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Electrohydraulic Rock Blasting: an Alternative for Minin in Urban Areas.

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ABSTRACT

Conventional rock blasting promotes many negative environmental impacts including ground vibration, flyrock, air blast, and the emission of noise, dust and gases. An unconventional alternative process is performed by using eletrohydraulic principles. Electrohydraulic blasting is able to create a state of fracturing and rupture in the rock, almost instantly. The energy is produced by a high current impulse generator, without the above environmental impacts caused by conventional explosives. It is particularly suited for application in urban areas. The paper describes laboratory experiments, theoretical analysis, consideration of the geomechanical criteria of rock failure and analysis of the electrical parameters of impulse generators related to rock fragmentation. The laboratory experiments included geomechanical and eletrohydraulic tests on limestone samples of up to 50 kg. The test results show satisfactory efficiency and energy losses.

KEYWORDS: electrohydraulic blasting, rock blasting, unconventional blasting.

INTRODUCTION

Conventional rock blasting promotes environmental risks and impacts including ground vibration, flyrock, air blast, the emission of noise, dust and gases, and slope and hanging wall instability. These environmental impacts motivated the study of alternative procedures for rock breaking in urban areas, which must be cleaner and safer from the environmental point of view, avoiding the use of conventional explosives. In this context, secondary blasting, adopting the electrohydraulic principle, may be adequate for mining limestone rock as a raw material for Portland cement production in João Pessoa city, Paraiba state capital, Brazil.

Unconventional rock fragmentation using the electrohydraulic principle is based on an electrical discharge (spark) of high-energy intensity that is made in a liquid medium inside a hole drilled in the rock to be fragmented. The technique uses electrical power to transform an electrolytic solution confined within the hole into a plasmatic volume and/or channel of high pressure and temperature. The plasma is produced by the rapid energy transference, causing expansion at greater speed than the speed of shock wave propagation in the rock. The sudden expansion produces a compressive stress field and tractions that promote rock fragmentation (Nantel et al., 1992; Nantel and Kitzinger, 1992a and 1992b; Hamelin et al., 1993; Klich and Rés, 1996).

The plasmatic state requires a high discharge of electrical current of high intensity inside the rock. Using an impulse generator of high current it is possible to produce the required electrical discharge to cause rock fragmentation. The discharge is made with the help of a depth gauge.

The high current impulse generator comprises a source of energy of alternating current (ac) and a rectifier to feed a bank of capacitors with continuous tension in the circuit itself. Pair of spark-gap spheres controls the discharge of electrical current. One of the spheres contains an electrode that is operated from the remote trigger circuit.

In Brazil, the use of the electrohydraulic principle in mining operations has yet to be explored commercially. The idea has been the subject of research aimed at advancing scientific knowledge about the fundamental and operational aspects involved with this technique of rock breakage. However, the present research aims to substitute electrohydraulic blasting for the conventional secondary blasting of rock blocks of over 2 metric tonnes in the quarrying of calcite limestone at the Cimento de Portugal – CIMPOR.

ELECTROHYDRAULIC PRINCIPLE: GENERAL ASPECTS

The electrohydraulic principle has been applied to crushing rock, drilling holes and secondary blasting (boulder fragmentation), at laboratory scale. Testing has been carried out on different kinds of rock including shale, chert, sandstone, limestone, marble and granite (Maurer, 1968; Kutter, 1969; Nantel et al., 1992; Nantel and Kitzinger, 1992a and 1992b; Hamelin et al., 1993; Klich and Rés, 1996). Other research dates back to Yutkin (1955), Titkov et al. (1957), Epshteyn et al. (1960) and Bergstrom (1961).

The electrohydraulic principle was used by Kutter (1969) to describe rock breakage by electrical discharges or sparks in a liquid medium, which generated a plasma and/or a vapour channel between two electrodes. The plasmatic channel expansion causes an explosive impact pressure in the water medium by means of the vapour bubbles generated, which is transmitted by the incompressible water medium until the rock breaks. When the spark is transmitted in air, the generated energy is not sufficient to cause rock fragmentation since the compressibility of the air prevents the development of sufficiently high pressures.

The electric discharge circuit consists of a power source that feeds a high-tension capacitor and a circuit that has a spark gap that is responsible for the sudden discharge of the stored electrical energy by a different tensile mechanism.

