CONTROLLED FOAM INJECTION
PROGRESS TOWARDS AUTOMATED HARD ROCK EXCAVATION

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ABSTRACT

The many attempts in recent years to develop non-explosive rock excavation techniques have used mechanical, hydraulic or gas pressurization approaches to exploit rock weakness in tension. The use of high-pressure foam to initiate, pressurize and propagate controlled fracturing in rock has been found to offer many advantages that have led to the development of a new technique. In the Controlled Foam Injection (CFI) method a viscous foam is injected into the bottom of a pre-drilled hole in the rock to be broken by means of a barrel incorporating an inexpensive and highly effective hole-bottom sealing method. Pressures needed to break rock with the CFI method are significantly less than are required in methods based upon the use of small explosive or propellant charges. The ability to tailor the viscosity and the stored gas energy of the foam to specific rock breakage characteristics results in highly controlled and predictable breakage. Airblast and flyrock are reduced to very benign levels, allowing the method to be applied in a continuous manner and in close proximity to personnel and equipment. The benign operating environment, the incremental breakage and the mobility and simplicity of the requisite hardware allow the method to be highly automated and fully integrated with other excavation operations such as mucking and ground support. Several development and demonstration programs have been conducted to further quantify CFI rock breakage and to provide the data needed to evaluate the applicability of the method to various mining operations. One of these programs was carried out in the Fecunis Adit near Sudbury, Ontario. This program demonstrated the ability of the CFI method to break the unusually competent rock, but revealed some rock characteristics and machine performance problems that reduced overall breakage effectiveness. With the indicated changes to foam properties and improvements in hardware, the CFI method remains attractive for rock breakage in many situations. Both secondary breakage and utility excavation are particularly attractive for further development and commercial application.

KEY WORDS

Rock excavation; High-pressure foam; Fracture pressurization.

INTRODUCTION

The development of new techniques for rock excavation in both mining and tunnelling has not kept pace with a growing need for alternatives to conventional drill and blast. Drill and blast methods, while being highly efficient, have the disadvantages of being disruptive and being ever more severely regulated. Addressing the need for improved rock fracture and excavation technologies requires two separate but interactive technology improvements. First, new rock breakage methods must be developed and these methods must be suitable for automation. Second, the automation and control of such methods must be developed in order for them to achieve the required production rates and become independent of both intensive labor and operational problems in the highly variable environments of rock excavation.

To date a variety of explosive methods has been used for most rock excavation, with the exception of major tunnel boring projects. This tendency to remain with explosive methods, despite the increasing problems of disruption, adverse environment, and explosive handling, is due to both the simplicity of explosive methods and the lack of viable alternatives. Rock fracture and excavation methods that could maintain the effectiveness of drill and blast without the adverse characteristics of explosives could find broad market acceptance.

BACKGROUND

For over a century explosive blasting has been the primary means used for hard rock excavation in both mining and tunnelling. 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 [1]. Conventional blasting is limited in that it requires special precautions due to the use of explosives and can cause excessive damage to the rock being broken. 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 blasting 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.

Controlled fracture methods, in various forms, have been proposed for several years as means to excavate rock more efficiently. Many of these methods, including hydraulic, mechanical and propellant loading methods are reviewed in reference [1]. This review of the desirable aspects and undesirable limitations of many of the controlled fracture rock breakage and excavation methods has led to the development of a new method. This method is based upon using high-pressure foam as the fracturing medium and is referred to as Controlled Foam Injection (or CFI) fracturing. Many of the earlier approaches have shown that a proper pressurization of preferred or controlled fractures is the most efficient way to break rock. 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. The propellant gas methods have the advantage over the water/steam pressurization methods in that the gases can expand as they flow into a developing fracture system and will thus maintain their ability to adequately pressurize fractures. The propellant gases are comprised primarily of carbon monoxide, however, which requires special ventilation considerations in restricted or underground situations.

A preferred excavation 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. The 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. After careful consideration it was realized that a water-based foam would be a fluid having all of the requisite properties. A high-pressure foam pressurization method could overcome many of the limitations of the existing explosive, propellant, high-pressure water and steam (electrical-discharge) fracture pressurization methods.

A foam suitable for fracturing hard competent materials by controlled 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 quar 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 using conventional high-pressure pumps and reservoirs and with a variety of mixing and blending means.

