*Rock Fragmentation by Blasting – Sanchidrián (ed)*
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# Control of rock fragmentation and muck pile geometry during production blasts (environmentally friendly blasting technique)

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ABSTRACT: This paper presents improvements of the blasting efficiency in open pit mines. The aim of the study is the development of an environmentally friendly, low-emission production of dimension stone and gravel in six different quarries by optimizing the blasting technology. Almost 60 blasts were performed and recorded. The individual blast designs base on the objective evaluation of the blastibility of the rock mass in each quarry and the principles of the momentum theory. Significant solid rock and solid rock mass properties, the geometric, blasting and ignition parameters plus the most crucial values of the blasting result were collected and analysed systematically. The muck pile composition and 3D joint pattern of the rock mass were determined by an area-related and photo-supported analytical method which allows the quantitative evaluation of the fragmentation effect. An optimal application of the ignition sequence leads to an improved energetic utilisation of the used explosive, with a higher fragmentation of the muck pile and an increased throw-off. Each type of rock mass shows a specific joint system and rock specific acoustic impedances. It is shown that the optimal blasting parameters can only be derived by considering these two important parameters. However, a postulation of a general energy balance of the used explosives for production blasts is currently not possible.

## 1 AIMS OF THE STUDY

Despite a number of innovative theoretical approaches a practically reliable and physical evaluation of the detonative reaction of the used explosives in a rock mass with all its related effects is still lacking. The available methods for

– the charge weight calculation and
– the dimensioning of the blasting system

are empiric for different aims of the blast. In order to change this situation the research project ‘environmental blasting technique’ under the leadership of the Movement and Blasting Consulting, Leipzig in cooperation with the TU Mining Academy Freiberg, Institute of Mining and Special Heavy Construction and Institute of Mine Surveying and Geodesy has been executed since February 2007. The project is supported by the Deutsche Bundesstiftung Umwelt DBU.

The aim of the study is the development of innovative, low-emission and flexible blasting methods for the environmentally friendly production of construction material from natural stone. For that the systematic improvement of the blast design, drilling and ignition parameters is necessary to achieve the most efficient detonative reaction of the used explosives. However, the perfect blast design is only realisable if the orientation of the joint system of the rock mass is considered.

It is demonstrated how an improved energetic utilisation of the used explosives can be guaranteed. The application of these improved techniques results in a pollution, e.g. vibrations impacts to the environment, at the lowest possible level during the fracturing of the muck pile. Finally, the sizing of the charge weight has to be adjusted to the geometric, blasting and ignition parameters on the base of a physically supported model. This model is unique for each quarry according to the particular natural conditions and the aim of the blasting.

The aforementioned modifications and improvements have to be applied in the way that the side effects are reduced, in particular the vibration emissions and disturbance of the residents. This aspect is discussed in a related article (Müller et al. 2009b), while the actual one will only focus on control mechanism of rock fragmentation and muck pile geometry.

Last but not least a better understanding of the relationships and interactions between the drilling, ignition and blasting techniques with the induced vibrations is essentially for a physically based, statistically proved and applicable vibration forecast and evaluation (Müller et al. 2009a, b).

The proposed methodology guarantees the environmentally friendly, low-emission production of fractured natural stone if the blast design is adjusted and optimised to the local situation of the quarry site.

## 2 THEORETIC BACKGROUND

### 2.1 *Determination of the rock resistance to blasting in the test quarries*

The blasting tests were performed in-situ in different types of rock masses and under normal mining conditions. The following German quarries were chosen (Table 1):

The different conditions in the test quarries were evaluated using the classification of Müller (2007) of rock and ground according to the rock-, tunnel- and blasting engineering (Figure 1). The classification was applied to guarantee the objective comparability and a scientific validation of the local conditions. The measured acoustic impedance of the rock is plotted at the ordinate and the average frequency of joint planes of the particular directions at the abscissa (Figure 1). The average frequency of the joint planes was determined in-situ in the quarries. An objective classification of the rock mass according to the following criteria was established including the parameters mentioned above:

– resistance to blasting/solidity for exploitation above and underground
– solidity for excavation in tunnels and caverns
– sensitivity to vibration.

