New Insight into the Methodology of Creating a Split Line for Protecting Hanging Wall Structures in Underground Mines

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Background

While working in an Northern Ontario underground nickel mine in the 90's, a problem arose that required the invention and design of a methodology using a shear line that could secure the integrity of a hanging wall (Norite) at the contact of an orebody where impurities were located. These impurities would affect the milling operation when mixed in with ore.

The idea was to develop a shear line (a controlled crack line – shear hole to shear hole) between the hanging wall contact and the rest of a blast to prevent the mixing of ore with the impurities. The shear line would stop cracking from the blast reaching and damaging the hanging wall. In theory this should prevent the impurities from mixing with the ore.
Electronic detonators were off in the distant future, so this author still had to cope with NONEL delays.

If the creation of a viable shear line was achievable, it could be extended to those cases when a hanging wall needed to be stabilized in the mining of narrow vein gold mines with the view of limiting dilution resulting from blasting close to the contact zone of host rock and gold veins. In this case shear blastholes would be drilled parallel to the ore contact at a set distance away to avoid damage to the contact.

Presplitting or splitting investigations in the past found that high gas producing explosives would produce a better fracture and might reduce or eliminate fine hairline cracks that may appear on borehole walls. In addition, there were claims the splitting action required the collision of stress wave reflections from adjacent shear holes from a shock viewpoint which may be in error.

This example/application of shear splitting in front of a hanging wall seemed to indicate that the shock wave magnitude from a detonating decoupled explosive might have had the strength to pull out scabs from the inside walls on opposite sides of shear boreholes. This scabbing action would create a notch that could easily concentrate gas expansion for the purpose of creating a well-defined split line. Figure 1 illustrates the idea of a scabbing mechanism produced by shock wave reflection from shear borehole walls.

In this case, it was desirous to use a high-shock cord based explosive (Primaflex) in order to create a notch from tensile scabs of adjacent borehole walls for gases to concentrate for the purpose of creating a well-defined split line.

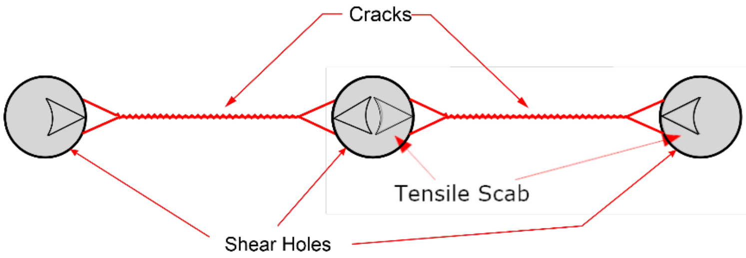


Figure 1 – Instead of borehole pressure and the hoop stress associated with splitting being the causative factors for this split design, the dynamic shock from the detonation wave front seems to have produced a reflection failuire at

the borehole wall generating scabs. Such a structure may have provided a notch as a focal point for gas expansion that generates and directs the cracking mechanism hole-to-hole forming the shear line.

The Problem

The first issue which had to be addressed, was that the blasting would be done in a blind stope – no topsill. Space would be needed to accommodate broken ore from blasted rings. Normally this is done using a blind raise placed in front of the contact zone. For this application, a different method would be used.

A concept - key to the protection of the ore contact required a shear line in front of the contact zone and would use fanned holes progressing upward to create void space. This is shown in Figure 2.

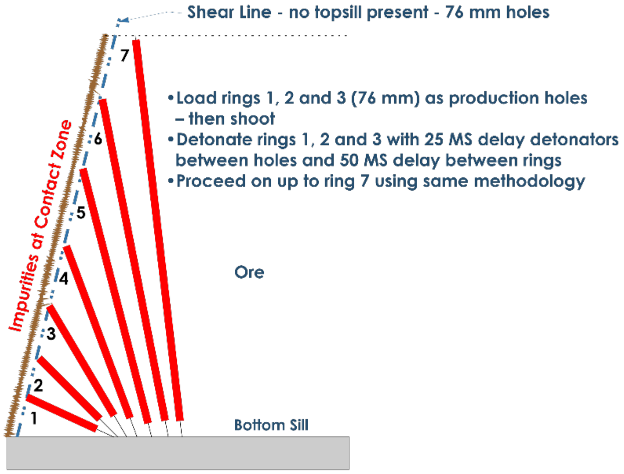


Figure 2 – The concept of creating a shear line using decoupled explosive charges placed at a distance from the contact zone with rings comprising fanned hole angled upwards in order to create void space for the broken ore. Production holes (fanned holes) and shear holes were 76 mm.