The general features of a device to use Controlled Foam Injection (CFI) for either rock excavation or secondary breakage are 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. A simple and inexpensive means to obtain the requisite seal has been developed and successfully tested. Consistent rock and concrete breakage have 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.

Foam, which is a two-phase mixture of a liquid and a gas, can be made to have a viscosity many orders of magnitude higher than a gas and even several orders of magnitude higher than water. Consequently, 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 low viscosity fluid is used. The use of water or even a viscous liquid is not sufficient because the 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.

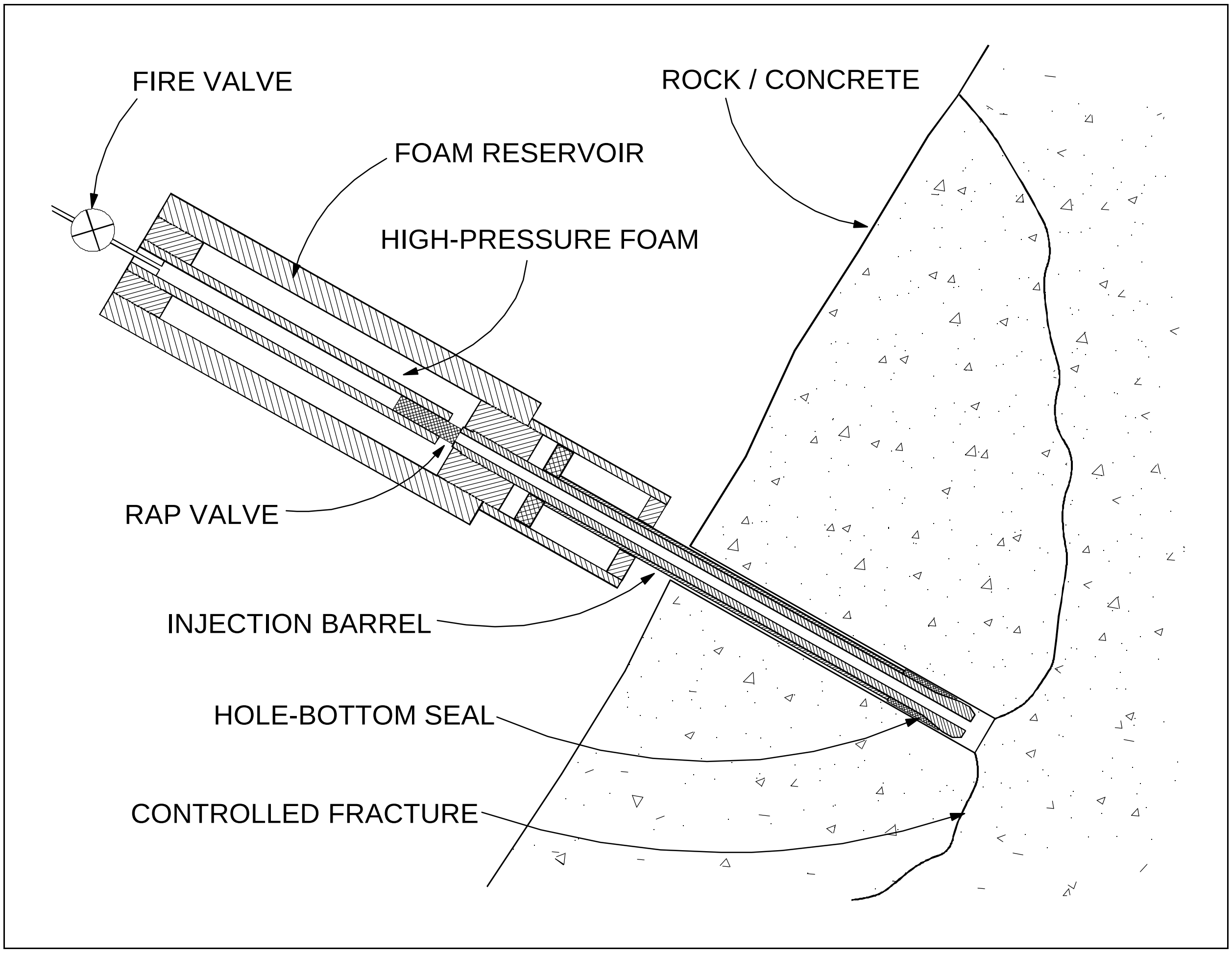

Figure 1. Basic hardware and geometry for Controlled Foam Injection (CFI) fracture of rock.