Table 1. Testing sites and associated rocks with indication of the resistance to blasting/blastibility according to the classification in Figure 1 (Müller 2007).

| No. | Quarry | Rock |
|---|---|---|
| 1 | Elbingerode | accretionary limestone (compact limestone) |
| 2 | Lueptitz | rhyolite (subvolcanic) |
| 3 | Winterberg | accretionary limestone (compact limestone) |
| 4 | Goersdorf | gneiss |
| 5 | Leukersdorf | rhyolite and rhyolite-pyroclastics (effusive) |
| 6 | Koschenberg | metaclastics/ metagreywacke |

Decrease of the resistance to blasting ↓

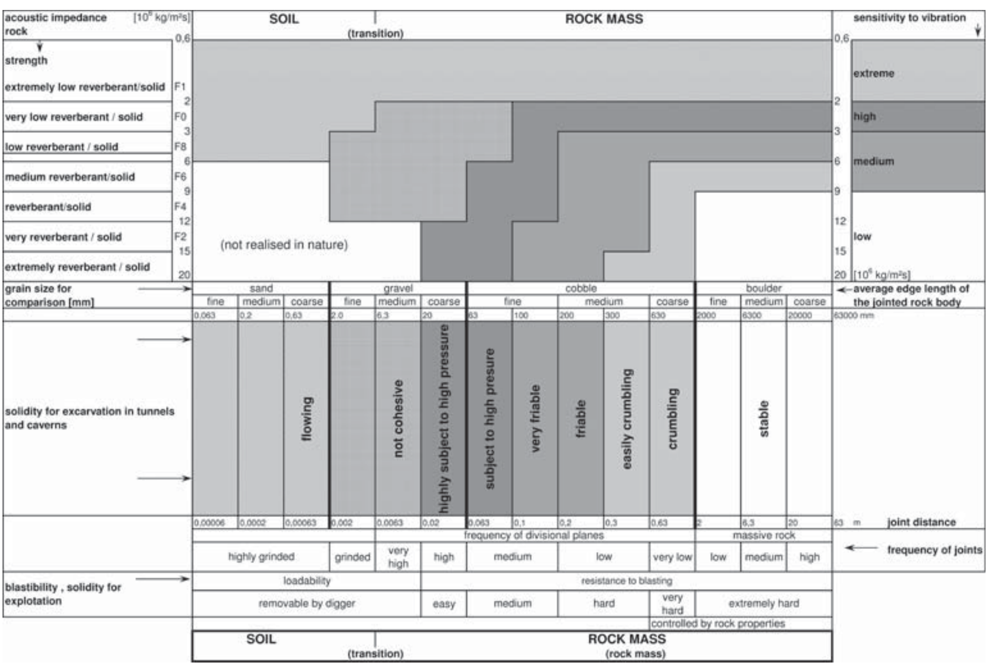


Figure 1. Rock mass and rock classification for rock and tunnel engineering and blasting technique (Müller 2007).

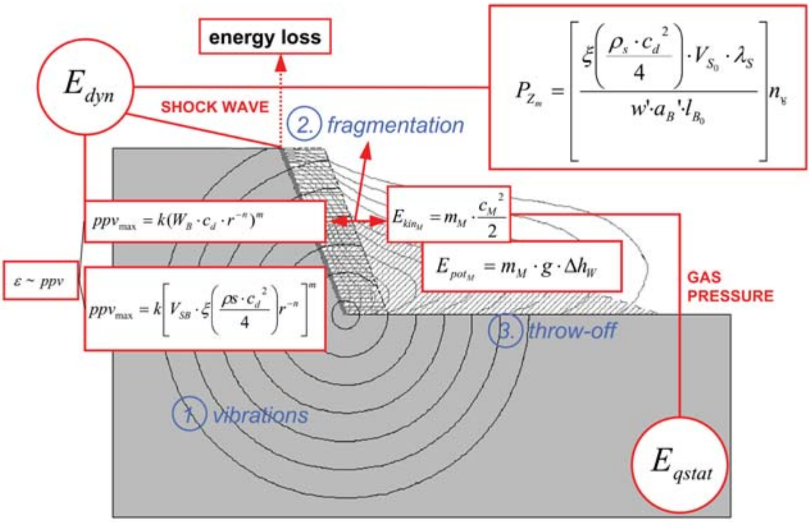


Figure 2. Physical effect model of a detonative reaction of explosives in a rock mass.