Klich and Rés (1996) used the electrohydraulic effect to conduct a shock wave through a liquid medium in order to affect rock breakage, which they called the Electro-Hydraulic Method (EHD). This method was developed for the secondary blasting of rock boulders and for the breakage of large rock blocks (of 3 to 6 metric tonnes). According to Klich and Rés, the main

conditions governing rock breakage are the circuit feeding tension (energy), the rock type, the rock volume, the hole depth and the percent of natural clay material present.
Kitzinger et al. (1992a and 1992b) and Nantel et al. (1992) also developed methodologies for rock breaking using the EHD principle, called "Plasma Blasting Technology" (PBT). Through a depth gauge, an electrical discharge was generated that was stored in a bank of capacitors, producing a high pressure and high temperature plasma in a liquid medium. The plasma expands at greater speed than the shock wave, generating a stress field that is responsible for rock fragmentation. An electrolytic solution of 5% copper sulphate (Cu_2SO_4) and bentonite was used as the liquid medium.
The electrical discharge of a high current impulse generator causes the electrolyte constituents to collide with the electrons of the discharge current. The rapid electron movement generates heat, promoting an increase in the temperature and pressure of the confined electrolyte, while the volume remains substantially constant. Under these conditions, the (confined) electrolyte constituents dissociate completely forming a high-density plasma, producing the electrohydraulic phenomena.
The ionisable (or electrolytic) solution required as the liquid medium for plasma formation may or may not contain electrical charges. However, any dissolved salts will destroy the crystalline structure of the solution, destroying also its capacity to conduct electricity (its electrolytic conductance). A greater concentration of dissolved salts exists in a water medium, which is considered an electrolyte (Bueno et al., 1978).

GEOMECHANICAL CONSIDERATIONS

The geomechanical considerations related to rock breakage are important in determining the equations and nominal energy levels applied to fail rock materials. These data were reproduced by the high current impulse generator used in the eletrohydraulic rock fragmentation tests. The methods used to define rock failure, relating tensile failure and rock strength were a) the Coulomb criterion and b) the Mohr criterion (Ladeira, s. a.; Coates, 1973; Obert and Duvall, 1967).
The Coulomb-Navier criterion is a modification of the Coulomb criterion, in which rock failure does not occur along planes on which the shear stress τ is a maximum, but rather, along planes on which τ minus the frictional strength $\mu\sigma$, is a maximum:

$$\tau - \mu\sigma = c \quad \textbf{(1)}$$

where σ is the normal stress applied to the rock; $\mu = \tan \phi$ and ϕ is the internal friction angle of the material. The Mohr criterion is also based on the relationship given by equation (1). The Mohr criterion considers that at failure the normal and shear stresses on the rupture plane are related as functions of the rock material. In this criterion: (i) rock fracture occurs on planes that are normal to the direction of the applied normal or shear stresses where the mobilised shear stress is a maximum and (ii) the values of the mobilised shear stress and internal friction angle can vary for the same rock with the confining stress level (Ladeira, s. a.).
The elastic deformation energy (W) per unit volume, can be determined for uniformly stressed materials using Hookes Law, given by the expression:
correct spacing

$$W = \sigma_t^2 V_{vol.\ rock} / 2E \quad \textbf{(2)}$$

where E is the elastic (or Youngs) modulus and $V_{vol.rock}$ is the rock volume. For most materials the elastic modulus under compression is equal to that under tension (Timoshenko and Gere, 1983). Equation (2) permits the theoretical estimation of the energy required for rock failure based on the geomechanical parameters of the material.

EXPERIMENTAL PROCEDURES

A research using Fortran 90-based simulation computer software, geomechanical laboratory tests and electrohydraulic laboratory tests were performed. Additionally, investigation of the energy-related geomechanical parameters of rock breakage was reproduced by a high current impulse generator.

A computer program written by Klich and Rés (1996) was modified for obtaining the electrical parameters of the rock. The input variables describing the stresses, current, potency and energy as functions of time, were taken from the literature in graphical form. Numerous adjustments were made to the input variables in an attempt to get output curves similar to those presented by Klich and Rés (1996).