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. 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.

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, the 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. Testing in preceding research programs to study both rock and concrete breakage and the current CAMIRO rock breakage program has shown that using an annular floating piston for foam volume control provides significantly improved operational control to the process.

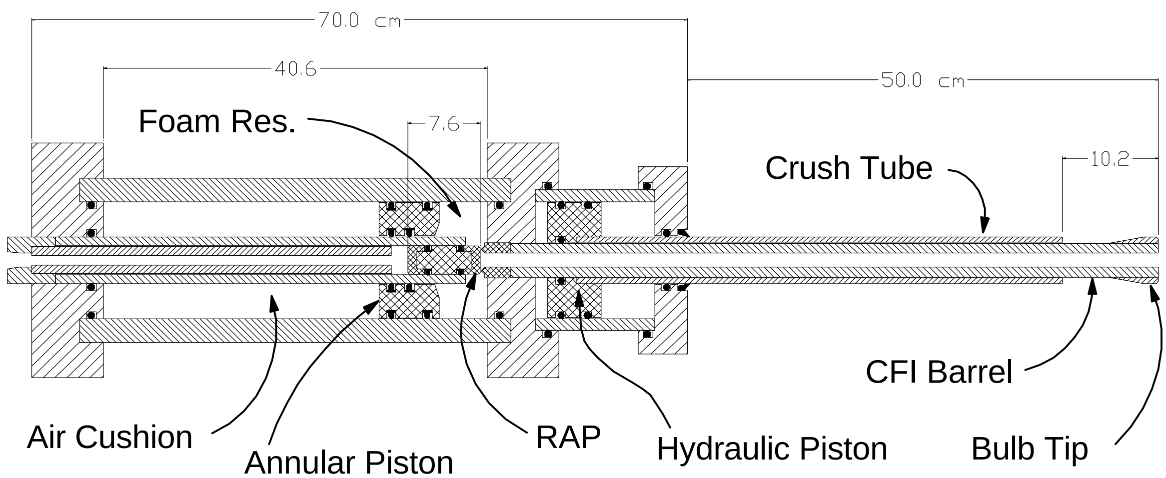

Figure 2. Details of Reverse Acting Piston (RAP) valve and of annular floating piston for controlled foam injection.

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. 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 could 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 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 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 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 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.

The benign nature of rock fracture and breakage characteristic of the CFI method promises to provide a method and means for hard rock excavation 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 tunnelling or mining operations, to small-scale selective mining, civil construction and boulder breaking, or to concrete stripping and demolition.

FECUNIS ADIT TEST PROGRAM

The successful application of a foam-based controlled-fracturing system will require several operational capabilities. A means for generating a foam of certain desirable physical properties must exist. A means to deliver the foam to the bottom of a pre-drilled hole on an as needed basis in terms of pressure, pressure time behavior and volume must exist. Finally, a means to limit or control the escape of foam from around the tube or barrel used to deliver the foam to the hole bottom must exist. Research carried out on three separate programs has addressed successfully many of the more critical aspects of the process and has provided the data needed to evaluate the applicability of the method to various mining operations. The first development program was funded by the national Science Foundation through the Small-Business Innovation Research (SBIR) program. The program, conducted in the first half of 1998, involved the development of near full-scale rock breakage and foam generating hardware and, then, the extensive testing of this hardware in the Colorado School of Mines test mine [2]. This program demonstrated the capability of the CFI method to fracture and excavate a hard competent gneiss and the importance of foam viscosity to successful breakage. A second program was conducted to evaluate the effectiveness of the CFI method for the breakage of concrete especially as applied to the stripping of reinforced concrete. This program was conducted in collaboration with the Mining Engineering Department of Michigan Technological University with funding from the Department of Transportation through the Great Lakes Center for Truck and Transit Research and was conducted at MTU during the period June-October 1998 [3]. The program demonstrated the ability of the method to strip concrete and revealed a significant increase in breakage efficiency due to fracture interactions with reinforcing steel. A third test program was carried out in the Fecunis Adit near Sudbury, Ontario during the period September-December 1998. This program received funding support from three CAMIRO sponsoring mining companies and the Industrial Research Assistance Program of the National Research Council of Canada.