A Possible Solution

The shear line was drilled along the contact with a separation of 0.25 m from it. Shear holes were 76 mm diameter spaced 0.93 m apart with the angled (fanned) borehole toe ends kept roughly 0.5 m from the shear line. The production holes that were directed to the split line were 76 mm diameter. Rather than create a raise in front of the contact to break into, an attempt was made to gradually create space using the angled (fanned) production holes.

Primaflex was detonated with a double wrap of Scuf-Flex (12.3 gm/m – 60 gr/ft) all shear holes were capped in groups of 3 so that they detonated instantaneously.

Three production rings were taken at a time delayed using standard NONEL detonators. The delays were set at 25 MS between holes and 50 MS between rings.

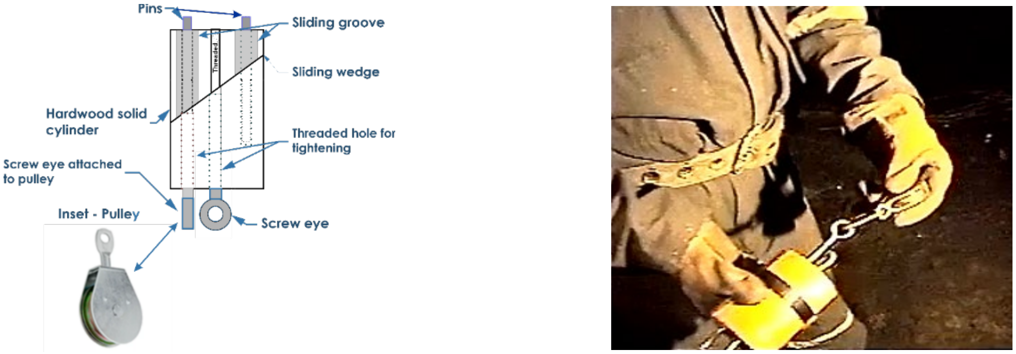
The hanging wall long section orientation shown in Figure 2 illustrates the position of the shear line with the contact zone and the borehole ends of the fanned holes. The contact zone was well defined and drilling the shear line posed no problems.

The shear line was fired first. A borehole camera was used to inspect the shear holes to ensure that a split line was in fact created as well as check on the tensile scabbing along the shear hole wall. The production holes were drilled remotely and then loaded pneumatically with ANFO.

Loading Upholes with High-shock Primaflex

Loading the shear holes with decoupled charges in upholes was a challenge and required the use of a wedge assembly made specifically for this application. The idea was to use a wedge pulley system along with nylon rope to pull double lengths of 85 gm/m (400 gr/ft) Primaflex to the top of each shear hole. The nominal diameter for a single length of Primaflex was 10.3 mm. Two lengths were used bringing the combined equivalent diameter to 14.6 mm. A total of 15 shear holes were drilled and detonated in groups of 3 separated by 15 MS delays. The shear line was detonated before the production holes were drilled.

The wedge assembly schematic is shown in Figure 3 frame 1. It was comprised of a machined wedge/solid hardwood cylinder with alignment pins and a screw "eye" in the center of a cylinder so that tightening the sliding wedge would expand to hold the complete assembly in place. The screw-eye provided the means of tightening the wedge assembly together against the borehole wall. To turn the screw-eye, blasting poles were modified with a slot to closely fit over the front portion of the screw-eye. A pulley was attached to a separate screw-eye that was offset from the wedge tightening screw-eye. Nylon rope was used via the pulley arrangement to hoist the Primaflex into place at the end of the borehole.



Frame 1 - General schematic of the wedge assembly for anchoring nylon rope in each shear borehole.

Frame 2 - The completed hardwood wedge assembly ready to be inserted into boreholes.

Figure 3 – Shows the wedge schematic in frame 1 along with a completed wedge assembly in frame 2 ready to be placed at the end of each shear borehole using a set of blasting poles.