The fundamental importance of these initial parameters, which are constitutional values of the resistance to blasting or blastibility, is well understood and had been verified by previous studies (Franklin & Katsabanis 1996, Müller 1974, Heinze 1993).

Figure 3 shows the measured acoustic impedances of the specific rock masses detected by supersonic-measurements. The cumulative curves of the joint distances of the three main joint directions are charted exemplary for the quarries Koschenberg, Lueptitz and Elbingerode in Figure 4.

The determined characteristics of the rocks and the rock masses were used as the basis for the classification of the resistance to blasting, statistical evaluation of the fragmentation size of the muck pile, and study of other corresponding correlations of main interest. Joint plane orientations and joint distances are the most important features of the rock mass affecting substantially the drilling and blasting result (Müller 1974, Heinze 1993, Moser 2005, Ouchterlony & Moser 2006). The blast effects are not interpretable without the knowledge of the joint plane system of the particular quarry site. For this reason the blasting tests were done under realistic mining conditions.

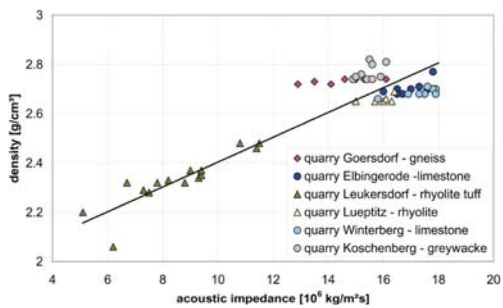


Figure 3. Correlation between the acoustic impedance and the rock density in the test quarries—initial rock parameters for resistance to blasting/blastibility (see Figure 1).

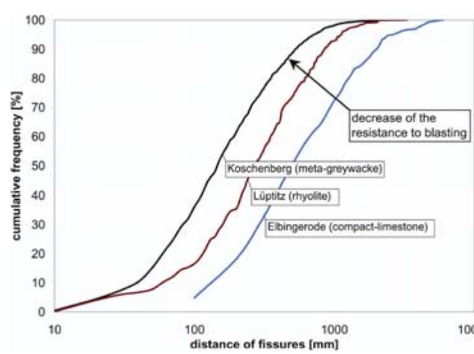


Figure 4. Cumulative curve of the three combined main joint directions for the metagreywacke (Koschenberg), rhyolite (Lueptitz) and limestone (Elbingerode) rock mass.

## 2.2 *Application of the principles of the momentum theory*

The practise-oriented study bases on the momentum theory for the detonative reaction of explosives. The application of the momentum theory allows the energetic evaluation of the action and the complete utilisation of the available blasting energy (Müller & Böhnke 2001). This presents a further development of the mentioned theory.

The rock mass remaining in situ during and after the blast (Rock Massive = *RM*) is hit by an impulse which originates in the explosive pressure:

$$I_{RM} = F \cdot \Delta t \qquad (\text{N·s}) \tag{1}$$

where:

$I_{RM}$ = momentum to the rock mass (N·s)
$F$ = force (N)
$t$ = time (s)

The phenomenon can be compared with the blowback of a firearm. Therefore, the induced vibration emissions can be interpreted as an impulse- or energy-distance-relation. The application of the momentum theory to the blast-induced emission allows vibration prediction (Müller et al. 2007, 2009a, b).