The testing in the NSF program indicated that the scale of rock breakage for mining applications should be slightly greater than the 41 mm injector barrel used in the CSM tests but that the existing foam reservoir was sufficiently large to support a 51 mm injector barrel. Consequently, it was possible to use the high-pressure reservoir body of the NSF breaker to carry a new 51 mm injector barrel. The breaker modifications also included a new RAP (reverse acting poppet) control tube which would allow both the poppet piston and the seal ring to be removed and serviced from the rear of the breaker without having to disassemble the high-pressure reservoir. An engineering layout of the modified breaker is shown in Figure 2, above. A photograph of the 51 mm breaker mounted on the indexing boom of the MacLean 829 is shown in Figure 3. The breaker is shown on top of the boom with the hydraulic rock drill carrying a 51 mm bit rotated 90° to the left. The indexer made it easy to rapidly drill a hole, index and insert the breaker into the hole.

Figure 3. Photograph of 51 mm CFI breaker mounted with a drill on the indexing boom of the MacLean 829 carrier.

The Fecunis test program was directed towards providing enough data on rock breakage, operational procedures and requisite supporting hardware (e.g. foam generation pumps) to allow for an evaluation of the potential applicability of the method to specific mining and hardrock breaking operations. For the testing and evaluation of CFI rock breakage two locations were identified. The first location was in the right rib of the main adit and only some 50 meters from the portal. As the "face advance" at this location was perpendicular to the adit, the advance was parallel to the hillside into which the adit was driven. The preexisting fracturing in the rock and the residual *in situ* stress orientation at this location both served to severely impair CFI rock breakage and excavation at this location. The second location in the Fecunis Adit was situated on the back of the loop encircling the original mine shaft. This location was over 500 meters from the portal and the rock did not have the open preexisting fractures nor the adverse *in situ* stress state which made breakage at the first location problematic.

Rock breakage tests in a face excavation geometry were conducted at both locations in the Fecunis Adit. At the first location, where most of the testing was conducted, the method was able to fracture the rock , but the breakage was compromised by several adverse rock conditions. The rock was fairly fractured with many fractures being open and the residual *in situ* stress strongly favored fracture propagation into the face rather than parallel to it. This resulted in a large portion of the injected foam volume (and energy) propagating into the face rather than into fractures suitably oriented for excavation. The testing revealed also that the foam generation system, although improved from earlier versions, had many deficiencies and was not able to deliver the volumes and pressures of foam needed to overcome the adverse rock conditions. Consequently the CFI technique, while able to fracture and excavate the rock, gave an average breakage for the 32 valid tests at this location of only 0.06 m^3 per break.

The second location in the Fecunis Adit was on the back side of a loop at the end of the adit which circled the old Fecunis shaft to the deeper workings of the mine. The face selected for testing on this loop was on the rear most portion of the loop and was thus oriented approximately perpendicular to the main adit. The rock did not have the open fracturing observed at the first location and any preferred fracturing and joint orientation was roughly parallel to the face. The CFI carrier and breaker are shown positioned for the first break at this location in Figure 4.

Only five CFI breakage tests were conducted at this second location. The first three of these tests gave very good rock breakage with the average volume of rock removed being 8.4 ft^3 (0.24 m^3) per break. A photograph of the face just after the first break is shown in Figure 5. The hole for this test was 8.0 inches deep and a very well defined spall type fracture, nearly parallel to the face, was developed to distances from the hole ranging from 1.0 ft (up to the left) to 4.0 ft (down to right). An excellent video clip of this test was obtained, with the video demonstrating the rather nonviolent nature of CFI breakage as the broken rock was "heaved" way from the face.

The second and third tests at the adit loop location also yielded excellent excavation. In the second test, a large spall fracture was developed behind the face with this rock slab being so well decoupled from the face that it was possible to manually bar down the rock, yielding approximately 9.4 ft^3 (0.27 m^3) of rock. In the third test, the breakage was again controlled by the development of a spall type fracture behind the face. In this test some 60 percent of the excavated rock was removed during the breakage process, one large slab comprising 20 percent fell from the face as the CFI injector was pulled back from the face and some 20 percent of the total rock came down with manual barring. The crater excavated by these three tests was some 7.5 ft (2.3 m) wide by 6.0 ft (1.8 m) high with an average depth of 8 inches (20 cm).

Figure 4. Photograph of the MacLean 829 positioned for the first CFI break at the second Fecunis Adit location.

Figure 5. Photograph of CFI breakage from the first test conducted at the second Fecunis Adit location.

