac{1}{2}\mathcal{E}_0\mathcal{E}_r E V_{ch} \quad (6)$$

where, E is the electric field, Vch is the volume of the plasma channel, $\mathcal{E}0$ is the vacuum dielectric constant and $\mathcal{E}r$ is the relative dielectric of dielectric. The electromechanical energy of the plasma channel, according to the above, is as follows [13]:

$$W_{em} = \frac{\mathcal{E}_0\mathcal{E}_r E^4}{8Y} V_{ch} \quad (7)$$

where, E is the electric field and Y is the modulus of elasticity. The total energy of the plasma channel is equal to the sum of the electrostatic and electromechanical energies [13]:

$$W_{tot} = \left(\frac{1}{2}\mathcal{E}_0\mathcal{E}_r E + \frac{\mathcal{E}_0\mathcal{E}_r E^4}{8Y}\right) V_{ch} \quad (8)$$

As the applied electric field increases and the plasma channel expands, the surface energy of the rock must be overcome. When the total energy inside the rock holes is greater than the rock surface energy (Wec), the plasma channel expands until the high and low voltage electrodes are connected (Similar to Fig. 4). Failure occurs at this point [13]:

$$W_{ec}=2G\pi rl \quad (9)$$

$$W_{tot} \geq W_{ec} \quad (10)$$

where Wec is the rock surface energy and G is the surface free energy of rock.

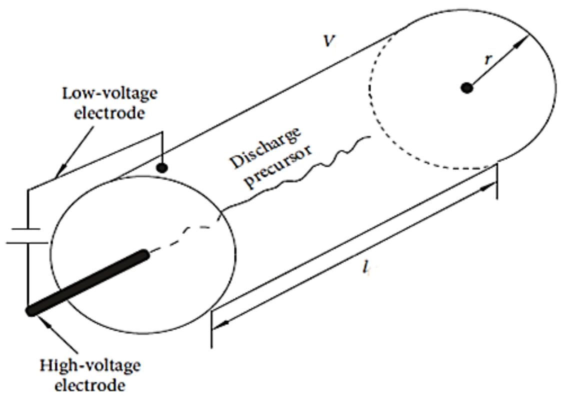

Fig. 3: Plasma channel model [10].

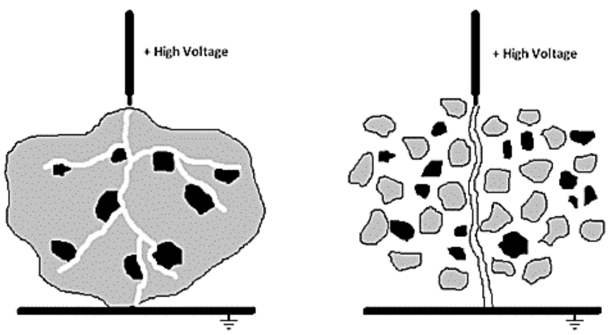

Fig. 4: Plasma channel expansion and failure [10].

According to the mentioned equations we have:

$$E = \left(\frac{2}{r\mathcal{E}_0\mathcal{E}_r}\left(\sqrt{r^2Y^2 + 4GrY} - rY\right)\right. \quad (11)$$

Once the high and low voltage electrodes are connected, the rock heat up rapidly along the plasma current, resulting in increased internal pressure. A sharp increase in pressure causes an explosion in the ore particle, resulting in a pressure pulse that shatters the rock. Under the influence of an external electric field, an inductive charge is generated at the end of the plasma channel, where there is a free charge. The charge changes the intensity of the electric field at the end of the channel. The relationship between the external electric field and the electric field at the end of the channel is as follows:

$$E_0=hE \quad (12)$$

where h is the coefficient of proportionality of the electric field distribution, which is expressed as follows:

$$h = \frac{k\,\mathcal{E}_r}{1+(k-1)\mathcal{E}_r} \quad (13)$$

That k is a dimensionless constant and corresponds to the size and direction of the plasma channel. According to [14], assuming that the inner hole is a normal sphere, the value of k is 36.