The so called blasting mass ($m_M$) is the muck pile (muck pile = $M$) which is the fractured rock mass thrown-off during the blast with the detected blow-out velocity ($c_M$). During this process the angular momentum can be determined as follows:

$$I_M = m_M \cdot c_M \qquad \left(\frac{\text{kg} \cdot \text{m}}{\text{s}}\right) \tag{2}$$

$$E_{kin_M} = \frac{m_M \cdot c_M^2}{2} \qquad \left(\frac{\text{kg} \cdot \text{m}^2}{\text{s}^2}\right) \tag{3}$$

where:

$I_M$ = momentum (kg m/s)
$E_{kin_M}$ = kinetic energy of the muck pile (kg m²/s²)
$m_M$ = muck pile mass (kg)
$c_M$ = blow-out velocity of the muck pile (m/s)

It is allowed to use this value under defined boundary conditions for calculations of the kinetic energy (3) of the muck pile. Optimal sizing of the charge weight and procedural methods are evaluated on the basis of the reacted energy of the explosives, their distribution in the blast design and the ignition sequence. In order to apply the principles of blasting on the base of the momentum theory suggested by Müller & Böhnke (2003) the ignition patterns has to be uniformly designed.

An example of a successfully applied ignition sequence is given in Figure 5 (Fischer et al. 2006). Evidence should be made that the simultaneous ignition of neighboured charges has a positive impact to the utilisation of the usable detonation energy. If the shock waves of the charges interfere with each other (see Figure 6), a similar throw-off should be possible (Figure 5).

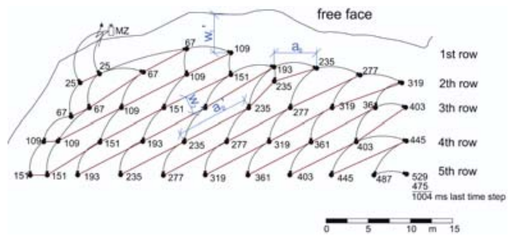


Figure 5. Drilling and ignition pattern of a test blasting with explanation; $w'_{1/2}$—blasted burden of the 1st row and the other rows (= blasted row distance $a'_R = W'_2$) (Fischer et al. 2006).

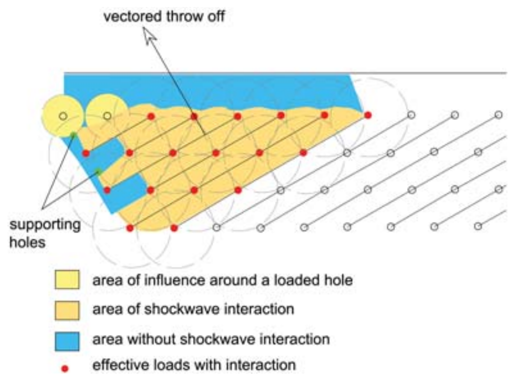


Figure 6. Principle of shockwave superpositioning during simultaneous ignition of charges according to the momentum theory.

## 3 USED MEASURING TECHNIQUES FOR DETECTION OF IMPORTANT INITIAL PARAMETERS

### 3.1 *Measurement of dynamic rock parameters*

The determination of the acoustic impedance of rocks according to Figure 1 is of practical interest for the evaluation of the resistance to blasting (Figure 1) (Müller 2007). In addition, the rock-dynamic measurements provide a number of interesting values which can be of essential importance within the evaluation of the blasting process.

The used instrument is a supersonic measurement system called UKS-D which is composed of the supersonic generator USG 40, the detector unit and a PC-oscilloscope called Pico Scope 3224. The solid rock samples used for measurement have to be extracted by core drilling and prepared to slenderness ratio 1:2.

The following characteristics can be precisely detected without destruction of the sample:

– acoustic impedance (density · P-wave velocity)
– dynamic elasticity modulus (Young's modulus)
– rigidity modulus
– P-wave velocity
– Rayleigh-wave velocity
– S-wave velocity
– Poisson's ratio.

The acoustic impedances of the rocks from the quarries studied are plotted in Figure 3.

### 3.2 *Detection of the geometric parameters and distances using LASER-techniques*

Using the 3D-laser scanner of the Institute of Mine Surveying and Geodesy at the TU Mining Academy Freiberg each blasting system and the blasted muck pile was measured before and after the blasting. The 3D data were utilised to calculate the volume of the blast design and muck pile, the loosening of the muck pile and other important geometric values (compare Figures 7 and 8).

In addition, the positions of the boreholes, the sites of the geophones, strain- and radar-sensors were surveyed using the laser distance instrument LEM 300 Geo. Both used laser systems were gauged to the benchmarks of the general quarry survey in order to get the exact position of the blasting system inside of the mine. In doing so, the orientation of the blasting system to geographic north and to the present joint plane system can be detected.