The last two tests conducted at the adit loop location resulted in the development of very well defined spall type fractures from the hole bottoms but did not succeed in completing the breakage process with removal of the rock. The spalled slab developed in these two tests was still so well bonded to the rock mass at the peripheries of the spall (at some 2.0 to 3.0 ft radii) that it was not possible to manually bar the rock down. This decoupled rock could have been removed with a conventional impact breaker or would have been excavated by interaction with subsequent CFI breaks.

In contrast to the breakage experienced at the first Fecunis Adit location, none of the tests at the second location experienced the problem of fracture propagation into the face and the concordant loss of foam pressure and energy. It appears that the major limitation on completely successful CFI breakage at the second location was due to the lack of adequate foam viscosity and/or delivered volume to complete the breakage process. Both of these deficiencies could be addressed by a proper re-engineering of the hardware. At the second location the rock exhibited much less fracturing, had minimal open fracturing and did not have the adverse *in situ* stress orientation. All of the tests conducted at this location developed very extensive spall fractures behind and roughly parallel to the face ranging up to one meter in radius. Where the delivered foam pressure, volume and energy were sufficient, the fracturing produced an average breakage of over 0.24 m^3 per break. This volume of rock removed is nearly that predicted by scaling of data from earlier smaller-scale tests and is considerably greater than that which would be obtained with propellant based breakage from the same size hole. Most of the problems encountered in conducting the Fecunis Adit testing were related directly to the performance and capabilities of the foam generating system. A breaker with greater foam delivery capability should give better performance.

The Fecunis program demonstrated the ability of the CFI method to break the unusually competent rock, but revealed some rock characteristics and machine performance problems that reduced overall breakage effectiveness. With the indicated changes to foam properties and improvements in hardware, the CFI method remains attractive for rock breakage in many situations. Both secondary breakage and utility excavation are particularly attractive for further development and commercial application.

The effectiveness of the CFI method as well as the advantages that might be obtained by operating the method on different size scales can be illustrated by comparing the results obtained to date with the breakage realized by the propellant based PCF (Penetrating Cone Fracturing) method [4]. The PCF method uses a breakage geometry very similar to that of the CFI method, has been under commercial development for eight years and is being applied commercially to two civil rock excavation projects (in Hong Kong and Sydney, Australia). Test data and projections for both CFI and PCF breakage are shown in Figure 6. The data are plotted as volume of rock removed versus hole diameter. The data could also be plotted as volume versus foam or propellant charge energy, but, as noted below, hole drilling represents the major energy expenditure and hole size is a good measure of overall system size and capital cost. Comparing the processes based upon hole size thus provides for a better overall comparison. In addition, the volume of rock removed would best be normalized for rock strength, fracture toughness, degree of natural fracturing, et cetera, but as enough data on the various rocks used to obtain the data of Figure 6 is not available this was not possible. Most data was obtained on dense, compact igneous or metamorphic rock with minimal natural fracturing and unconfined compressive strengths over 170 MPa (25,000 psi).

The data for the two locations in the Fecunis adit are shown separately with the two data points demonstrating the differences between breakage at the two locations. The data for the second (adit loop) location are from rock comparable to the rock in most CFI and PCF testing, while the data from the adit entry location has been adversely affected by the unusual preexisting fracturing at this location. The CFI data from the second location shows nearly the degree of nonlinear (Moore-Gault) scaling expected from the NSF/CSM and the earlier, ¾inch prototype testing. The CFI data also indicate further that CFI breakage should be much more efficient than PCF breakage at any scale. Finally, a nonlinear scaling projection from the existing data (but excluding the adit entry location data) indicates that CFI hardware built for 76 mm (3.0 inch) holes should be able to remove nearly a cubic meter of rock per break.

