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Study of fracture mechanism by measuring pressure history in blast holes and crack lengths in rock

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ABSTRACT

The mechanism of rock fracture by explosive is a fundamental in rock blasting. It is generally believed that the shock waves from the detonation initiate the fractures. Then the detonation gases penetrate into the fractures and elongate them. However, our previous researches indicated that the detonation gases do not contribute significantly to the fracture propagation. In our latest experiment, blasts have been carried out in 8 large granite blocks. The main goal was to study the fracture mechanism, namely to determine whether the shock waves or the detonation gases fracture the rock.

Two holes were drilled parallelly in each block, charged in the same manner and fired simultaneously with electronic detonators. Charges were decoupled, ϕ 17 mm (0.67'') explosive cartridge in ϕ 38 mm (1.5'') holes. In four of the blocks, blast holes were lined with steel pipes to prevent the detonation gases from entering into the rock. Two explosives, one emulsion and one cautious blasting explosive called Gurit B were studied. Borehole pressure history in the blast holes, VOD in the explosive and vibrations on the block surface were measured. After blasting, the blocks were cut, polished and the fracture patterns were studied.

The measurements showed the emulsion detonated at a speed of 4700 m/s (15420 ft/s) while Gurit B at a speed of 2500 m/s (8200 ft/s). Despite of this large difference in the VOD of the explosives, the quasi-static borehole pressure was nearly the same in all holes, approximately 0.15 GPa (1.5 kbar). The duration of the pressure was approximately 2 ms. However, the high VOD emulsion did generate a high but short, approximately 25 μs, pressure pulse in the blast holes, before the pressure in the holes reached the quasi-static state. The study of the post-blast fractures suggested that the shock waves from the detonating explosive are responsible for fracturing the rock, while the gases are responsible for moving or throw of the fractured rock.

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1 INTRODUCTION

The energy in a detonating explosive is transferred to the surrounding rock by two means, the shock waves and the gaseous detonation products. According to the classic theory of rock breakage mechanism (Lanefors and Kihlström 1973), the shock waves are responsible for the initiation of fractures. After the passage of the shock waves, the high-pressure detonation gases penetrate into the fractures and elongate them. However, the studies by Brinkmann (1990) and Olsson (2000) do not support this theory, since the possible effects of gas penetration could not be confirmed. Neither did the measurements of gas pressure in rock near blast holes provide evidence of gas penetration into the surrounding rock (LeJuge et al 1994, Sarma 1994, Ouchterlong et al 1997, Brent and Smith 1999). The only cases where gas pressure in surrounding rock has been recorded were in presplitting blasting (Ouchterlong et al 1997). Therefore, the roll of the detonation gases in fracturing the rock is undefined. Such knowledge certainly increases our understanding of the rock blasting process and provides basis for damage control.

However, this knowledge is not readily accessible. The measuring techniques suitable for field application are limited. Actually there is no method to monitor the rapid fracturing process in rock. Velocity of detonation (VOD) of the explosive and vibration in rock have been the only parameters one can measure in field with good accuracy. Nevertheless, with the new measuring technique developed at SveBeFo, the so-called LHM (Location-fixed Hydrostatic Measuring-cup) technique ([1]Nie 1999, [2]Nie 1999, Persson 1999, Nie et al 2000), pressure history in a blast hole can be measured.

This paper describes a series of 8 model blasts in large granite blocks. The goal of the study is to define the roll that the shock waves respectively detonation gases play in fracturing the rock. The LHM technique together with VOD measurement, vibration measurement and technique to study the post-blast fractures (Olsson and Bergqvist 1996) have been implemented in this study. Several conclusions can be drawn based on the measurements.

2 LHM TECHNIQUES FOR MEASUREMENT OF PRESSURE HISTORY IN BLAST HOLE

A measuring technique for measurement of pressure history in blast hole, the so-called LHM (Location-fixed Hydrostatic Measuring-cup) technique (Persson 1999), has been developed at SveBeFo and applied in both model and field blasting practices ([1]Nie 1999, [2]Nie 1999, Nie et al 2000). The essence of the method is a measuring cap that is placed in the bottom of a blast hole and measures the pressure history there. The earlier construction of the measuring cup has been described elsewhere ([1]Nie 1999, [2]Nie 1999, Persson 1999, Nie et al 2000). In this study, the measuring cup has been modified and was shown in Fig. 1. This measuring cup has the following features.