### 3.3 *Measurements with the radar sensor*

Results of record and calculation of the blow out velocity of the blasting mass were presented before e.g. by Bode et al. (2003). The authors used a modified rain radar sensor. The sensor is installed in a safe distance at ≥300 m in front of the intended blast. The radar beam has to be adjusted to the free face of the blast design. The so-called Doppler effect allows the measurement of the blowout velocity ($c_M$) of a production blast by radar (radio detection and ranging). In this way the blowout velocity of the moved muck pile can be recorded for a larger section of the blasting system.

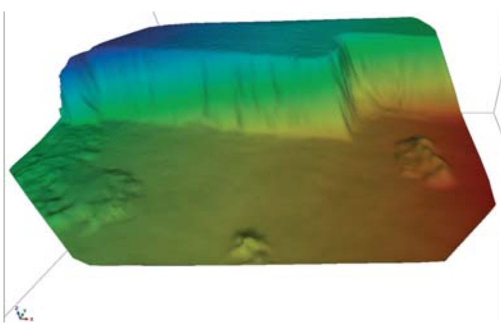

Figure 7. Laser scanner supported detection of the bench and the blasting system before blasting; The false colour plot is used to image the details of the bench morphology.

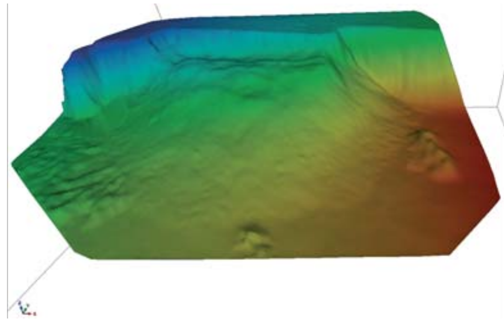

Figure 8. Laser scanner supported detection of the muck pile volume, the loosening and the new created bench; The false colour plot is used to image the details of the bench morphology.

For the purpose of interpretation the three recorded parameters have to be combined. The first parameter is the reflectivity, which relatively or indirectly indicates the size of a particular flying mass portion of the muck pile. The second is the blowout velocity and the third the time ($t$). In doing so, the average blowout velocity can be calculated (Müller & Böhnke 2003).

### 3.4 *Muck pile analysis*

In order to verify the achieved fragmentation effect after the blasting a muck pile analysis was required. Because previously applied automated photogrammetric grain size analyses turned out to be too imprecisely for this study, a new, manual, photo-supported analysis was developed by the authors on the base of the DIN 66175 (1976) and Franklin & Katsabanis (1996). The method allows the derivation of data, which utilises a straight line within the Rosin-Rammler-Sperling-Bennet grain size distribution diagram (RRSB). The muck pile analysis suggested is done stepwise separated for the surface and the interior as follows:

1. Photographic documentation of the surface and the interior of the muck pile using a high resolution digital camera, each with 10 pictures plus a benchmark 2 × 1 m in size
2. Skewing of the photos according to the benchmark within the pictures in order to get true in scale photos

3. Classification of defined grain sizes (>16 mm) according to the plane method
4. Enumeration of the grain sizes and calculation of the grain size percentages
5. Charting of the grain size distribution as cumulative curve and a straight line within the RRSB-grain size distribution diagram (DIN 66145, 1976; Rosin-Rammler-Sperling-Bennet with the special scaling for grain analysis data)
6. Determination of muck pile related values like average grain size, directional factor (slope) and the muck pile index as a multiplication of the values aforementioned
7. Calculation of the specific surface of the fragmented muck pile and the present composition of the jointed rock bodies.

In order to get an objective record of the real fragmentation effects of the blasting tests (Müller 1974), the grain size distributions were compared with the joint body dimension of the rock mass. The developed and described methodology generates a higher resolution of the small grain size fraction down to 16 mm and more precise grain size curves of the blasted muck pile in comparison with other methods.

### 3.5 *Vibration measurements*

In addition to the aforementioned gained data vibration and strain measurements were done. Therefore multiple 3-component-geophones and strain sensors (Baumann & Müller 2000) were installed in the close-up and the far range of the blast site. The data and the found coherencies are presented in another publication (Müller et al. 2009a, b).