According to Equations (11)-(13), the electric field required to crush the rock will be as follows:

$$E_0 = \frac{1+2\mathcal{E}_r}{3\mathcal{E}_r}\left(\frac{2}{r\mathcal{E}_r\mathcal{E}_0}\left(\sqrt{r^2Y^2 + 4GrY} - rY\right)\right)^{\frac{1}{2}} \quad (14)$$

The electric field required to break a rock depends on the mechanical properties of the material according to Equation (14). Changes in the electric field relative to the mechanical properties of the rock are shown in Figs. 5- 8.

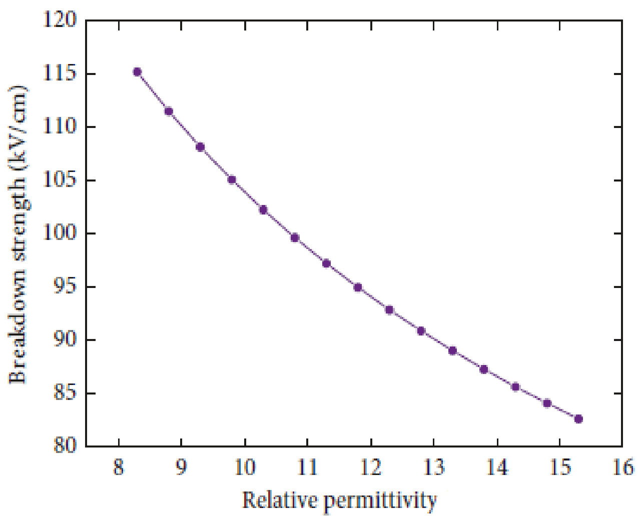

Fig. 5: Changes in the electric field relative to relative permittivity.

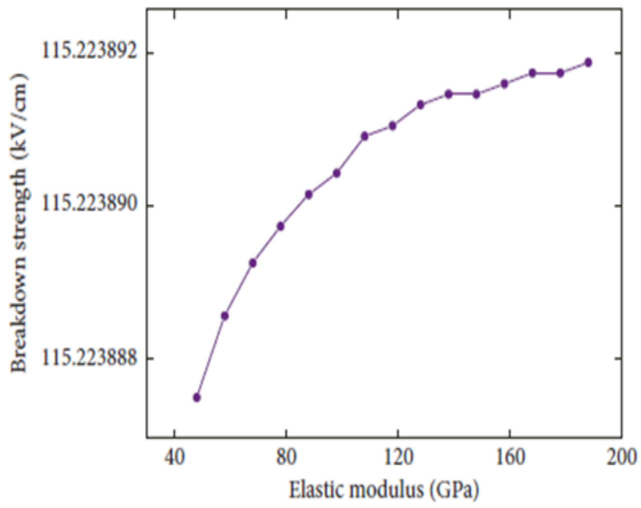

Fig. 6: Changes in the electric field relative to elastic modulus.

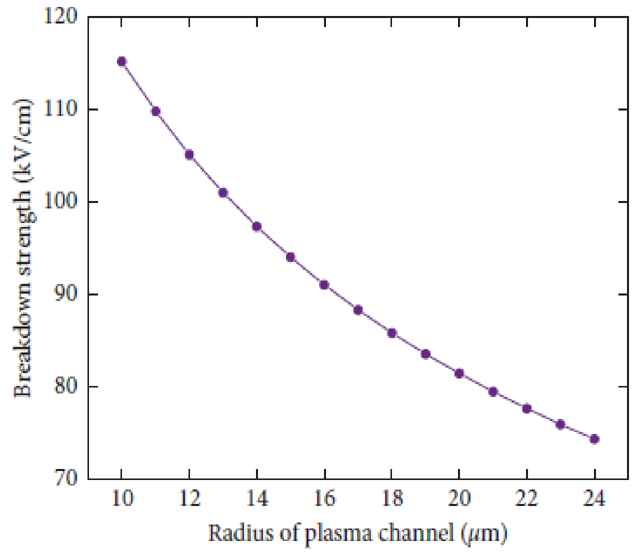

Fig. 7: Changes in the electric field relative to radius of plasma channel.