- The pressure sensor is a carbon resistor with a nominal resistance of 470 Ω.
- The sensor is protected against the electro-magnetic pulse from the detonating explosive by a sealed steel case.
- The Epoxy filling in the cup works as the pressure bearing media while it provides mechanical protection for the sensor.
- This construction of the measuring cup is strong enough to measure high pressure, 5 to 10 GPa (50 to 100 kbar).

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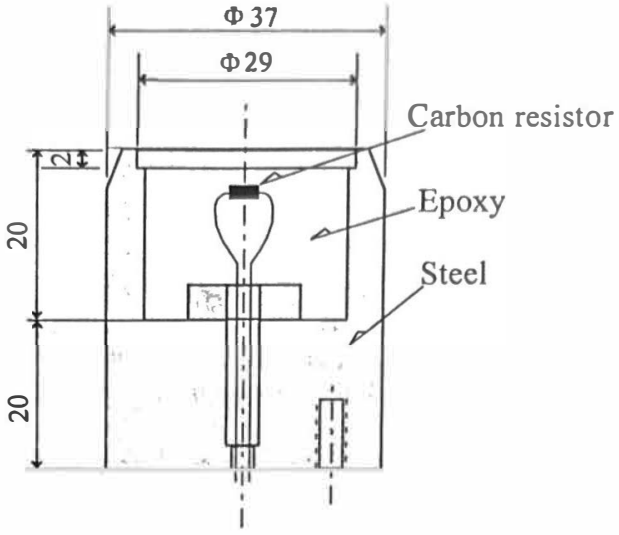

Fig. 1: The measuring cup used for measurement of borehole pressure history, units in mm and 1 mm = 0.03937 inches.

The pressure sensitivity of such carbon resistor has been calibrated by several researchers under both dynamic and static pressures (Nie et al 2000). The following pressure sensitivity has been employed in our analyses, based on the calibrations by Persson (1999) and by Ginsberg and Asay (1991).

$$P = 0.4075 \cdot (R_0/R-1)^{0.8734} \qquad (R/R_0 \geq 0.44)$$

$$P = 7.001 - 4.345 \cdot (R_0/R) + 0.364 \cdot (R/R_0) - 8.40 \cdot e^{-R/R_0} \qquad (R/R_0 < 0.44)$$

Where: P is the pressure (GPa or 10 kbar), R is the resistance of the resistor under pressure (Ω) and R_0 is the resistance of the resistor at the atmospherical pressure (Ω).

3 EXPERIMENTS

Blasting experiments were carried out in large granite blocks. Fig. 2 is an illustration of the blast holes, charges and the measurements carried out during the blast. Since the main goal was to study the roll of the shock waves respective the detonation gases on fracturing the rock, a test matrix was constructed, as shown in Table 1. A description of the experiment follows.

Explosives studied: Two explosives were studied. One is an emulsion explosive, Emulite 100, with a density of 1200 ~ 1250 kg/m^3 (74.9 ~ 78 lb/ft^3) and a detonation velocity of approximately 4500 m/s (14764 ft/s) in ϕ 17 mm (0.67'') cartridge. The other is Gurit B, a low VOD explosive designed for cautious blasting. Its density is 1000 kg/m^3 (62.4 lb/ft^3) and VOD is approximately 2200 m/s (7218 ft/s) in ϕ 17 mm (0.67'') cartridge. Both explosives are cap sensitive and both are provided by Dyno Nobel AB.