Next, the program was used to optimise the parameters of the impulse generator applied to secondary rock fragmentation in the laboratory. *continue paragraph*

The high current impulse generator used essentially consisted of a high voltage transformer with a rectifying diode, capacitors, inductors, resistors, a pair of firing spheres (spark-gap) and a control board. The equipment reproduces exponential normalised current impulses, with 4/10 and 8/20 wave forms (respectively, high current and atmospheric discharges), and also current impulses of square waveform. The generator can be assembled with eight stages (eight 2μF capacitors), producing a total impulse current of up to 160 kA (Haefely, s.d.) (Figures 1 and 2).

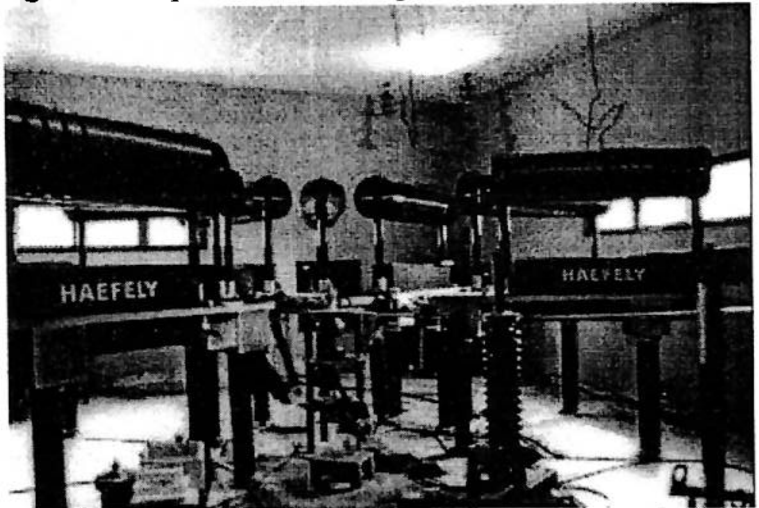

Figure 1 - High current impulse generator used in the electrohydraulic tests conducted at the High Voltage Laboratory of Paraiba Federal University

The current to the high voltage transformer is controlled by a control board. The high voltage is rectified and the bank of capacitors C_B delivers continuous current. The values of C, L and the electrolyte resistance, define the impulse current wave form. The source capacity determines the shortest charging time of the bank of capacitors (Haefley, w.d.). If the voltage in the capacitor bank attains a predetermined value, a command is actuated and discharge will occur in the electrolyte.

The discharge promotes an intense flow of electrons between the two separated electrodes of the depth gauge. The depth gauge and the gauge/rock stoppage valve, specially developed for this research, are firmly fixed in a previously drilled hole in the rock (Figure 2).

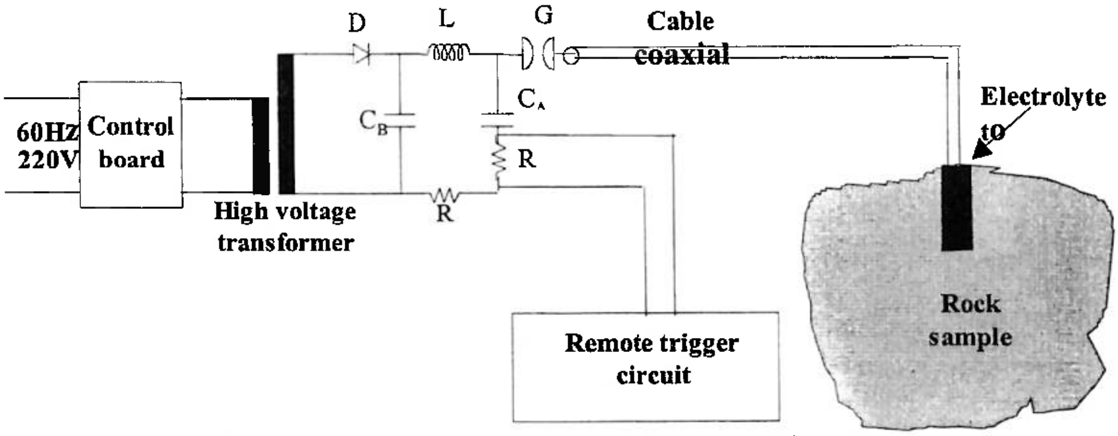

Figure 2 - Experimental flowchart of the high current impulse generator

The hole was drilled to a depth of one third to half of the total thickness of the rock, approximately 12 to 15 cm. The hole was capped by the gauge and must be completely filled with the electrolyte. The activation of the electrical discharge in the gauge from the electrolyte is made with the help of a pair of spheres (spark-gap), controlled from the control board (Figure 3). The spark-gap is formed by two hemispheres with a diameter of 200 mm. The upper hemisphere contains the ignition electrode. The distance between the spheres is controlled remotely from the control board. The maximum distance between the spheres is 330 mm, and is adjusted according to the voltage level in the bank of capacitors (Figures 3 and 4). This system corresponds, by analogy, with a conventional rock blasting system.