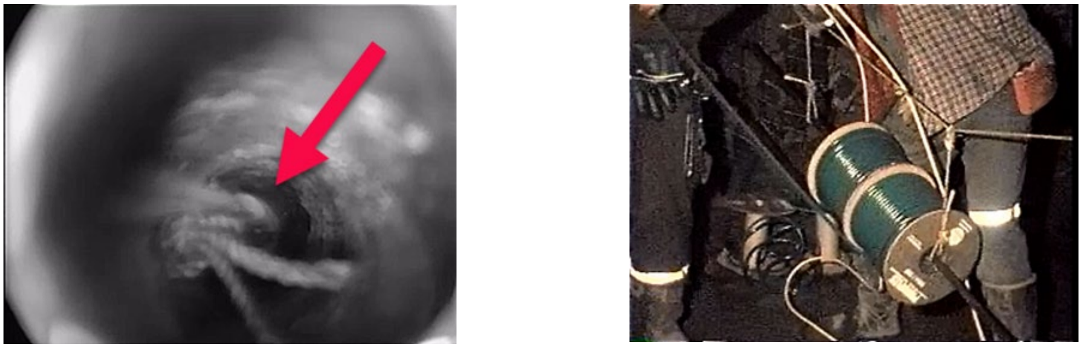
A wedge assembly was positioned and set at the end of each shear borehole using the blasting pole as an extended screwdriver. Figure 4 frame 1 shows the wedge just before insertion into a shear borehole. Frame 2 shows the wedge/blasting pole arrangement being inserted into a shear borehole.

Frame 1 – Wedge assembly ready to be inserted into shear borehole. A borehole camera would be used to ensure that the wedge had expanded to the shear borehole wall.

Frame 2 – Wedge assembly positioning with a blasting pole that acts like a giant screwdriver. Note that there are 3 wedge installations already set.

Figure 4 – Presents the methodology of using wedges to hoist decoupled explosives (in this case using Primaflex) into specially prepared shear boreholes to generate a shear split line.

In Figure 5 frame 1, a borehole camera inspection reveals an installed wedge assembly at the top of a shear hole ready to hoist the Primaflex into place. Frame 2 shows two lengths of Primaflex being loaded into the shear borehole from reels.



Frame 1 – Shows wedge and pulley assembly secured at the top of a borehole along with nylon rope.

Frame 2 – Loading 2 stands of Primaflex into shear boreholes using the wedge/pulley/rope method.

Figure 5 - Shows the methodology behind loading a decoupled explosive charge (Primaflex) into specially prepared boreholes drilled 0.93 m apart for generating a shear split line to protect the contact zone at the hanging wall.

Design Principles Using a High-shock Decoupled Charge to Create a Split Line

It should be noted here that the detonation reaction consists of two components, one due to shock (detonation wave shock) and the other due to gas expansion (thermochemical creating borehole pressure). Both are separate entities and combine to create rock/ore fragmentation particulate that is processed by mining operations. The thermochemical or borehole pressure has been found to be about 1/2 the detonation pressure. Primaflex is considered to be a low-gas explosive but high in shock and would promote the tensile scab on each side of a shear borehole wall to be formed.
Primaflex will generate 790 dm^3/kg or 790 l/kg in gasses.

The standard method for a split line setup using decoupled charges focuses on determining the thermochemical pressure from the splitting explosive and working out a decoupling pressure on the borehole wall. This method, therefore, relies on the gas expansion component of the detonation reaction. For the standard method, the dynamic tensile strength is used as a guiding factor for determining the spacing between holes for the split action to occur. In fact, to ensure a complete split between holes along a shear line, the actual dynamic tensile strength generating a consistent shear line for open cast mining would be a good match for developing perimeter control practices in low rock stress environments.
However for underground mining that is subject to significant ground control practices due to in situ stresses that are much higher than those found in surface mining, the preference would be to use a larger value of dynamic tensile strength as the limit for calculating spacing between holes for decoupled charges. The method applied here will rely on the shock component of the detonation reaction which is dynamic and will depend on the dynamic tensile strength used as the factor that promotes a clean split action between properly spaced shear holes - as well as the gas expansion component. Gas expansion from the detonation process is considered to be a quasi-static process acting over a longer period of time.
To get started, the detonation pressure of the explosive must be known. For Primaflex (a

military/molecular explosive) the detonation velocity is about 6500 m/s. The detonation pressure can be evaluated using the equation below;

$$\boldsymbol{P_d = \rho \times D \times W} \qquad \textbf{-1}$$

where:

P_d = **detonation pressure**
P = **explosive density**
D = **detonation velocity**
W = **particle velocity**

Particle velocity (W) has been experimentally evaluated as 1/4 of the detonation velocity of an explosive using flash X-Ray photography (closely approximates the value of the unconfined gas expansion velocity). The above equation then becomes;

$$\boldsymbol{P_d = \rho \times \frac{D^2}{4}} \qquad \textbf{-2}$$

The detonation pressure above should not be confused with thermochemical or borehole pressure. It is a shock pressure that travels from the blasthole out into the rock/ore mass preconditioning the media it is traveling through. It can produce microcracking along its path and when hitting a free face will reflect back into the transmission medium as a tensile wavefront. This is an important characteristic of this dynamic wave.