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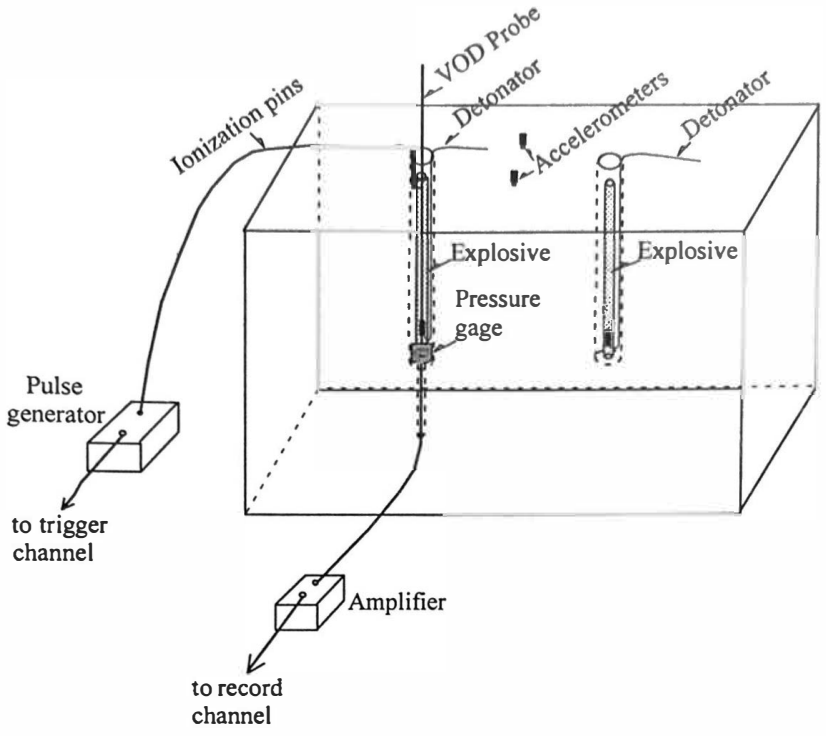

Fig. 2: Layout of the blasting experiments in granite blocks.

Table 1: Test matrix.

Nos. of blasts	Explosive studied	Fracture mechanism involved	Blast hole preparation	Stem-ming of charge	Expected results			
					VOD	Borehole pressure	Vibra-tion	Cracks
2	Emulite 100	Shock waves	Steel pipe lining	None	ca 4500 m/s *	High but short	High	More c.f. Gurit; Shorter c.f. stemmed Emulite
2	Emulite 100	Shock waves and gases	No lining	Cement	ca 4500 m/s *	High and long	High	More c.f. Gurit; longer c.f. unstem-med Emulite
2	Gurit B	Shock waves	Steel pipe lining	None	ca 2200 m/s *	Low and short	Low	Fewer c.f. Emulite; Shorter c.f. stemmed Gurit
2	Gurit B	Shock waves and gases	No lining	Cement	ca 2200 m/s *	Low but long	Low	Fewer c.f. Emulite; Longer c.f. unstem-med Gurit

*: 4500 m/s = 14764 ft/s and 2200 m/s = 7218 ft/s.

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Fracture mechanism studied: According to the classic theory (Lanefors and Kihlström 1973), both shock waves and detonation gases contribute to fracturing the rock. This study has the attention to separate those two mechanisms. Two measures were taken. Firstly, by lining the blast hole with a steel pipe, the detonation gases are prevented from entering into the rock. Only the shock waves can be propagated into the rock. Hence the effect of the detonation gases on the fracture propagation is excluded. On the contrary, by stemming the explosive in the hole, the gases are kept in the hole for a longer time and their effect on fracturing the rock is pronounced.

The granite blocks: Volumes of the blocks varied from 1.9 to 3.9 m^3 (67.1 to 137.7 ft^3), lengths from 1.5 to 2.3 m (4.9 to 7.5 ft), widths from 1.1 to 1.5 m (3.6 to 4.9 ft) and depths from 0.93 to 1.4 m (3.1 to 4.6 ft). The granite is competent and the stones are in good quality with very few visible cracks.

Blast holes: Two blast holes were drilled parallelly in each block with a hole spacing of 0.8 m (2.6 ft). The depth of the hole was 0.7 m (2.3 ft). Beneath one of the blast holes, a ϕ 19 mm (0.75'') cable hole was drilled through the block coaxially with the blast hole, see Fig. 2. This hole was used for the passage of the signal cable from the pressure gage. Various measurements will be carried out in this blast hole.