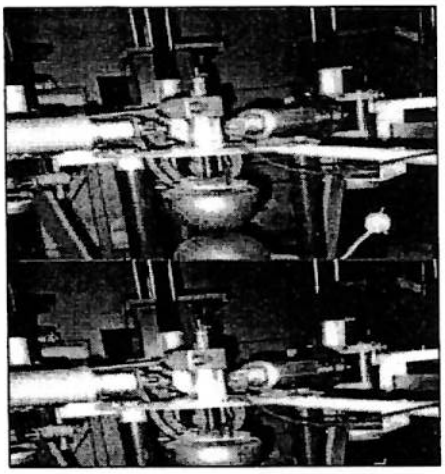

Figure 3 - Spark-gap used in the high current impulse generator of the High Voltage Laboratory of Paraiba Federal University

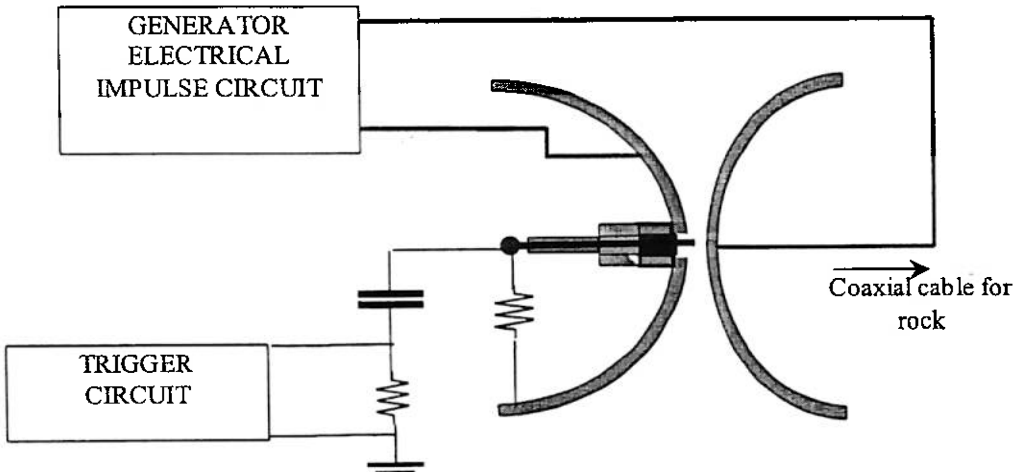

Figure 4 – Experimental schedule of remote trigger circuit.

Based on Nantel (1992) and Kitzinger et al. (1992), the concentration of the ionisable (or electrolytic) solution adopted in the electrohydraulic tests was 5% of copper sulphate (Cu_2SO_4), corresponding to 50g of Cu_2SO_4 dissolved in 1000ml distilled water on a mass to volume basis.

The geomechanical tests were conducted in the Rock Mechanics Laboratory - LMR of the Mining Engineering Department of the Polytechnic School of the University of São Paulo, EPUSP, using a servo-controlled MTS testing machine. Testing included uniaxial compression strength (σ_c); elastic or Young Modulus (E), Poisson ratio (ν), indirect tensile strength test (Brazilian method) (σ_T); cohesion (c); internal friction angle (ϕ) and shear strength at failure ( ). The test methods were based on the guidelines contained in the International Society of Rock Mechanics - ISRM, and gave the results: σ_c = 42.9 MPa; E = 9,485 MPa; ν = 0.23; σ_T = 4.6 MPa; c = 7.02 kPa and ϕ = 53.7°.

Table 1 gives the energy levels determined from geomechanical principles on the failure of sedimentary calcareous rock blocks (Mabessone, 1988). However, the maximum shear stress at rupture (τ = 65.42 MPa), based on the Coulomb-Navier and Mohr criteria was used.

