Controlled-foam injection for hard rock excavation

Chapman Young
Applied Geodynamics Inc., Steamboat Springs, Colorado, USA

ABSTRACT: A new non-explosive method to excavate hard rock and concrete has been developed, tested and demonstrated in a mining environment. The method uses high-pressure foam to initiate, pressurize and propagate controlled fracturing in rock. The foam is injected to the bottom of a relatively shallow pre-drilled hole in the rock or concrete to be broken by means of a barrel incorporating a hole bottom sealing method. The high viscosity of the foam (as compared to a gas) combined with its stored energy characteristics (as compared to a liquid) result in consistent and controlled breakage. The pressures required to fracture and excavate rock are significantly less than required in methods based upon the use of small explosive or propellant charges. Airblast and flyrock are reduced to very benign levels, allowing the method to be applied in a continuous manner and to be used in urban and other sensitive environments.

1 INTRODUCTION

For over a century explosive blasting has been the primary means used for the excavation of hard rock. Conventional blasting is limited in that it requires special precautions due to the use of explosives and can cause excessive damage to the rock or concrete being broken. In recent years several small-scale methods employing small explosive or propellant charges or specialized mechanical and hydraulic loading means have been proposed as alternatives to conventional blasting. The smaller-scale specialized techniques, while finding many niche applications, have been limited in their ability to break harder rocks or in having undesirable operating characteristics. For example, the small-charge explosive and propellant techniques still generate significant airblast, flyrock and toxic fumes.

Efforts to develop alternatives to conventional explosive excavation have included water jets, firing high-velocity slugs of water into pre-drilled holes, rapidly pressurizing pre-drilled holes with water or propellant generated gases, mechanically loading pre-drilled holes with specialized splitters, various mechanical impact devices, and a broad range of improvements on mechanical cutters. Each of these methods may be evaluated in terms of specific energy (the energy required to excavate or demolish a unit volume of material), their working environment, their complexity, their compatibility with other excavation operations, and their suitability for automation. A review of the positive and negative aspects of these methods indicates the directions that efforts to develop improved methods might take.

2 BACKGROUND

Controlled fracture methods, in various forms, have been proposed for several years as means to excavate or demolish rock and concrete more efficiently. Denisart (1976) proposed the rapid pressurization of a pre-drilled hole by firing a steel piston into a water filled hole such that a preferred (controlled) fracture would be initiated at the hole bottom. By propagating back to the surface from which the hole was drilled, this fracture would efficiently remove a volume of the material. Lavon (1978, 1980) proposed a variety of hydraulic cannons such that a high-velocity slug of liquid (water) could effect an efficient fracturing, excavation or demolition upon being fired into a pre-drilled hole. Cooper (1978) proposed a mechanical splitter such that both radial and axial forces could be exerted upon a pre-drilled hole. Fracturing would be initiated near the hole bottom and would propagate essentially parallel to the face from which the hole was drilled. Additional research and development on the radial-axial splitter has been carried out by the U. S. Bureau of Mines (Anderson, 1990).

Realizing the benefits that might be achieved with the controlled fracturing of a material with a properly applied gas pressure, Young (1990, 1992) proposed the use of small propellant charges to provide the requisite pressurization of a pre-drilled hole. Young noted that such pressurization would have to be restricted to the bottom of the hole by appropriate sealing means. When such sealing was achieved a characteristic fracture would form at the sharp corner of the hole bottom. This characteristic fracture would initially propagate down into the material but would then turn back to the surface from which the hole was drilled as free surface effects began to control fracture propagation. The resulting breakage often left a cone on the rock face with the bottom of the pre-drilled hole defining the top of the cone. The method has since come to be known as the Penetrating Cone Fracture (PCF) method. Van Der Westhuisen (1990) also proposed a propellant based device for breaking boulders or other rocks with numerous free faces. As this device did not provide for any sealing near the hole bottom, it would not be expected to be efficient in excavating in place rock. Finally, work by the U. S. Bureau of Mines has resulted in a patent for a propellant based device incorporating a provision for borehole sealing (Ruzzi & Morrell, 1995).