Blast holes in 4 of 8 blocks were lined with steel pipes. The wall thickness of the steel pipe was 1.5 mr (0.06'') and the length was the same as the blast hole. The gap between the pipe and the hole wall wa filled with a chemical grouting agent. Therefore, the acoustic contact between the pipe and the rock was very good to facilitate the propagation of the shock waves from the explosive into the rock.

The inner diameter of the steel pipe was 38.5 mm (1.51'') and holes with lining were drilled in 43 mm (1.7'') in diameter. Other blast holes without lining were drilled in 38 mm (1.5'') in diameter. Therefore, the final diameter of all the blast holes were approximately the same i.e. 38 mm (1.5'').

Charging method: The same explosive was charged in both holes in a block. The charge in each hole was a 0.5 m (1.6 ft) long and ϕ 17 mm (0.67'') cartridge. The packing material of the cartridge was a thin plastic pipe.

Holes with the steel pipe lining were not stemmed, so that the gases can be vented quickly. Meanwhile the holes without lining were stemmed by cement. The length of the stemming was approximately 0.2 m (0.66 ft).

Initiation: Holes in each block were initiated simultaneously by means of electronic detonators provided by Dyno Noble AB. Charges were initiated in the bottom of the holes to make the VOD measurements possible.

Instrumentation of the measuring hole: One of the two blast holes in each block was instrumented with a VOD probe and a LHM measuring cup. The VOD probe is a small but rigid resistance wire with a uniform resistance of 322.5 Ω/m (98.3 Ω/ft). The rate of resistance decrease in the wire was registered by a MiniTrap VOD Recorder and converted to VOD. The LHM measuring cup, as shown in Fig. 1, was mounted at the bottom of the blast hole. The signal cable was drawn through the cable hole and connected to a recording channel of a LeCroy digital oscilloscope, see Fig. 2. The cable hole was then refilled with cement. A pair of ionization pins were inserted into the upper end of the cartridge and the ionizatior f the pins by the detonating explosive was used to trigger the oscilloscope.

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Furthermore, a pair of accelerometers were mounted on the top surface of the block, symmetrically to the blast holes. Acceleration was recorded by a digital tape recorder, Sony SIR-1000.

Post-blasting analysis: The post-blast fracture patterns in the blocks were studied by a method which has been proven successful in many previous blasts (Olsson and Bergqvist 1996). Namely, after blasting, the blocks were cut by a rotary diamond saw perpendicular to the blast hole. On one of the new surfaces, a penetrant was sprayed so that the cracks became visible by naked eyes. Numbers and lengths of the cracks were then studied.

3 RESULTS

VOD: Records from all blasts are of high quality and the VOD values agree well with the expectation. VOD for Gurit B lies between 2210 and 2510 m/s (between 7251 and 8235 ft) and for the emulsion explosive between 4640 and 4740 m/s (between 15223 and 15551 ft). No obvious run-up or run-down was observed.

Vibration: It has been observed that the vibration records have a base frequency of 15 ~ 30 kHz. These frequencies are too high for the recording instrument, a Sony SIR-1000 digital tape recorder which has a bandwidth of 20 kHz. Therefore, the recorded vibration amplitudes are not reliable and no further analysis was made.

Borehole pressure: The records of all 8 borehole pressure histories were collected in Fig. 3. Following observations and analyses have been made.

- Generally speaking, the pressure histories from the low VOD Gurit B are smoother that those from the high VOD emulsion. This can imply that Gurit B works more gently than the emulsion explosive in the holes.

- A high frequency component is superimposed on the base signals. However, the amplitude of this component is much higher in holes with the emulsion explosive than in holes with Gurit B. The frequency of this component lies between 14 and 30 kHz. For each pressure history, the frequency coincides with the frequency in the corresponding vibration record. This fact indicates that the oscillation induced by the shock waves in the blocks resulted an oscillation of pressure in the boreholes. Moreover, the higher the VOD is, the stronger the oscillation in the borehole pressure is.

- The pressure decay in the holes with the emulsion explosive accelerates after approximately 0.5 ms of recording and the records continue to levels below zero. This phenomenon was caused by the heating of the carbon resistor, as observed by Wilson et al (1987). Therefore, the pressure records longer than 0.5 ms are not the true pressure histories in the holes with the emulsion explosive. Instead, they were a combination of the pressure decays in the holes and the heating of the resistors.