Most blasting personnel skilled in the art recognize the fact that it is the borehole pressure that does work on the borehole wall. This level of pressure creates enormous hoop stresses that is a primary mechanism for dissociating rock/ore structures and for providing the heaving action of an explosive. Thermodynamic or borehole pressure is the pressure available to do useful work due to gas expansion for a fully coupled charge against the borehole wall.
Borehole pressure is represented by this equation;

$$\boldsymbol{P_b = \rho \times \frac{D^2}{8}} \qquad \textbf{-3}$$

where:

P_b = **thermochemical or borehole pressure**

Primaflex used as a split explosive is completely decoupled in a 76 mm borehole to create the split line. The borehole pressure for this configuration needs to be evaluated - considering the differences between the effective diameter of two lengths of Primaflex (14.6 mm) and the shear hole diameter (76 mm). The shear hole length is 30 m with a 1 m collar. The effective borehole pressure for two lengths of Primaflex in a 76 mm diameter borehole is;

$$\boldsymbol{P_b = \rho \times \frac{D^2}{8} \times \left(\frac{r_c}{r_h} \times \sqrt{L_c}\right)^{2.4}} \qquad \textbf{-4}$$

where:

P_b = borehole pressure
ρ = explosive density
D = detonation velocity
r_c = equivalent radius of two lengths of Primaflex and separately - one length of Primaflex
r_h = radius of shear hole
L_c = percentage of column loaded

Parameter Values:

P_b = units of MPa
ρ = 1.391 gm/cc
D = 6500 m/s
r_c = 7.3 mm for two lengths of Primaflex and separately - 5 mm for one length of Primaflex
r_h = 38 mm
L_c = .93

Total gasses – 790 l/kg for Primaflex (PETN).
For one 25 m length the total weight (PETN) 85 x 25 = 2125 gm. For two lengths the total weight is 4250 gm (4.25 kg). This represents 3358 l of gas.
Considering that ANFO generates roughly 1000 l/kg of gas, aside from the fact that in this application, it could not be loaded, the quantity of gas generated would be much greater than that produced by Primaflex.

Calculations for Generating a Split Line between Shear boreholes

The important parameter for determining a good quality split line as far as rock properties are concerned is the tensile strength value. The tensile strength is highly dependent on structure so a range of values between the dynamic tensile strength and the static compressive strength is valid in calculating the spacing between shear boreholes.

Values of tensile strength that approach the dynamic compressive strength of a rock/ore type should not be used.

Substituting the parameter values listed above into the equation for P_b gives the following result for two lengths of Primaflex and one length of Primaflex:

Result Using Two Lengths of Primaflex:

$$P_b := 1.391 \cdot \frac{gm}{mL} \cdot \frac{\left(6500 \cdot \frac{m}{s}\right)^2}{8} \cdot \left(\frac{7.3 \cdot mm}{38 \cdot mm} \cdot \sqrt{0.93}\right)^{2.4} = 128.5\ MPa$$

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Result Using One Length of Primaflex:

$$P_b := 1.391 \cdot \frac{gm}{mL} \cdot \frac{\left(6500 \cdot \frac{m}{s}\right)^2}{8} \cdot \left(\frac{5 \cdot mm}{38 \cdot mm} \cdot \sqrt[2]{.93}\right)^{2.4} = 51.8\ MPa \qquad \textbf{- 6}$$

To generate the splitting action between shear boreholes drilled near the contact zone of the hanging wall, the following equation is presented;

$$S_p = d_h \times \left(\frac{P_b + T_s}{T_s}\right) \qquad \textbf{- 7}$$

where:

S_p = spacing between two boreholes containing decoupled charges
d_h = diameter of the shear borehole
P_b = thermochemical pressure (borehole pressure due to decoupled charge)
T_s = tensile strength – range between dynamic tensile strength and static compressive strength

Rock Properties of Norite

The values contained in the AEGIS database presented in Appendix A are based on dynamic measurements (modulus) taken using seismic methods. Note the values for the dynamic tensile strength as well as the static compressive strength. The pressure required to produce a split between shear boreholes should be between the range of 6.6 MPa and 138.9 MPa

Dynamic Tensile Strength for Norite – Regional Rock Type:

Dynamic Tensile Strength	*10.0*	*MPa*
	1450.4	*psi*

Because of the variation in tensile strength due to structure and in ground stresses, the tensile strength value to generate the split line can be much higher than standard measured values.