A high-pressure water injection device has been proposed by Kolle & Monserud (1991) and the rapid discharge of electrical energy from a high-voltage capacitor has been proposed by Nantel et al. (1990). Again, neither approach stipulated any sealing near the hole bottom. Breakage from the high-pressure water injection device is limited by the low expandability of water as compared to a gas and the associated limits upon maintaining adequate fracture pressurization. Breakage from the electrical discharge device is limited by the rapid quenching of the electrical discharge generated gases once the gases (essentially steam) enter the rock fractures, with the consequent loss of adequate pressure for efficient fracturing.

The above mentioned approaches have shown that a proper pressurization of preferred or controlled fractures is the most efficient way to excavate rock or demolish concrete. The propellant techniques have the advantage of providing a high-pressure gas for this controlled pressurization but are hindered by the fact that the low viscosity of these gases require that the breakage process be completed in a very short period of time (before the gases can escape). This requires that the initial gas pressures be quite high, on the order of 300 MPa (45,000 psi) or higher. These high pressures result in significant airblast and flyrock which detract from the utility of the process.

A preferred excavation/demolition method should have the ability to pressurize a controlled fracture (or system of fractures) in such a manner that pressures to adequately propagate the fractures (without over-pressuring them) can be maintained. A fluid to achieve such controlled pressurization should have a viscosity such that the fracturing process can occur over a longer time period and thus at lower pressures. The fluid should be able to store energy that can be used to maintain a desired pressure as the fluid expands into the developing fracture system. A water based foam would be a fluid having all of the requisite properties. A foam pressurization method could overcome many of the limitations of the existing explosive, propellant, water and steam (electrical-discharge) methods.

As foam, which is a two-phase mixture of a liquid and a gas, can be made to have a viscosity several orders of magnitude higher than a gas or even water, foam will escape from a developing fracture system much more slowly than a gas or water. With a much slower escape of the fracture pressurizing medium, the pressures required to initiate, extend and develop the desired fractures can be much lower than if a gas is used. The use of water alone is not sufficient because this relatively incompressible liquid will rapidly lose pressure as the fracture volume increases with fracture growth. The fracturing process will usually occur so rapidly that the needed fluid pressure in a water based system cannot be maintained by injecting additional liquid down the injection tube or barrel. A foam, in contrast, can maintain the pressures for efficient fracturing due to the expansion of the gaseous phase of the fluid. A foam thus has the ability to provide the pressures for efficient controlled fracturing without requiring the excessively high pressures associated with explosives, propellants, water cannons or electrical discharge.

A foam suitable for fracturing hard competent materials by penetrating foam injection may be made from any combination of a liquid and a gas. The most obvious liquid and gas to use are water and air. The surface tension properties of water alone are such that a water/air foam would rapidly separate into its two components. This separation may be slowed or nearly eliminated by using any of numerous commercially available surfactant materials, such as conventional soaps and detergents, or specific surfactant compounds such as Lauryl sulfate (sodium dodecyl sulfate). The stability and viscosity of a foam may be increased by adding a gel such as guar gum or hydroxypropyl guar. By varying the ratios of water, air, surfactant and gel, foams with a very broad range of viscosity and stored energy can be made. The foam may be generated externally to the actual controlled fracturing device in a conventional high-pressure reservoir using a variety of mixing and blending means.

The general features of a device to use Controlled Foam Injection (CFI) for rock excavation or concrete demolition is illustrated in Figure 1. A foam injection tube or barrel is inserted into a pre-drilled hole. The successful sealing of this tube into the hole, as indicated in Figure 1, is needed for the proper operation of the CFI process. Consistent rock breakage has been obtained with relatively crude foams, indicating that the successful commercial development of the process will not depend upon unduly sophisticated means for generating unique or complicated foams.