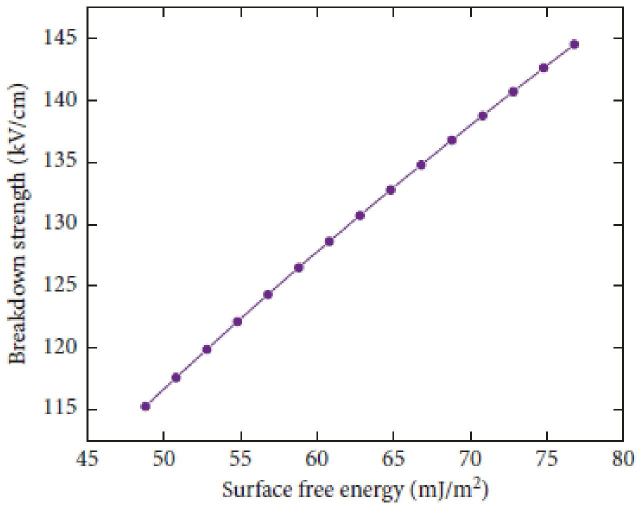

Fig. 8: Changes in the electric field relative to surface free energy.

In Fig. 8 surface free energy or interfacial free energy or surface energy quantifies the disruption of intermolecular bonds that occurs when a surface is created. In the physics of solids, surfaces must be intrinsically less energetically favorable than the bulk of a material (the atoms on the surface have more energy compared with the atoms in the bulk of the material), otherwise there would be a driving force for surfaces to be created, removing the bulk of the material. The surface energy may therefore be defined as the excess energy at the surface of a material compared to the bulk, or it is the work required to build an area of a particular surface. Cutting a solid body into pieces disrupts its bonds and increases the surface area, and therefore increases surface energy. If the cutting is done reversibly, then conservation of energy means that the energy consumed by the cutting process will be equal to the energy inherent in the two new surfaces created. The electric field required to crush several mineral samples has been calculated (The table numbers are based on [15]).

2.2. Modelling the Circuit Required to Break the Rock

A circuit similar to Fig. 9 is used to create the electric field needed to break the rock. Capacitive pulse generators are mostly used in electro discharge technologies. Capacitor C is used to store energy from the source and create the necessary electric field. As mentioned, water acts as an insulating material. The resistance of the R_z circuit includes the resistance of the capacitors, wires and switches, while the inductor is intended for induction in the connecting wires and discharge channel. When the switch is closed, the capacitor pulse generator generates a high pressure pulse to strike the rock and produce the plasma channel. The energy stored in the capacitor is injected into the plasma channel. This energy increases the pressure of the channel, creating mechanical pressure that causes the rock to break. Rock impedance extends from electrical insulation to electrical breakdown, in which a plasma channel is created, which is associated with discharge time and current. In this paper, the Weizel-Rompe model is used for the plasma channel [10], which expresses impedance as a current integral:

$$R_{td}(t) = K * l(\int_0^t i^2(t)dt)^{-1/2} \quad (15)$$

whrere K is the coefficient of resistance (611V.S1/2/m) [11] and l is the length of the plasma channel (equal to the distance between the electrodes). The distance between the electrodes is 10 mm, and i is the circuit current. According to Kirchhoff equations, the following equation is obtained for the circuit of Fig. 9:

$$L\frac{\mathrm{di}}{\mathrm{dt}} + (R_Z + R_{td})\, i(t) + U_C(t) = 0 \quad (16)$$

In this equation, i is the current of the circuit, L is the inductance of the circuit, and Uc is the instantaneous voltage of the capacitor, which is obtained from the following equation:

$$i(t) = C\frac{dU_C}{dt} \quad (17)$$

By placing equations (15) and (17) in equation (16), the following equation is obtained:

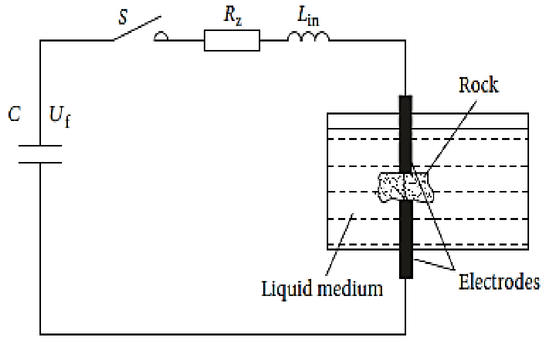

Fig. 9: The equivalent circuit creates a high voltage pulse to break the rock.