## 4 RESULTS

### 4.1 *The physical effect model of the detonative reaction of explosives*

In the following a model of the detonative reaction of explosives is suggested, which bases on the energetic analysis of all blast influencing parameters. The simplified model plotted in Figure 2 is the result of the data analysis. Great attention was paid to physically provable parameters during the development of the model and, in particular, to the better understanding of the energetic processes.

The terms in Figure 2 and the formulas (4) to (13) are defined in Table 2.

The measurement results and literature data indicate that the explosive density and detonation velocity are the main factors affecting the dynamic energy ($E_{dyn}$) during the 1st blasting phase (e.g., Cooper 1996, Heinze 1993, Persson et al. 1994, Rossmanith & Müller 2001). The detonation pressure can be calculated according to Cooper (1996) as follows:

$$P_0 = \left(\frac{\rho_s \cdot c_d^2}{4}\right)\left(\frac{\text{kg}}{m \cdot s^2}\right) \tag{4}$$

The utilisation of the correlation (5), which includes the pressure formula, allows the calculation of the possible energy of the blasting charge $E_s$ in the blasting system:

$$E_s = V_s \cdot \left(\frac{\rho_s \cdot c_d^2}{4}\right)\left(\frac{\text{kg} \cdot \text{m}^2}{s^2}\right) \tag{5}$$

Table 2. Terms and units.

| Symbol | Term | Unit |
|---|---|---|
| $w'$ | average blasted burden | m |
| $a_B'$ | average blasted borehole distance | m |
| $l_{Bo}$ | unit length of one borehole [1 m] = const. | m |
| $n_{Vo}$ | number of unit volumes | – |
| $c_d$ | detonation velocity | m/s |
| $\Delta h_w$ | proportionate bench- or throw height | m |
| $V_o$ | unit volume as a product of $w' \cdot a_B' \cdot l_{Bo}$ [$l_{Bo}$ = 1 m] of one borehole | m³ |
| $V_{so}$ | volume of explosive for blasted unit volume $V_o$ | m³ |
| $V_{SB}$ | volume of explosive in one borehole | m³ |
| $V_s$ | volume of explosive of the whole blasting system | m³ |
| $\xi$ | fill factor (volume of explosive vs. volume of the borehole) | – |
| $\lambda_s$ | spacing (borehole distance vs. burden) | – |
| $\rho_s$ | explosive density | kg/m³ |
| $c_M$ | Blow-out velocity of the muck pile | m/s |
| $m_M$ | muck pile mass | kg |
| $W_B$ | charge weight of one borehole | kg |
| $q$ | specific charge | kg |
| $P_o$ | detonation pressure of the explosive | kg/m s² = Pa |
| $P_{Zo}$ | effective detonation pressure of the explosive per unit volume | kg/m s² = Pa |
| $P_{ZM}$ | effective detonation pressure of a blasting system | kg/m s² = Pa |
| $E_{kinM}$ | kinetic energy of the muck pile | kg m²/s² = J |
| $E_S$ | energy of the blasting charge | kg m²/s² = J |
| $E_B$ | energy of the charge weight of one borehole | kg m²/s² = J |
| $E_{potM}$ | potential energy of the muck pile | kg m²/s² = J |
| $E_{dyn}$ | dynamic energy | kg m²/s² = J |
| $E_{qstat}$ | quasi static energy | kg m²/s² = J |
| $AGSM$ | Average Grain Size Mass ($AGSM$)—product of the spherical volume of the representative grain size ($d$ = 63.2%) in the cumulative curve and the rock density | kg |
| $g$ | acceleration due to gravity = 9.80665 | m/s² |

The charge weight of one borehole $W_B$ contains the energy (6):

$$E_B = V_{SB} \cdot \left(\frac{\rho_s \cdot c_d^2}{4}\right) \left(\frac{\mathrm{kg \cdot m^2}}{s^2}\right) \quad (6)$$