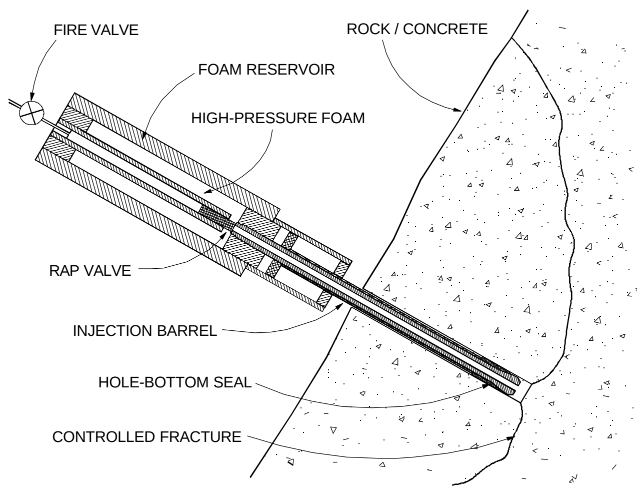

Figure 1. Basic hardware and geometry for controlled foam injection (CFI) fracture of rock.

Once the device reservoir is charged with the desired foam at the desired pressure, the foam is released into the pre-drilled hole by means of a rapid acting reverse firing poppet valve. A reverse acting poppet (RAP) valve, as indicated in Figure 1 and illustrated in more detail in Figure 2, is attractive for controlling high-pressure foam injection because the valve has only one moving part, the poppet, which will open very rapidly when the pressure is dropped in the RAP control tube behind the poppet. As soon as the poppet moves, the reservoir foam pressure will act on the full sealing face of the poppet causing it to retract or open quite rapidly. The high-pressure foam will then be rapidly delivered to the bottom of the hole and effect a controlled fracturing of the rock. Rapid opening is important so that the bottom of the pre-drilled hole may be brought to a high enough pressure rapidly enough to induce the desired combination of hole-bottom fracturing and radial fracturing needed to achieve complete fragmentation.

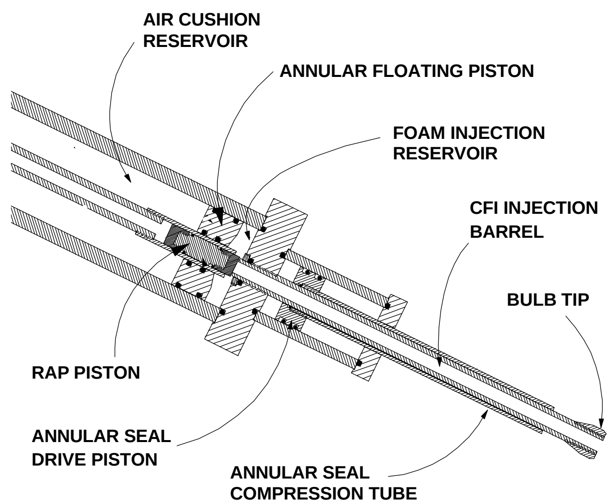

Figure 2. Details of reverse acting piston (RAP) valve and of annular floating piston in CFI breaker.

It is desirable to avoid injecting more foam than is needed to achieve the desired fracturing. Excess foam injection represents a waste of energy and would result in some increase in the albeit low airblast and flyrock associated with CFI fracturing. An effective means to control the amount of foam injected is to incorporate an annular floating piston into the foam reservoir as shown in Figure 2. This piston separates a rear portion of the reservoir, which need only contain a high-pressure air cushion, from a forward portion which contains the desired foam. The accumulator effect of this piston is to allow for the displacement and injection of a desired foam charge into the barrel and hole bottom without a significant drop in pressure. Without such an accumulator, a foam would have to be over-pressurized such that the necessary pressure was acting after injection with expansion into the hole, resulting in an energy inefficiency. The forward foam injection reservoir need only be filled with the quantity of foam to just give the desired fracturing resulting in further energy efficiency of the process.