From equation 5, the borehole pressure P_b from two lengths of Primaflex is given as 128.5 MPa. Using the dynamic tensile strength of 10.0 MPa as a lower limit for the split line, the spacing between shear boreholes is calculated to be;

Presplit Spacing Based on Dynamic Tensile Strength with Calculations for Two Lengths and One Length of Primaflex

For Two Lengths of Primaflex:

$$S := \frac{76 \cdot mm \cdot (128.5\ MPa + 10.0 \cdot MPa)}{10.0 \cdot MPa} = 1.053\ m \qquad \textbf{- 8}$$

From equation 6, the borehole pressure P_b from one length of Primaflex is given as 51.8 MPa. Using the dynamic tensile strength of 10.0 MPa as a lower limit for the split line, the spacing between shear boreholes is calculated to be;

For One Length of Primaflex:

$$S := \frac{76 \cdot mm \cdot (51.8\ MPa + 10.0 \cdot MPa)}{10.0 \cdot MPa} = 0.47\ m$$

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To ensure that the tensile split is formed due to the tensile scab generated by a shock wave coming from the detonation of the Primaflex and reflected off the borehole wall, the magnitude of the dynamic tensile strength of Norite can be increased by 15% and 30% which is still well below the dynamic compressive strength of Norite estimated to be 166.7 MPa.

The input table for the spacing calculation at a 15% and 30% increase in dynamic tensile strength is given here for two lengths of Primaflex:

H_d (mm)	P_b (MPa)	T_{ds} (MPa)
76	128.5	10
76	128.5	11.5
76	128.5	13

-T1

The resulting spacing calculation produces the spacing between shear holes as;

$$S := \overrightarrow{\frac{H_d \cdot (P_b + T_{ds})}{T_{ds}}} = \begin{bmatrix} 1.053 \\ 0.925 \\ 0.827 \end{bmatrix} m$$

- **10**

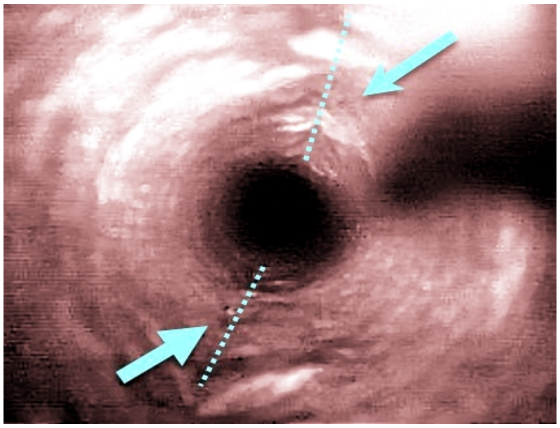
where:

S = spacing between shear holes (mm)
H_d = shear hole diameter (mm)
P_b = decoupled borehole pressure (MPa)
T_{ds} = dynamic tensile strength (MPa)

Results for Split Line Near Hanging Wall

For two lengths of Primaflex decoupled in a 76 mm diameter shear hole, the borehole pressure generated was 128.5 MPa which is well over the dynamic tensile strength value of 10 MPa for Norite. With this amount of stress, it was anticipated that tensile wedges would be pulled out (scabbed) of the shear hole wall. A schematic of this event is represented showing first, the cleanly split shear holes and second, the borehole camera image of both scabs and hairline split created at the shear hole wall.

Frame 1 - Shear holes are split cleanly using two Primaflex lengths with a 15% increase in dynamic tensile strength – 11.5 MPa from Table T1.



Frame 2 - Borehole camera view of scabbing on borehole wall due to reflective shock after detonating lengths of Primaflex in 76 mm boreholes.

Figure 6 – Note the half holes generated by the use of Primaflex in small diameter shear boreholes that primarily used shock wave impact on adjacent borehole walls creating a tensile wedge failure providing a split path.