$$\frac{d^2i(t)}{dt^2} + \left[\frac{R_z}{L} + \frac{Kl}{L}\left(\int_0^t i^2(t)dt\right)^{-\frac{1}{2}}\right]\frac{di(t)}{dt} - \frac{Kl}{2L}\left(\int_0^t i^2(t)dt\right)^{-\frac{3}{2}} i^3(t) + \frac{1}{LC}i(t) = 0 \quad (18)$$

$$\begin{cases} x_1 = i(t) \\ x_2 = \frac{di}{dt} \\ x_3 = \int_0^t i^2(t)dt \end{cases} \quad (19)$$

Second-order differential equations (19) can be turned into a first-order differential equation system. From the system of equations (19) we can conclude:

$$\begin{cases} \frac{dx_1}{dt} = x_2 \\ \frac{dx_2}{dt} = \frac{Kl}{2L}x_3^{-1.5}x_1^3 - \left(\frac{R_z}{L} + \frac{Kl}{L}x_3^{-1.5}\right) - \frac{1}{LC}x_1 \\ \frac{dx_3}{dt} = x_1^2 \end{cases} \quad (20)$$

The initial conditions of the system of equations (20) will be as follows:

$$\begin{cases} x_1(0) = 0 \\ x_2(0) = \frac{U_0}{L} \\ x_3(0) = 0 \end{cases} \quad (21)$$

According to the equivalent circuit of Fig. 9, the plasma channel energy can be expressed as follows:

$$W(t) = \int_0^t i^2(t)\, R_{td}(t)\, dt \quad (22)$$

According to the law of energy stability, the energy from the power supply is injected into the plasma channel and when the plasma channel expands, it is converted into heat wave energy and mechanical stress. The energy stability equation is as follows [7]:

$$\frac{dW}{dt} = \frac{P*dV}{dt} + \frac{1}{\gamma-1}\frac{d(PV)}{dt} \quad (23)$$

where γ refers to the entropy index by which the energy distribution of the shock wave and heat in the plasma channel is determined. For condensate materials, its value is from 1.05 to 1.25 and its value in this article is 1.1 [7]. Impulse wave pressure (P), which is caused by the expansion of the plasma channel can be expressed as follows:

$$P = \frac{\gamma-1}{V*\gamma}\, W \quad (24)$$

For rocks, the generated plasma channel can be thought of as an expanding cylindrical piston. According to the plasma cylindrical channel model and the Rankine-Hugoniot relationship, the relationship between the volume of the plasma channel and the energy injected into the plasma channel is as follows:

$$\frac{dV}{dt} = \left(\frac{\sqrt{7}\,\alpha^{\frac{1}{14}}}{3\sqrt{\rho_0}}\right) * \left[\left(\frac{W}{V} * \frac{\gamma-1}{\gamma} + \beta\right)^{\frac{3}{7}} - \beta^{\frac{3}{7}}\right] * \left(\sqrt{\frac{V}{\pi l}} * 2\pi l\right) \quad (25)$$

where α and β are the shock wave coefficients (3.001*108 Pa and 3*108 Pa, respectively) [15] and ρ0 is the density of the substance in question. Using the variable change and the Euler's method for the common solution of equations (15) – (25), we obtain the changes in the discharge voltage, the discharge current, the plasma channel energy and the shock wave pressure.

3. Simulation and Analysis of Results

The equivalent circuit of Fig. 9 is simulated in MATLAB with all the items intended for it. Simulations are performed for three minerals, copper ore, chalcopyrite and hematite. In the following, a case study and feasibility study of using the phenomenon of electromechanical breakdown for crushing minerals will be discussed. In this simulation, a shock wave is used to create the electric field needed to break the rock. The shock wave is 1.2/50 microseconds. The value of the inductor in the circuit is equal to 5μH and the resistance *Rz* is equal to 1Ω. In the simulation for all three minerals, the parameter of Table 1 is used. By performing the simulation, the breakdown voltage required to crush the three studied minerals is obtained as shown in Table 2. The capacitive generator can be used to generate a shock wave. The simulation is performed for 1 cm^3 pieces of rock samples and the required voltage and power as well as the current drawn from the source are calculated.