- The borehole pressures in the holes with Gurit B rapidly reached a quasi-static state. On the contrary, a rapid rising, high amplitude but short duration pulse has been recorded in the beginning of the borehole pressures in the holes with the emulsion explosive. After this, the borehole pressures reached the quasi-static state. This pulse was probably a result of the high detonation pressure from the emulsion explosive propagated through the air gap in the hole. According to the measurements, the amplitude of this short pulse can be as high as 0.65 GPa (6.5 kbar) while the duration is only approximately 25 μs. However, due to the limited response time of the gauge, the true amplitude of this pulse could not be measured. Nevertheless, it proves that the high VOD explosive does generate a high impact pulse on the borehole wall, while the low VOD explosive works on the wall more gently.

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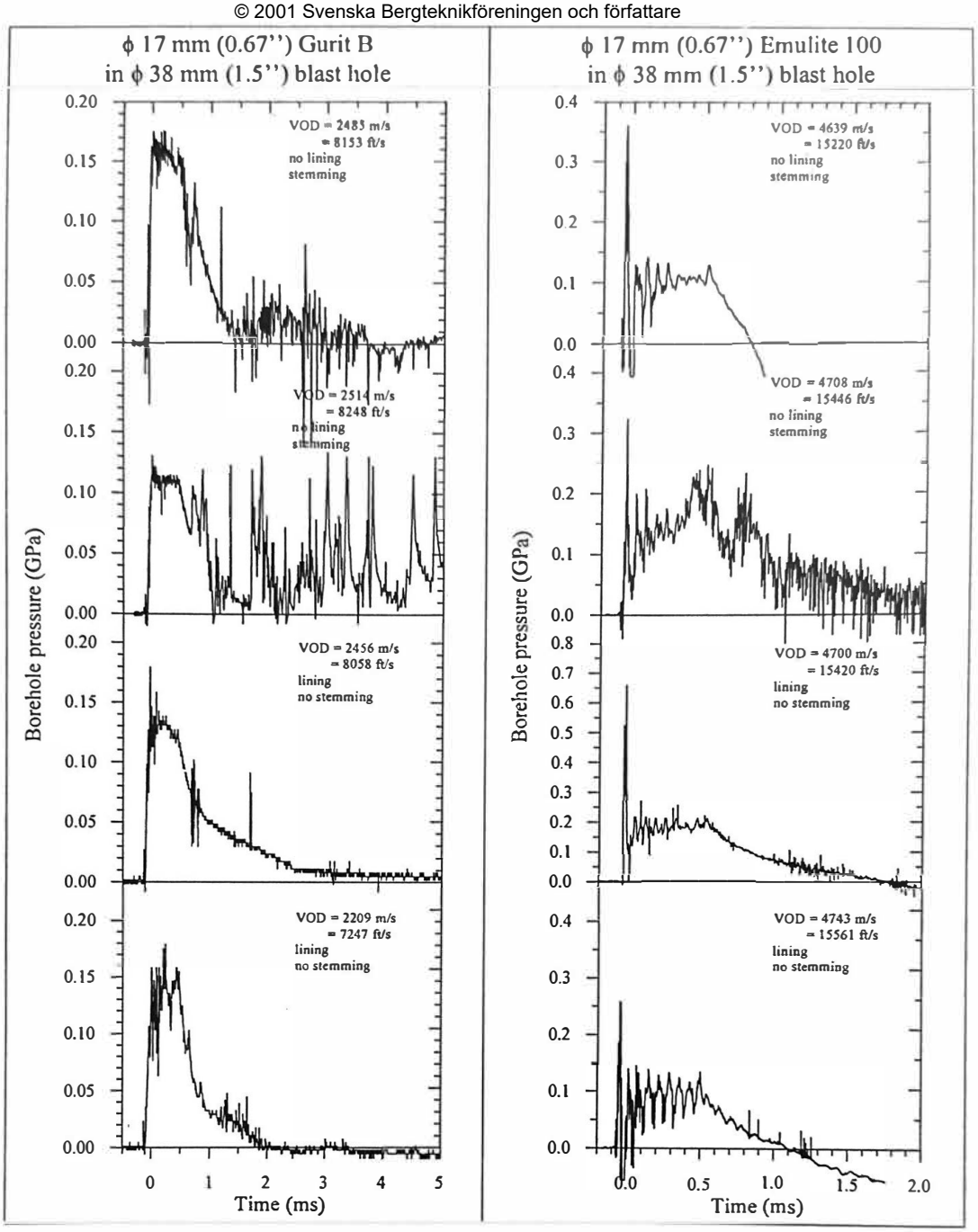