Synopsis

Using a high-shock detonating cord, in this case Primaflex, tensile scabs were created in shear boreholes providing focal points for borehole pressure to concentrate in producing a clean split line along the plane of weakness by the shear holes. At the time, instantaneous initiation using high gas explosives such as ANFO, was considered to be a contributor to ragged break along the shear line. Since Primaflex was a shock contributor, this effect was not observed. With the use of new technology in the form of precision delays using electronic detonators, a new timing scheme could be considered.

Observations

1. To produce a shear line using high shock-based explosives similar to Primaflex, calculate a decoupled borehole pressure using a value for tensile strength well over the actual value of dynamic tensile strength for a particular rock/ore type. Make sure that the value chosen is well below the dynamic compressive strength for the same rock/ore type.

2. When detonating a shear line, divide up the number of shear holes that fire instantaneously for the minimum number possible. For the application discuss here, 15 shear holes were grouped in threes so that only 3 holes were fired instantaneously.

Recommendations for Future Work

The use of electronic detonators in splitting applications has not been seriously investigated. From the standpoint of using gassy explosives such as ANFO as a split explosive in underground mining is an investigation unto itself.

Electronic detonators have scatter around 0.01% for any programmed delay interval that can be up to 20 seconds. Noting that firing all shear boreholes instantaneously might produce damage simply because of the concentration of charge energy, an alternate timing using electronic detonators may be appropriate and more exact.

Using the above example, the distance between shear holes was 0.93 m. Using the P wave velocity of the rock/ore, in this case 4030 m/s, timing could resolve to a time interval of 0.226 MS (the distance from hole to hole of the shear boreholes divided by the P wave velocity). To allow time for the detonation of the split explosive to complete, the length of the Primaflex used, divided by its velocity would be 4.2 MS. Adding the two events together would produce an overall time delay of 4.4 MS between shear boreholes.

Simple formulae can be developed to provide the time delay for each shear borehole forming the split line as shown here (for use with electronic detonators only);

$$t_{delay} = t_{exp} + T_{pw} \qquad \text{-11}$$

$$G_w = \sum_{n}^{n+1} t_{delay} \qquad \text{-12}$$

where:

t_{delay} = total time delay
t_{exp} = time for the length of explosive charge to detonate
T_{pw} = time for the P wave to reach an adjacent shear borehole (spacing between shear boreholes)
G_w = time delay for the nth shear borehole in a series of shear boreholes
t_{delay} = time for complete detonation of a charge having a specific length
n = shear borehole number

For the above illustration, the parameters are listed here:

Parameter Values:

t_{exp} = 4.154 MS
T_{pw} = 0.226 MS
n = 15

$$t_{delay} := t_{exp} + T_{pw} = 4.38\ ms \qquad \text{-13}$$

$$G_w := \sum_{n=1}^{n} t_{delay} = 65.695\ ms \qquad \text{-14}$$

The time for complete detonation of the split line using 15 shear boreholes is 65.695 MS.