A promising sealing means for CFI fracture utilizes an injection tube with a bulb enlargement at its tip and an annular hydraulic piston acting around the smaller barrel of the tube, as illustrated in Figures 1 and 2, above. Sealing is effected by crushing an annulus of deformable material between the bulb tip and the annular piston. The crushing is effected with the annular sleeve on the CFI barrel driven by an annular piston. The crushing of this material along the axis of the hole causes it to expand radially and seal against the hole wall near the bottom of the hole. Application of high-pressure foam will cause the barrel and bulb tip to retract and further jam the material against the hole wall. With the proper selection of bulb tip angle and deformable material, the recoil will further jam the material against the hole wall and maintain a very effective seal. Any deformable material may be used, but granular materials such as sand, fine gravel or a cementitious mix have been found to work well. By using a cementitious material similar to conventional mortar mix, replaceable seals may be made at very low cost. Tests made to date with a variety of cementitious materials have given excellent sealing, with negligible gas/foam leakage occurring around the barrel when breaking a hard granite at pressures as high as 83 MPa (12,000 psi).

Other significant benefits derive from the unique viscous properties of foams. The viscosity of a foam depends strongly upon foam quality, defined as the volume fraction of gas. Foams of quality below 50% (gas volume less than 50%) typically have viscosities only slightly higher than that of the liquid phase. As foam quality increases above 50% and up to about 90%, foam viscosity increases markedly and can be much more than an order of magnitude higher than that of the liquid phase. As foam quality increases above 95%, the foam breaks down into a mist and the viscosity drops rapidly to approach that of the gas phase. In a CFI fracturing operation the foam might be generated initially with a quality below 50%, albeit at very high pressure. As the foam expands into the developing fracture system, foam quality will increase with a concordant increase in viscosity until the foam has expanded to a 95% or greater quality. This variation of effective viscosity with expansion serves to improve the efficiency of the CFI process in two ways. While the highest pressure foam is being generated, delivered to the injection device and injected via the barrel into the hole, viscosity will be low, as desired. Once the rock or concrete begins to fracture, the foam expands and viscosity increases preventing the premature escape of the pressurizing medium before breakage is complete. Once breakage is complete the foam expands further, and as a foam quality over 95% is realized, the viscosity drops, allowing the foam (now a gas mist) to escape more rapidly and thus reducing the time that high-pressure foam can accelerate fragments of the broken material. By appropriately designing the foam, a sequence of viscous behaviors optimally tailored to the foam-injection/material-breakage process can be achieved.

Initial testing was done with very small-scale prototype CFI equipment on large blocks of granite and concrete. These tests demonstrated a consistent ability to fracture, in a face excavation geometry, a hard competent granite. Besides being able to break rock, these tests demonstrated that the CFI method generates minimal flyrock and airblast, both of which were significant with the PCF method and other small-charge approaches. The small-scale tests have shown also that a hard competent granite may be fractured, without the benefit of edge effects, at foam pressures in the range of 10,000 psi. These pressures are one fifth to one tenth those required for fracturing with propellant gases, as used in the PCF method. The lower pressure required is a result of the lower rate of the process which is possible because of the viscosity of the foam and the improved hole-bottom sealing as described above. Based upon these initial results, a Phase I SBIR (Small-Business Innovation Research) grant was received from the National Science Foundation in early 1998. The research efforts on this grant resulted in the development of improved foam generating hardware, the study of foam formulations capable of giving the very high viscosities (greater than 1,000 centipoise) envisioned as necessary and the construction and in-mine testing of near full-scale hardware. For testing CFI breakage on a realistic scale, a CFI injector with a 1- $^5/_8$ diameter barrel was designed and built. The design of this injector was essentially identical to that shown in Figure 2, with the injector barrel being 20 inches (51 cm long).