According to the voltage and power diagrams, it is observed that with increasing the yang modulus of the ore, the amount of voltage and power of the source also increases and may limit the use of this method. By increasing the constant dielectric value, the breakdown voltage decreases and consequently the energy required to crush the rock also decreases.

4. Feasibility Study of Using Electromechanical Breakdown Method For Crushing Rock

One of the factors that can limit this method is the dimensions of the sample to be crushed, so for this purpose, the effect of stone dimensions on the voltage required to crush the stone is investigated. According to Fig. 19 and Fig. 20, with increasing rock thickness, the voltage required to break the rock decreases and with increasing rock area, the required voltage increases. According to studies, the greatest effect on the voltage required for crushing rock is related to the Young's modulus.

5. Discussion and Conclusion

In this paper, the use of electromechanical breakdown phenomenon for crushing minerals was investigated. This method consumes less energy than other mechanical methods for crushing rock, and since energy consumption in the mining industry and in the world in general is one of the main concerns, this method can be a good option. According to the simulation, it is concluded that with increasing the relative dielectric constant and the radius of the plasma channel, the breakdown electric field decreases and with increasing the Young's modulus and the surface free energy, the breakdown electric field increases. Once the breakdown is complete, energy consumption can be improved by using a high-capacity current source. The energy required to crush the mentioned mineral samples is calculated from the following equation in joules:

$$W = ½ C (V_{max})^2 \quad (26)$$

where C is the capacitance of the sample, $Vmax$ is the maximum voltage required, and W is the energy discharged by the electrodes in joules.

According to Table 1, the energy required to crush each 1cm^3 of the samples is less than the mechanical energy required. According to Fig. 11, Fig. 14, and Fig. 17 After the rock is crushed, the electrodes are shorted and according to Fig. 10, Fig. 13 and Fig. 16 a strong current is drawn from the power supply, so it is necessary to install relays to cut off the power supply. This method can be used to weaken rocks and create cracks in them that mechanical crushing machine requires less energy. That is, a device consisting of an electric crusher and a mechanical crusher is made to weaken the rock in the first stage under electric field stress and then crush it with a mechanical crusher, although considering the possibility of using this method in three samples of ore, the amount of electric field required is in the right range and it is possible to supply the required energy. In this method, the breakdown electric field strength depends on relative permittivity, surface free energy, radius of channel and Young's modulus, which is the effect of each factor according to Figs. 5- 8.

The field required for breakdown in this method depends on the mechanical and electrical properties of the ore. If multiple pulses are used instead of one pulse to crush the rock, the performance of the system will be improved as the energy required will be reduced. By using the modelling, time-varying waveforms of voltage, current, and power can be obtained numerically according to different electrical parameters. As mentioned, according to Fig. 19 and Fig. 20, as the thickness of the stone increases, the voltage required to break the stone decreases, and as the surface of the stone increases, the required voltage increases. This may cause limitations in the use of this method and it is not possible to use it in some samples. This study is important for the effect of using high voltage to improve rock breaking efficiency, reduce energy losses and select drilling process parameters.

The mathematical model and numerical simulation model used in this study are useful in analysing the effect of different factors on this process under different conditions. The results of this article show the possibility of better optimization of the rock breaking process using high voltage.

Table 1: Physical properties of studied minerals.

Mineral	Y (GPa)	$\mathscr{E}_r$	G (j/m^2)	E (kV/cm)
Copper ore	128	5.6	1.65	1847
Chalcopyrite	115	1.6	1.45	1906
Hematite	220	1.9	1.9	1790

Table 2: Sample breakdown voltage.

Mineral	Supply Voltage (kV)
Copper ore	426
Chalcopyrite	345
Hematite	1360

Table 3: Energy required to crush minerals.