Appendix A – Rock Properties for Norite

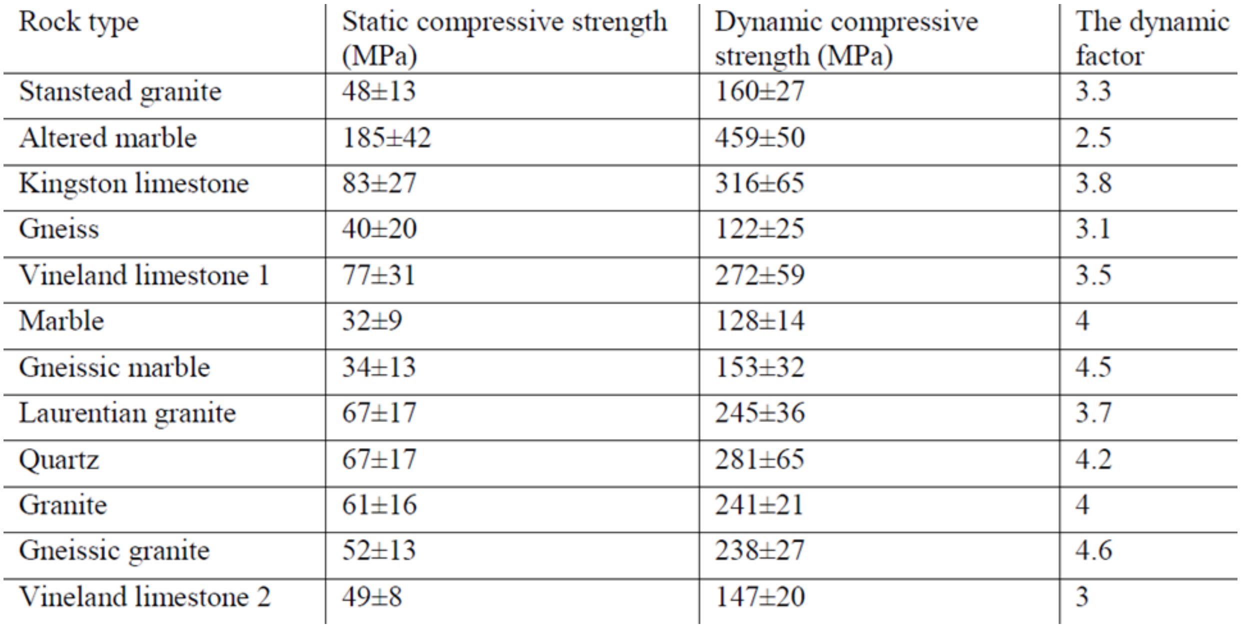
Rock Properties – Norite

Rock Name	*NORITE HOST ROCK LOW STRENGTH*	
Alias		
Type	*REGIONAL METAMORPHIC ROCK*	
Information Source	*MINE SPECIFIC*	
P-Wave Velocity	*4030.1*	*m/s*
S-Wave Velocity	*2262.1*	*m/s*
Young's Modulus	*39.6*	*GPa*
Bulk Modulus	*28.7*	*GPa*
Shear Modulus	*15.6*	*GPa*
Poisson's Ratio	*0.3*	
Impedance	*12267664.9*	*Pa·s/m*
Fracture Index	*0.1*	
Crack Velocity	*248.2*	*m/s*
Density	*3.0*	*g/cc*
Specific Density	*0.3*	*cc/g*
RMR	*81*	
Q	*50*	
JRC	*8*	
Static Tensile Strength	*3.9*	*MPa*
Dynamic Tensile Strength	*10.0*	*MPa*
Strength Ratio	*2.6*	
Insitu Tensile Strength	*3.7*	*MPa*
Insitu Compressive Strength	*61.6*	*MPa*
Static Compressive Strength	*65.2*	*MPa*
Dynamic Compressive Strength	*166.7*	*MPa*

From AEGIS Database for Rocks/Ore

Appendix B – Comparison of Dynamic and Static Compressive Strengths

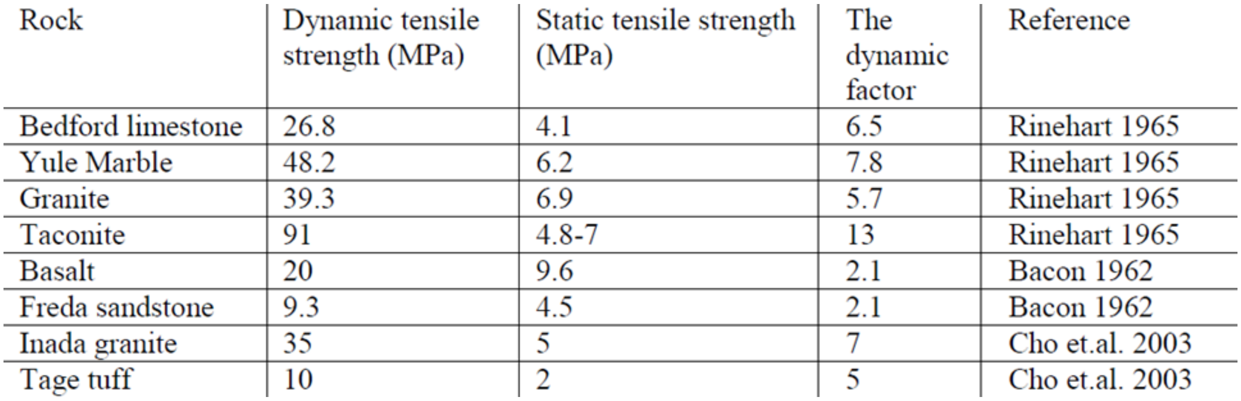
(Rinehart, Bacon Cho and Changshou Sun)