3 FIELD TESTING OF CFI BREAKAGE

Field tests with the 1- $^5/_8$ inch device were carried out at the Colorado School of Mines (CSM) test mine located in Idaho Springs, Colorado. Rocks available in this mine range from highly fractured gneiss to massive and competent schist and gneiss. Tests in the mine environment allowed also for the effects of developing face geometry and successive breakage interaction to be observed. For example, rock anisotropy and jointing were evaluated for their influence upon breakage. Similarly, the sensitivity of breakage to foam properties as controlled by surfactant, additives and gas concentration were studied. The CFI injector was mounted on one of two booms on a small rail jumbo at the mine. Both booms carried conventional screw feeds which were approximately six feet long. The screw feed on the CFI boom was found to be completely adequate for displacing or inserting the CFI barrel into the drilled holes, even for holes high on the face. The other boom carried a conventional rock drill for drilling the holes for CFI breakage. Once the drill and the CFI breaker were similarly aligned, albeit on separate booms, it was relatively easy to drill a hole, swing the drill boom out of the way, swing the CFI boom into position and insert the barrel into the hole.

The test face used at the CSM mine was some 1,500 feet into the mine and under over 700 feet of burden. The rock at this face was an unusually competent gneiss, with moderate jointing and some schistose and/or fractured zones. This face provided enough variation in rock type and condition to reasonably evaluate the effectiveness of CFI breakage in a drifting or tunneling environment. Typically, holes with depths ranging from 5.0 to 8.0 inches were drilled and then fractured using a variety of seal designs and foam compositions and pressures.

The most difficult breakage geometry involves removing rock from a solid face such as at a tunnel or mine heading. For single face breakage the barrel seal must be able to adequately prevent the escape of foam until an adequate fracture system is developed and must be able to keep the barrel locked into the hole while the requisite fractures are developed. Initial tests conducted with the prototype ¾ inch CFI device indicated that a seal of crushed granular material (e.g. medium sand) would meet these requirements. The testing of seal designs within the NSF Phase I program involved the design and evaluation of prefabricated granular material segments that could be readily affixed to the CFI barrel just before insertion into the hole. A variety of designs, including sand of differing coarseness mixed with Rockite cement or epoxy resin so as to form a solid seal segment were fabricated and tested. The seal segments were simply halves of the full seal geometry, including a tapered section to fit over the taper on the back of the bulb tip.

Both the Rockite and epoxy bonded seals were fabricated in a Teflon mold which comprised a base section in the shape of one half (180º) of the barrel and bulb tip and a cylindrical one-half tube section to form the exterior (hole side) of the seal. The seal segments so formed could be rapidly attached to the end of the CFI barrel in the mine. A few seals with fine (less than 0.25 mm) and coarse sand (0.5-1.0 mm) were made and tested but it was found that very coarse sand (1.0-2.0 mm) gave the best performance.

In very tight rock, both the Rockite and epoxy bonded seals could sustain a hole pressure of over 60 MPa (8,700 psi) for several minutes. Both the ease of fabrication and their ready attachment to the CFI barrel makes the use of such granular material seal designs attractive for the necessary CFI hole sealing. The very low cost of the ingredients to make these seals (less than $0.10 per seal) indicates that reliable and inexpensive hole sealing will not pose any impediment to the commercial application of the CFI process.

The ability of the seals to hold a high pressure as well as the performance benefits of the air-cushion reservoir (as discussed above) are illustrated in Figure 3. Two pressure records obtained in one of the better CSM rock breaking tests (Rock-15) are shown in this figure. The pressure data was obtained with Cooper Instruments model PTT-222 0-15,000 psi transducers with the data recorded on a Tektronix 2214 digital storage scope run in the roll mode with a data sampling rate of 32 data points per second. The digitized records were then transferred to a personal computer for data reduction, analysis and presentation.

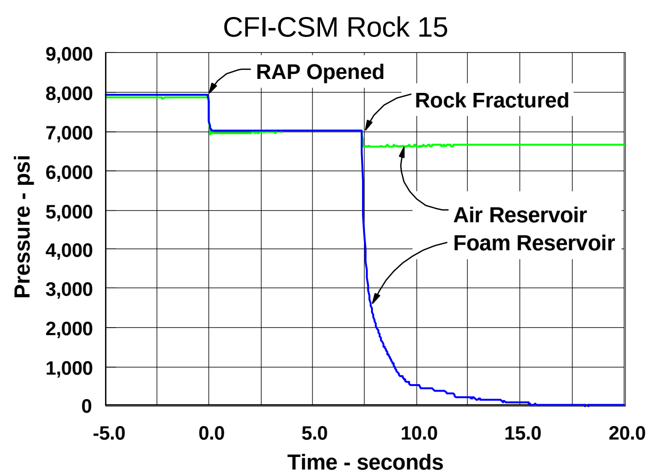

Figure 3. Pressure records from a CFI rock breaking test showing delayed rock fracturing.