Sample	Energy (mj)
Copper ore	44.96
Chalcopyrite	8.42
Hematite	155.5

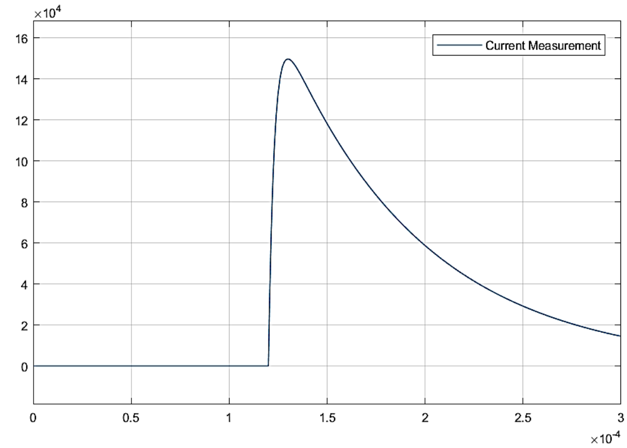

Fig. 10: Current drawn from the source to break the chalcopyrite ore.

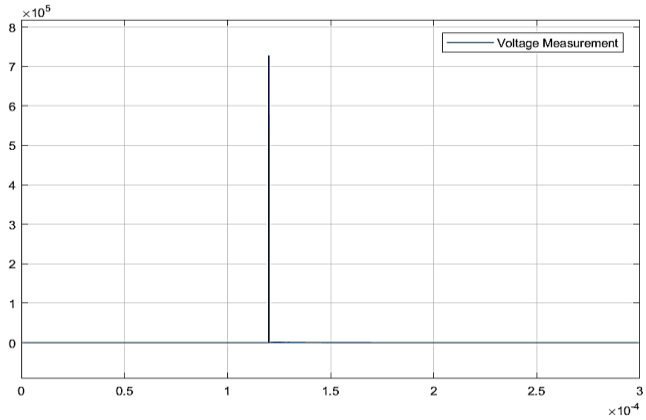

Fig. 11: Voltage required to break chalcopyrite ore.

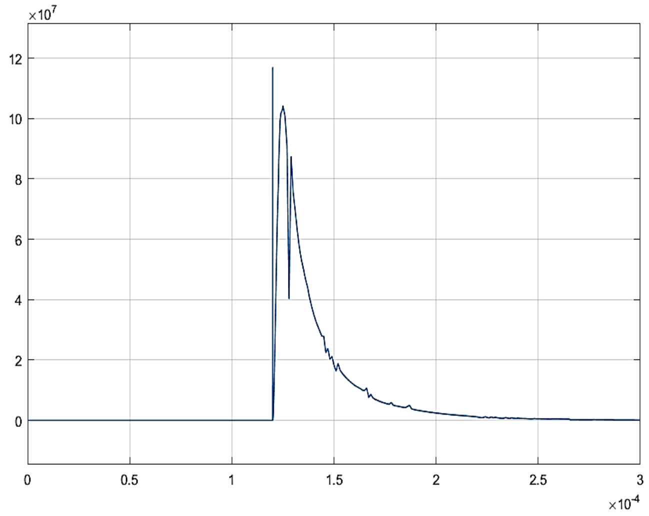

Fig. 12: Source power required to break chalcopyrite ore.

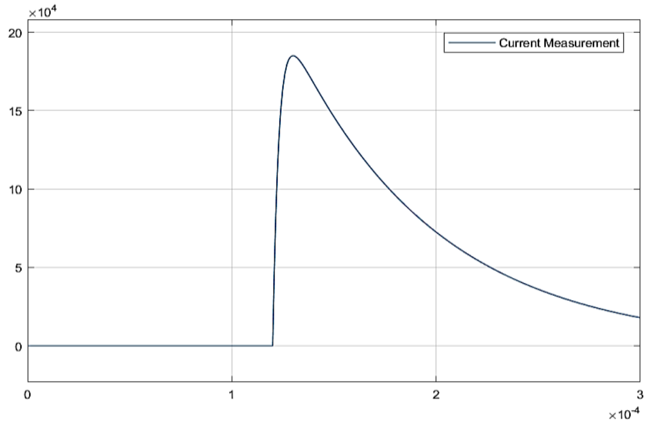

Fig. 13: Current drawn from the source to break the copper ore.