Rock type	Static compressive strength (MPa)	Dynamic compressive strength (MPa)	The dynamic factor
Stanstead granite	48±13	160±27	3.3
Altered marble	185±42	459±50	2.5
Kingston limestone	83±27	316±65	3.8
Gneiss	40±20	122±25	3.1
Vineland limestone 1	77±31	272±59	3.5
Marble	32±9	128±14	4
Gneissic marble	34±13	153±32	4.5
Laurentian granite	67±17	245±36	3.7
Quartz	67±17	281±65	4.2
Granite	61±16	241±21	4
Gneissic granite	52±13	238±27	4.6
Vineland limestone 2	49±8	147±20	3

Appendix C – Comparison of Dynamic and Static Tensile Strengths

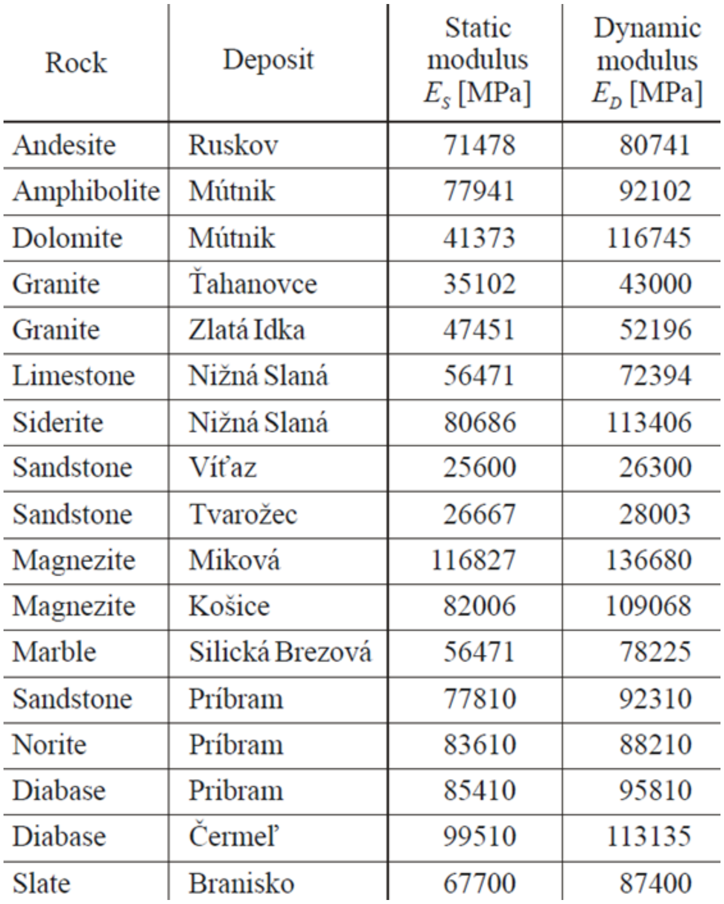
(Rinehart, Bacon Cho and Changshou Sun)



Rock	Dynamic tensile strength (MPa)	Static tensile strength (MPa)	The dynamic factor	Reference
Bedford limestone	26.8	4.1	6.5	Rinehart 1965
Yule Marble	48.2	6.2	7.8	Rinehart 1965
Granite	39.3	6.9	5.7	Rinehart 1965
Taconite	91	4.8-7	13	Rinehart 1965
Basalt	20	9.6	2.1	Bacon 1962
Freda sandstone	9.3	4.5	2.1	Bacon 1962
Inada granite	35	5	7	Cho et.al. 2003
Tage tuff	10	2	5	Cho et.al. 2003

Appendix D – Comparison of Static and Dynamic Modulus

(Rinehart, Bacon Cho and Changshou Sun)



Rock	Deposit	Static modulus E_S [MPa]	Dynamic modulus E_D [MPa]
Andesite	Ruskov	71478	80741
Amphibolite	Mútnik	77941	92102
Dolomite	Mútnik	41373	116745
Granite	Ťahanovce	35102	43000
Granite	Zlatá Idka	47451	52196
Limestone	Nižná Slaná	56471	72394
Siderite	Nižná Slaná	80686	113406
Sandstone	Víťaz	25600	26300
Sandstone	Tvarožec	26667	28003
Magnezite	Miková	116827	136680
Magnezite	Košice	82006	109068
Marble	Silická Brezová	56471	78225
Sandstone	Príbram	77810	92310
Norite	Príbram	83610	88210
Diabase	Pribram	85410	95810
Diabase	Čermeľ	99510	113135
Slate	Branisko	67700	87400