Fig. 3: Measured histories of the borehole pressure in all 8 blasts. In the figures, the VODs and charging conditions were also stated i.e. whether or not the hole was lined with a steel pipe and whether or not stemming was used.

- The pressure level at the quasi-static state is approximately 0.12 to 0.16 GPa (1.2 to 1.6 kbar) for Gurit B and 0.1 to 0.2 GPa (1 to 2 kbar) for the emulsion explosive. There is no significant difference between the two explosives. However, according to the following empirical formula based on earlier measurements ([1]Nie 1999), the borehole pressure in the holes with the emulsion explosive should be approximately 0.7 GPa (7 kbar) and in holes with Gurit B 0.15 GPa (1.5 kbar). The estimation differs much in the case of the emulsion explosive.

$$P_b = \frac{\rho_0 \cdot VOD^2}{8}\left(\frac{r_e}{r_b}\right)^2$$

Where: P_b = borehole pressure (Pa or 10 kbar)
ρ_0 = density of the explosive (kg/m^3 or 62.428·10^{-3} lb/ft^3)
VOD = VOD in the explosive (m/s or 3.2808 ft/s)
r_e = charge diameter (m or 3.2808 ft)
r_b = blast hole diameter (m or 3.2808 ft)

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- For Gurit B, the LHM measuring cup did measure the entire borehole pressure history. The duration of the borehole pressure is approximately 1.5 ms for holes with stemming and 2 ~ 3 ms for holes without stemming. This result is not expected. The possible explanation is that the holes without lining expanded much rapidly than the holes with lining. This rapid expansion might cause a more rapidly decay of the borehole pressure in the holes without lining, even though stemming was applied.

- For the emulsion explosive, it can be concluded that the duration of borehole pressure is longer than 1 ms. However, the exact pressure duration could not be determined from the measurements owing to the heating of the resistors.

Fragmentation: Field observations showed that when a blast hole was lined and no stemming was applied, the block did not fall apart after the blast, although the block was fractured by cracks. On the other hand, when stemming was applied, the fragments spread in a larger area.

Crack pattern: The crack patterns were studied on the cross sections perpendicular to the blast holes. Numbers and lengths of the cracks were recorded. Two major results are:

- In the vicinity of the blast holes charged with the emulsion explosive, a small crush zone was formed.

- Outside this crush zone, there is no significant difference in either the numbers or the lengths of the cracks induced by the two explosives.

However, it should be mentioned that it is difficult to analyze the fracture patterns in the blocks which were fallen apart after blasting. In those blocks, there is really no "remaining rock" in the traditional meaning as in a tunneling or bench blasting round. The longest cracks here are the cracks which broke the block into pieces. In our analysis, such cracks were excluded. Instead, the cracks in the largest remaining fragment are studied.

4 CONCLUSIONS

Fracture mechanism: The observation of fragmentation and study of the crack patterns indicated:

- The shock waves are responsible for fracturing rock, while the detonation gases are responsible for moving the fractured rock or throw.

- The detonation gases have no remarkable effect on the remaining rock. However, it can not be excluded that cracks can be widened or elongated by bending or swelling during the movement of the fractured rock.

Borehole pressure: The measurements of the borehole pressure history revealed how different explosives work on the rock.

- A low VOD explosive works more gently on the rock, while a high VOD explosive will subject the rock for high impact pulses.

- The pressure levels of the quasi-static borehole pressure are much lower than the predictions by the empirical formula for the high VOD emulsion explosive.

- The construction of the LHM measuring cup will be improved to protect the sensor from heating, so that the gauge can measuring the entire expansion process.

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