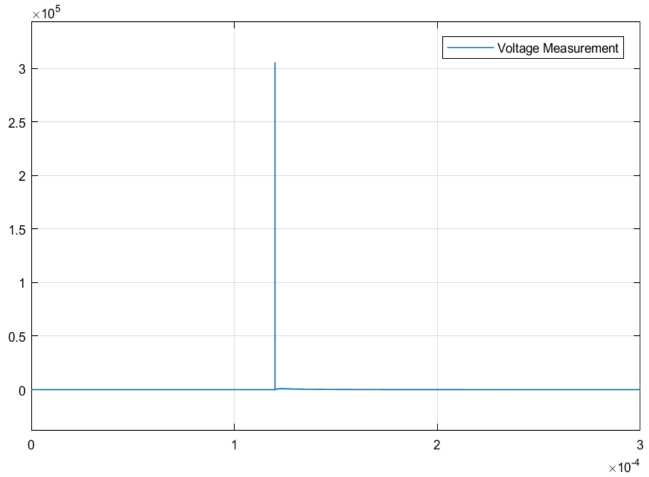

Fig. 14: Voltage required to break copper ore.

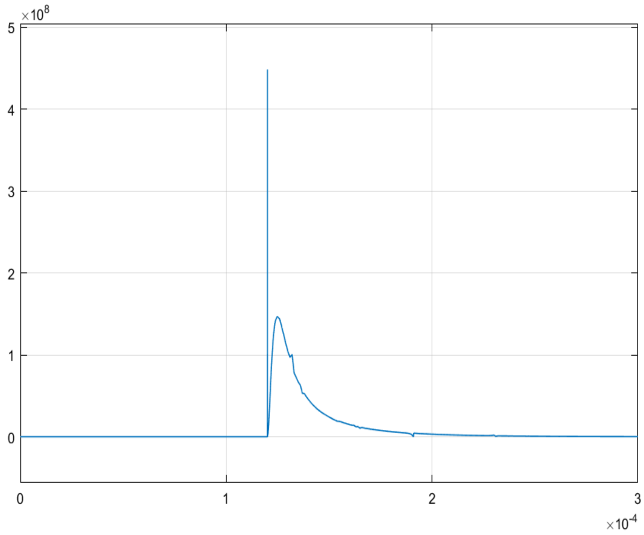

Fig. 15: Source power required to break copper ore.

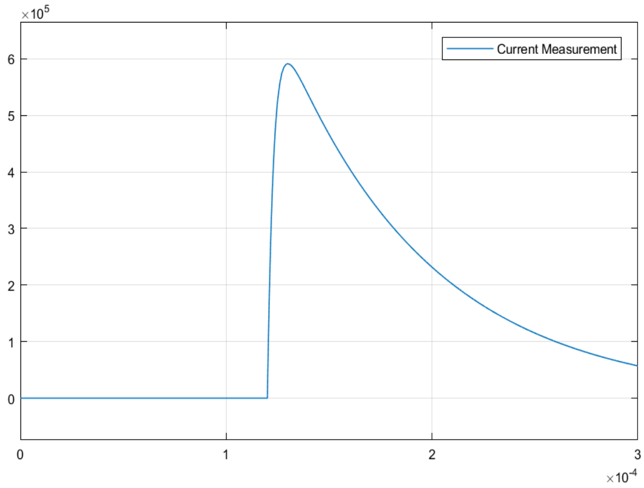

Fig. 16: Current drawn from the source to break the hematite ore.