One record in Figure 3 is for the air-cushion reservoir, behind the annular floating piston (see Figure 2), and the other is for the foam reservoir. The records in Figure 3 show the pre-shot pressure of nearly 8,000 psi prior to opening of the RAP valve and the rapid drop of both pressures to 7,000 psi as the hole is charged. As indicated in Figure 3, the 7,000 psi foam pressure was not able to immediately fracture the rock, as no water pre-fracture treatment was done, and there was a 7.4 second delay before the rock fractured. Once fracture was initiated the fracture process was completed quite rapidly, with over 6.0 ft^3 of rock being excavated in a fraction of a second. Once fracture was initiated the foam pressure rapidly dropped to zero and the air-cushion pressure dropped 6,600 psi, corresponding to the injection of the residual foam in the foam reservoir down the barrel.

Over thirty tests were performed in the CSM mine with 22 of these being directed towards rock breakage. The other tests were related to CFI injector performance and seal design. Based upon the volume of rock removed or mucked from the drift after the completion of testing, the 22 rock breaking tests succeeded in excavating some 6 tons of rock. This translates to some 12,000 pounds (5440 kg) or some 72 ft^3 (2.0 m^3), with an average break per test of 3.3 ft^3 (0.1 m^3) per each of the 22 tests. As many of these tests represent two or more pressurizations of the same hole, due to inadequate foam pressure or viscosity, or due to a two cycle breakage method, the actual number of hole breaks is 15. For the 15 effective tests the breakage is 4.8 ft^3 (0.14 m^3). This compares to the average breakage of 1.8 ft^3 (0.05 m^3) for PCF, propellant breakage on the same scale (Young et al. 1990).

The CSM mine testing revealed that a very high viscosity foam might not be the best for fracture initiation, indicated by the pressure records shown in Figure 3, above. Despite the fact that the mine face was moderately jointed and fractured, with joint/fracture spacing of less than 12 inches (30 cm) it was found that nearly every hole was so tight that some form of fracture initiation was required. If an unfractured hole was charged with foam only, the pressure to initiate fracture could be as high as 10,000 psi (69 MPa) and several minutes could elapse as the foam diffused into the rock enough to effect fracture initiation. Conversely, it was found that this same rock (even the same hole) could be fractured at pressures as low as 3,000 psi (21 MPa) with plain water. As operating the CFI process at the pressure levels required for foam only fracture initiation would result in excess airblast and flyrock and would represent a waste of energy, three methods for fracture initiation were devised and evaluated. A CFI pre-shot could be conducted with a small water only charge, the requisite fractures could be initiated by hydraulically fracturing the hole or the hole could be loaded with water (a water pad) which would transmit the CFI foam pressures to the bottom of the hole. The CFI pre-shot approach would require firing a second foam injection cycle of the CFI hardware to extend the water initiated fractures to a successful excavation. The hydraulic fracturing approach would require a second high-pressure pumping system to deliver the needed water as well as appropriate modifications to the CFI hardware. The hole loading approach would be the simplest to implement, with the high-viscosity foam being delivered to the hole bottom only after fracture initiation was effected by the water pad. All three approaches were investigated, with the hole loading approach working as well as the other two.

The in-mine tests demonstrated the importance of high foam viscosity to the effectiveness of the method. In testing the water only pre-shot approach above it was found that even when large charges of water at high pressure were used, no rock was excavated. The rock would be well fractured but fracture pressurization was not sufficient to “lift” the rock from the face. Also several tests were performed with a relatively low viscosity foam which succeeded in fracturing but not excavating the rock. These tests were immediately (the CFI injector was still sealed in the hole) followed by a test with a higher viscosity foam with the result that fracturing was completed and the rock excavated.