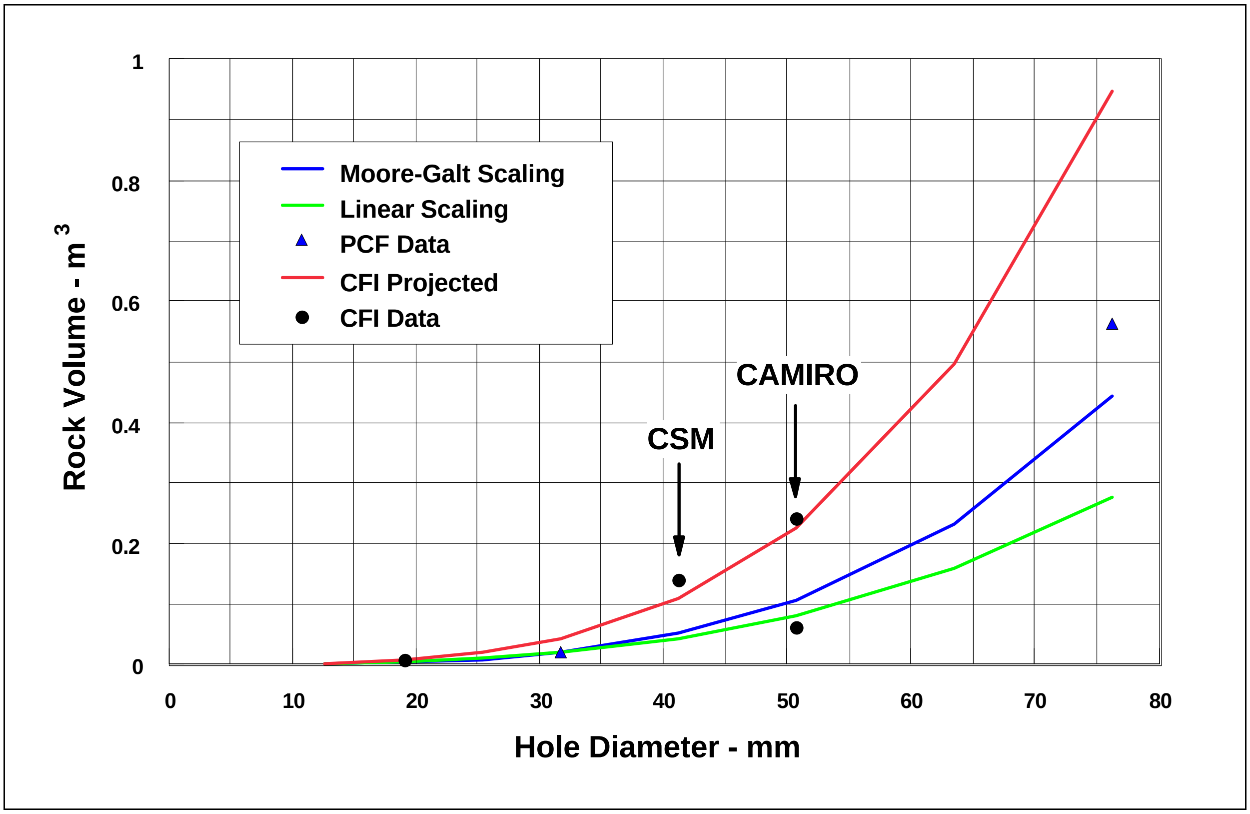

Figure 6. Plot of CFI rock breakage as a function of hole diameter showing comparison to PCF breakage and scaling effects.

The effectiveness of the CFI method can also be evaluated by comparing the energy expended by the process with the energy used in other methods, such as explosive, impact and water jet breakage. An approximate calculation of the energy used in the CFI process can be obtained by treating the gas in the high-pressure CFI foam as an ideal gas. At a pressure of 8,000 psi or 55.2 MPa, the relative volume change from one atmosphere (0.1 MPa) is 552. For an ideal gas this compression will involve an internal energy change, at constant temperature, of 15,380 Joules per Mole of gas. At 55.2 MPa, one Mole of gas will occupy 0.041 lt. or 41 cc. Thus the gas will have an internal energy of 379 J/cc and the 475 cc of gas in a 950 cc CFI charge at 50 percent foam quality will contain 161,076 Joules.

For the second Fecunis Adit location, each CFI break removed 8.4 ft^3 or 0.24 m^3 of rock on average, giving a specific energy for CFI rock breaking of 0.68 J/cc of rock removed. This energy is for the gas in the foam only. A small amount of energy will be in the compression of the liquid phase of the foam, but this energy will be less than 1 percent of the gas energy. For the entire CFI process the largest expenditure of energy will be for hole drilling. For each CFI break at the second adit location the holes were typically 51 mm in diameter by 21 cm (8.3 inch) deep. The rock drilled out to make each hole is thus 432 cc. Using 1,000 J/cc as the specific energy for drilling [5], gives 432,000 Joules expended in drilling. This results in a specific energy for the drilling to break out 0.24 m^3 of rock of 1.81 J/cc. The total specific energy for the CFI process is thus on the order of 2.49 J/cc with 73 percent of this energy being for drilling. Drill and blast typically has specific energies of over 10 J/cc and most mechanical excavation means have specific energies of over 100 J/cc. The total gas energy of 161,076 Joules above corresponds to the energy in only 40 gm of TNT explosive. PCF breakage on this scale would use 0.1 kg of propellant and explosive loading might use around 0.2 kg of explosive to achieve the same breakage. The CFI process is thus intrinsically much more energy efficient. This lower energy to break is manifested in the low airblast and flyrock typical of the CFI method and in the minimal residual damage imparted to the remaining rock.