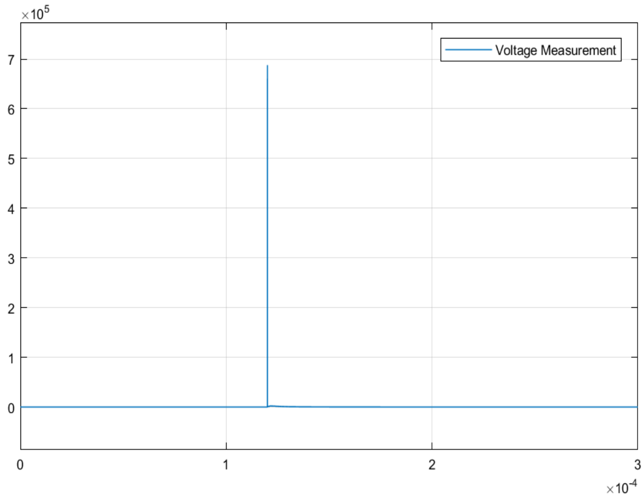

Fig. 17: Voltage required to break hematite ore.

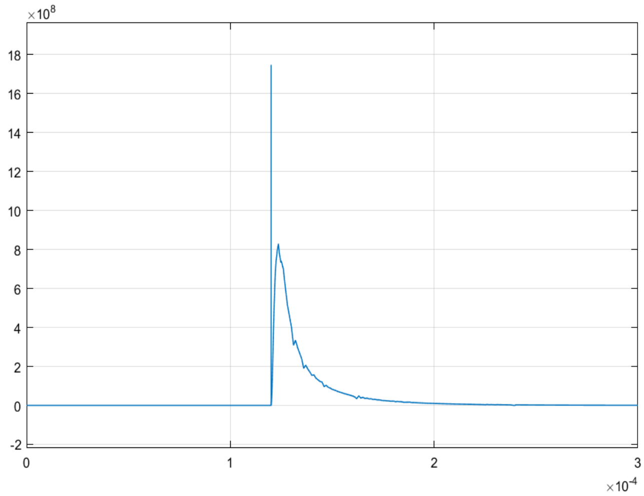

Fig. 18: Source power required to break hematite ore.

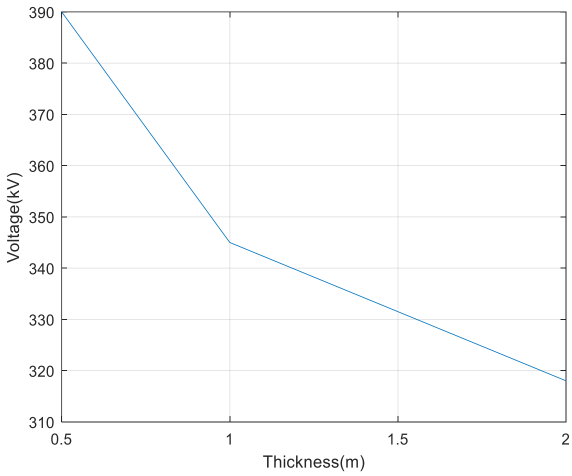

Fig. 19: The change in voltage required to crush the rock relative to the change in rock thickness.

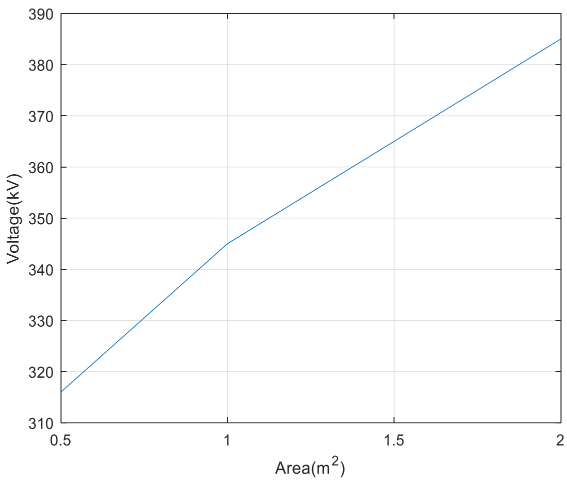

Fig. 20: The change in voltage required to crush the rock relative to the change in rock area.

CRediT Authorship Contribution Statement

Asaad Shemshadi: Conceptualization, Formal analysis, Funding acquisition, Project administration, Supervision, Validation, Roles/Writing - original draft. **Mohamad Reza Khojaste:** Data curation, Investigation, Methodology, Resources, Software, Visualization, Writing - review & editing.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the author.

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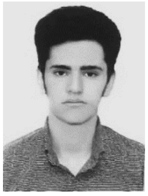

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