Table 1. Nominal (theoretical) rupture energies for calcareous rock blocks.

Energy	**Sample**	
	A (24 kg)	B (42 kg)
Geomechanical (nominal)	2,166 kJ	3,790 kJ
Electrical (effective)	6,272 kJ	7,200 kJ

RESULTS AND DISCUSSION

The results obtained from the computational work were important for the estimation of the electrical parameters used in the tension, current, power and energy curves of Klich and Rés (1996). The values obtained for the impulse generator parameters were: C = 1780mF; L = 13,3 mH and R = 38,6 mW. It must be noted that the electrohydraulic method was used at a mean 60% of the energy supplied to the system (Nantel et al., 1992; Nantel and Kitzinger, 1992a and

1992b). That is, the energy values used in the program correspond to total values, ignoring the test rate.
The effective energy rates developed by the high current impulse generator in the eletrohydraulic tests were calculated from the expression:

$$W_{electrical} = CV^2/2 \quad \textbf{(3)}$$

where C corresponds to the total capacitance (µF) of the generator and V is the charging voltage of the bank of capacitors (kV). Thus, a correlation was attempted between the electrical energy rates of the impulse generator (effective energy for rock breakage) and the geomechanical energy required to fail the rock (theoretical energy). In this way it is possible to estimate the efficiency and losses presented by the studied technology.
The (energy) rates of efficiency and losses obtained in the electrohydraulic tests were satisfactory, based on the fragmentation state and simple rupture patterns, as presented by the samples shown in Figure 5.

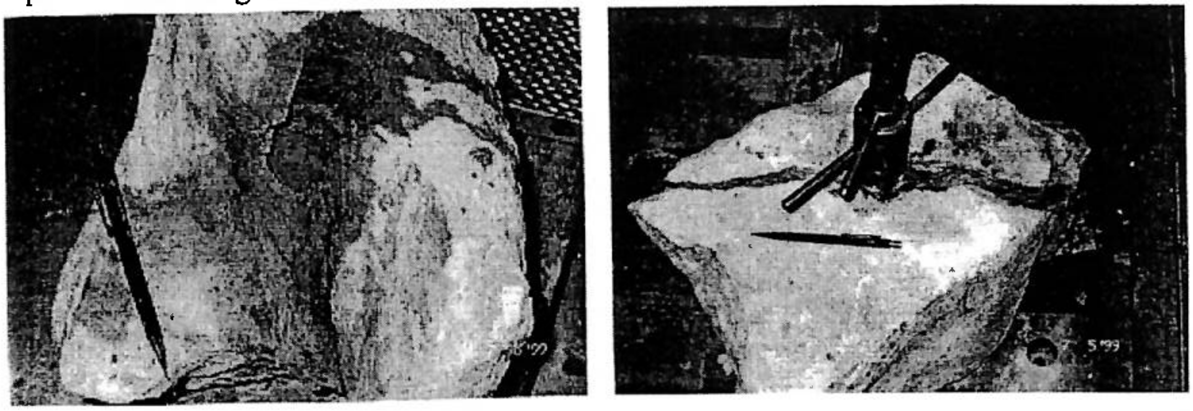

Figure 5 - Physical results of tested samples (fragmentation state and simple rupture patterns)
The energy values obtained from elastic theory (geomechanical parameters), and from the electrical variable values used in the electrohydraulic tests, presented the following results: efficiency 34.5 to 52.6% and 47.4 to 65.5%, respectively. Nantel (1992) and Kitzinger et al. (1992) achieved rates of 60% and 40%, respectively for efficiency and losses, similar to the present laboratory scale results.
The efficiency and losses obtained in the electrohydraulic tests can be related to: (i) electrolyte leakage that cause air sparks, producing insufficient plasmatic volume to generate the tension field to fragment and/or failure the rock; (ii) lower plasmatic volume generated because the electrode mean exposed length did not reach 12 cm. This length is required to elevate the plasma volume to promote better fragmentation and/or failure.

CONCLUSIONS

The research shows promising potential for the application of the electrohydraulic principle to rock fragmentation, with satisfactory efficiency and losses being obtained at laboratory scale. However, more attention should be paid to the geomechanical concepts and other electrohydraulic mechanisms. The next research challenge is the application of the electrohydraulic rock breaking pilot model to blocks of over 2 metric tonnes.

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