The tests conducted at the CSM Experimental Mine provided also some confirmation on scaling of the CFI process. Existing data on rock breakage by a variety of methods (Young et al. 1993) indicate that the efficiency of breakage improves with the scale of the breakage. Thus, the energy required to excavate a unit volume of rock decreases with increasing scale of breakage. This effect is primarily due to the interaction of larger and weaker defects (fractures, joints, parting planes, et cetera) with the process at larger scales. For propellant, gas-driven fracture the scale enhancement is approximately 50 percent for each doubling of the linear scale. That is, a doubling of device dimension will result in the breakage or removal of twelve times as much material. Linear scaling would yield only eight times the material. The data for CFI breakage in the CSM test mine along with data for PCF breakage in the same mine are shown in Figure 4. Both PCF and CFI breakage follow a nonlinear scaling. This nonlinear scaling would be manifested both in a reduction in the pressure required to break rock, and in an increased breakage efficiency at larger scales. Both the rock volume and pressure data from the CSM mine tests indicate strongly that the nonlinear scaling expected for the CFI process is existent.

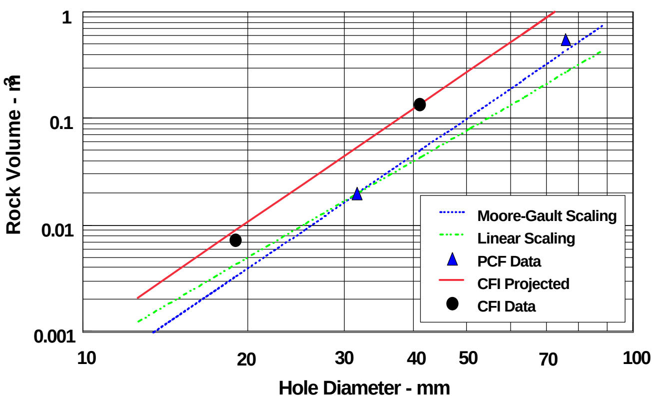

Figure 4. Log-log graph showing nonlinear scaling of CFI and PCF rock breakage.

During the course of the experimental efforts to evaluate the ability of the CFI method to break rock in the CSM mine, considerable experimental data on the CFI process was obtained. These data served to both confirm the proper functioning of the prototype CFI equipment and to provide guidance for the measurements that might be utilized for process control in more commercial applications of the method. It was determined that control of the CFI process, including control of foam quality, could be achieved with simple pressure measurements of gas pressure in the air-cushion reservoir, foam pressures in the foam generator and subsequently the foam reservoir. It was found that the measurement of foam opacity with a high-pressure sight glass and measurement of the volume of the liquid phase of the foam solution injected into the foam generator were sufficient to control foam quality (percent gas) and proper foam mixing. Other aspects of a commercial CFI process, such as hole drilling, indexing for CFI injector placement and hole-seal crushing could all be monitored and controlled by existing hardware and techniques utilized in commercial automated machinery.

4 CONCLUSIONS

The benign nature of rock and concrete breakage characteristic of the CFI method promises to provide a method and means for the excavation of rock or the demolition of concrete which can be applied on a nearly continuous basis with minimal disruption of the environment and minimal hazard to nearby personnel and equipment. Because a controlled foam injection device can be built to achieve any desired scale of breakage, the CFI method can be applied equally well to large-scale tunneling or mining operations, to small-scale selective mining, civil construction and boulder breaking, or to concrete stripping or demolition. Due to the simplicity of the process, extensive additional engineering is not required to implement the technology. Much of the requisite supporting hardware, such as pumps, rock drills, hydraulic systems, et cetera, are commercially available. Finally, the very low expendable material costs and the low environmental impact of the method provide additional benefits.

5 ACKNOWLEDGMENTS

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