Nearly all operational problems during the testing were related to the performance of the foam generating hardware. The problems with foam generation were nearly all caused by the use of the compressed air driven pumps and the very small displacements per stroke provided by these pumps. The small volumes displaced per stroke result directly from the fact that the pumps required very high area ratios between the low-pressure (120 psi) air drive pistons and the high-pressure (up to 15,000 psi) output pistons. For the three pumps employed the area ratios ranged from 110:1 to 152:1 and the pumps had displacements per stroke ranging from 0.04 in^3 for the liquid pump to 1.2 in^3 for the gas booster pump. It thus required several minutes to pump the nitrogen bottle gas up to the desired air-cushion and foam pressures and one to five minutes to mix and then displace to the breaker the desired foam charge.

Based upon the experience gained in the NSF/CSM, the DOT/MTU and, finally, the CAMIRO rock breaking program, a totally new foam generating capability, employing hydraulically driven boosters and pumps is now under development. Such a system, with low area ratios between hydraulically driven pistons and the high-pressure output pistons, would allow foam mixing and subsequent displacement to the breaker to be done with a single pump cycle. A reasonably sized foam generator would be able to generate and then deliver 0.5 to 1.0 liter of foam per complete cycle. A standard 3,000 psi hydraulic power source would be able to make foams at pressures up to 12,000 psi. In order to generate and deliver 1 liter of foam per minute, a hydraulic flow rate of only 8 liter per minute would be required. An improved foam generating and delivery system will be critically important to the further development and commercial application of the CFI technology.

POTENTIAL APPLICATIONS OF CFI BREAKAGE

Of the many rock breakage and excavation areas in which CFI breakage might be successfully applied, boulder or secondary breakage operations would require the least hardware development and complicated process control. The foam requirements for boulder breakage, as indicated by the NSF/CSM testing, are such that a foam generating and control system for boulder or secondary breakage could be built with minimum re-engineering effort. The NSF/CSM data, as well as an evaluation of the foam properties required for boulder breakage, show that foam properties for boulder breakage are much less stringent than the properties required for the face excavation of a compact hard and tough rock, such as encountered in the Fecunis Adit. Due to the rather straight forward hardware and system development needed for a commercial boulder breakage system, boulder or secondary breakage offers a most attractive niche market for the further application of the CFI technology.

A second area that could be considered for CFI application is utility excavation. Utility excavation is defined as hard rock excavation in areas where high excavation rates are not of paramount importance and where other alternatives for excavation are less attractive. In general, utility excavation would include smaller excavation projects where the given excavation had to be performed (high-value excavation) and/or where explosive or mechanical means could not be employed. Although utility excavation projects exist in the mining environment it is anticipated that most such projects would exist in the civil sector. Many mining operations could benefit from the development of additional galleries or crosscuts which would be difficult and/or expensive to develop with explosive methods.

The CFI hardware for utility excavation would be more complex that that for boulder breakage but would be less complicated than the hardware for other general areas of excavation, as discussed below. Perhaps the greatest demand that might be placed upon a CFI system for utility excavation would be for system flexibility. This flexibility would be in the area of foam properties, as discussed above, and in CFI system mobility. This mobility should include CFI breakage hardware capable of working over a broad range of hole depths, boom/indexer capabilities capable of attacking the rock over a broad area and carrier capabilities to operate with onboard air, water and power.

A third well defined area in which CFI breakage might be successfully applied is in selective mining operations. Selective mining is especially attractive for CFI application because the method allows for the very controlled removal of rock and imparts minimal damage to remaining (non-excavated) rock. The CFI method could be engineered to extract rich ore bearing rock separately from barren waste rock. If such differentiation can be effected as the mine is developed, then it would be possible to significantly decrease the amount of rock hauled or lifted to the surface and to increase the grade of ore run through the mill and smelter operations. In addition the barren rock not mixed with ore could be kept underground and used for backfilling operations. The reduced damage aspect of CFI breakage could serve to reduce the amount of ground support required in the mining operations.

CFI hardware for selective mining would require more development than would hardware for utility excavation as discussed above. Selective mining hardware would have to have the production capability and the operational reliability needed to be competitive with existing mining methods in terms of ore produced. In addition, it might be necessary to include some form of mucking or rock removal capability in the machine carrying the CFI breakage hardware. Finally, the hole location, drill, index and break cycle would have to be fairly highly automated so that intensive operator surveillance would not be required.

The final area considered attractive for the application of CFI breakage technology is in mine drift development and tunnelling. This area will require the most engineering development of any of the applications discussed here. A CFI system for mine drift development or for civil tunnelling will require all of the features of CFI systems for the less demanding areas discussed above but will also require a very high degree of system integration. Such a CFI system would need high and reliable productivity, a high degree of automation and, perhaps most importantly, a capability to carry out breakage and mucking operations simultaneously. A CFI based machine for mine drift development or tunnelling would most probably be rather large with a concordantly high capital equipment cost.

CONCLUSIONS

The test program conducted to evaluate the effectiveness of CFI breakage for hard rock excavation representative of mine drift development operations succeeded in demonstrating the potential capabilities of the method but revealed several areas in need of further study. The CFI method is certainly capable of fracturing and excavating rock at foam pressures that are both easy to obtain with fairly conventional hardware and which result in a very environmentally benign breakage.

The energy required by the CFI method in terms of energy expended per unit volume of rock removed is especially noteworthy. This energy is on an order of magnitude less than required for any explosive method and is much more than an order of magnitude less than for any water jet or impact breakage method. The low energy expenditure characteristic of the CFI method makes the method attractive for further study and possible application both in terms of energy costs and in terms of the less attractive attributes of high-energy methods. These attributes include airblast, flyrock, unnecessary damage and higher capital equipment costs for equipment to both deliver the necessary energy and to resist the wear associated with higher energy delivery.

The foam generating hardware used in the CAMIRO program was not able to deliver the volumes and pressures of foam needed to overcome the adverse rock conditions. Also, the foam generating hardware was found be much more difficult to operate and maintain than had been expected. This latter problem was primarily related to the use of air driven pumps in the system. Despite these problems, the CFI technique was found to be able to fracture and excavate a significant amount of rock, with breakage efficiencies of 0.06 m^3 per CFI break at one location and of 0.24 m^3 per break at a second location in the Fecunis Adit. The primary reason for the difference in breakage at the two locations is related to the existence of adverse natural fracture and *in situ* stress conditions at the first location.

Most of the problems encountered in conducting the Fecunis Adit testing were related directly to the performance and capabilities of the foam generating system. A breaker with a larger and more viscous foam delivery capability would have given better performance. The air driven pump system for generating and delivering foam was particularly inadequate. A foam generating and delivery system employing hydraulic pumps and intensifiers would be able to deliver the volumes and qualities of foam required in a much more expeditious manner. With the indicated improvements in the hardware, the CFI method remains attractive for rock breakage in many situations. Both secondary breakage and utility excavation are particularly attractive for further development and commercial application in the near term. The application of CFI breakage to these areas will not require undue engineering development but will provide the experience and technology development that will be necessary to build fully integrated systems for selective mining, mine drift development and tunnelling.

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REFERENCES

[1] Young, C., Controlled-foam injection for hard rock excavation, *Proc. 37th U.S. Rock Mechanics Symposium*, Vail, CO, June 1999

[2] Young, C., Controlled-Foam Injection for the Fracturing of Rock and Concrete, Final Report on National Science Foundation Grant No. DMI-9761109, 1998

[3] Otuonye, O. F. & C. Young, High-Pressure Foam method for the Fracture, Demolition and Stripping of Concrete Structures, Final Report DOT Grant DTRS95-G-0005 Purchase Order No. H85771, 1999.

[4] Young, C., J. D. Watson & A. K. Levien, Full-scale Testing of the PCF Rock Excavation Method, *Proc. VII Tunnelling Conf*, Sydney, Australia, 1993.

[5] Young, C. & D. E. McCarthy, Application of PCF Rock Excavation to the Controlled Excavation of Cross Cuts and Galleries, *Proc. 1995 Rapid Excavation and Tunneling Conference,* San Francisco, California, 1995.