The smallest blasted volume $V_o$—called unit volume (7):

$$V_0 = w' \cdot a_B \cdot l_{B0} (\mathrm{m^3}) \quad (7)$$

is calculated from the volume of explosive $V_{so}$ using the specific charge $q$ and the explosive mass. The single values for $w'$ and $a_B'$ have to be taken from the documented blasting system (Figure 5). It's generally known and accepted that a high fill factor $\xi$ and a large spacing $\lambda_s$ increases the blasting effect. Based on this relationship, the created effective detonation pressure per unit volume $P_{Zo}$ can be calculated as follows (8):

$$P_{Z0} = \frac{\xi\left(\frac{\rho_s \cdot c_d^2}{4}\right) \cdot V_{S0} \cdot \lambda_S}{w' \cdot a_B' \cdot l_{B0}} \quad \left(\frac{\mathrm{kg}}{\mathrm{m \cdot s^2}}\right) \quad (8)$$

Formula (9) is the result of mathematical reduction of formula (8):

$$P_{Z0} = \frac{\xi\left(\frac{\rho_s \cdot c_d^2}{4}\right) \cdot V_{S0}}{w'^2 \cdot l_{B0}} \quad \left(\frac{\mathrm{kg}}{\mathrm{m \cdot s^2}}\right) \quad (9)$$

The effective detonation pressure of a blasting system $P_{ZM}$ can be derived by multiplication with the number of unit volumes $n_{Vo}$ as follows (10):

$$P_{ZM} = P_{Z0} \cdot n_{v0} \quad \left(\frac{\mathrm{kg}}{\mathrm{m \cdot s^2}}\right) \quad (10)$$

The exhausted energy proportions for vibrations, fragmentation and the early throw-off phase of the rock mass are estimated as a dynamic energy of the detonation phase during explosive reaction. The energy loss during chemical reactions, heat development and air pressure during shock wave propagation cannot be detected.

Due to the reaction of the explosives large amounts of the blast fume are set free during the throw-off of the muck pile, which generate a gas pressure. According to the general assumption the gas pressure is predominantly responsible for the throw-off of the blasting mass. The detected blasting mass and its blow-out velocity is utilised to calculate the kinetic energy of the thrown-off muck pile $E_{kinM}$ (11):

$$E_{kin_M} = \frac{m_M \cdot c_M^2}{2} \quad \left(\frac{\mathrm{kg \cdot m^2}}{\mathrm{s^2}}\right) \quad (11)$$

In order to complete the energetic balance of the throw-off, the potential energy of the generated oblique throw is needed, even this parameter has an insignificant relevance to the blast technique (12):

$$E_{pot_M} = m_M \cdot g \cdot \Delta h_w \quad \left(\frac{\mathrm{kg \cdot m^2}}{\mathrm{s^2}}\right) \quad (12)$$

The energy proportions (11) and (12) can be considered as a quasi static energy proportion $E_{qstat}$ (Figure 2).

## 4.2 *Proved correlations und their blast technical interpretations*

The comparison of the calculated effective detonation pressures $P_{Zo}$ according to formula (9) and the fragmented size of the muck pile reveal the correlation shown in Figure 9. The representative grain size at $d = 63.2\%$ of the cumulative curve is used to calculate a spherical volume of an idealised grain. In a second step this value is multiplied by the rock density. The gained average grain size mass (*AGSM*) of the muck pile decreases with increasing effective detonation pressure $P_{Zo}$. The delay intervals are kept constant in all blast designs. Therefore they have no impact to the finding. Remarkable of this correlation is that the unit volume changes only with the variation of the ignition sequence. The unit volume $V_o$ is the product of the borehole distance $a_B'$, the burden $w'$ and the borehole length $l_{Bo}$. The specific charge remains constant if the borehole length is set 1 m. In the suggested ignition system the boreholes are fired in a front which is angular directed to the free face. This leads to a shortening of the blasted burden (Figure 5) and a decrease of the unit volume. Thus, the available explosives were utilized in an increased energetic way. The relatively low correlation factor of 70% can be explained by the negative impact of the energy loss during the detonative reaction of explosives e.g. chemical reactions, heat development and induced air pressure.

Therewith the primary aim of the study is achieved. The statement can be confirmed the plot of various blasts, which were fired using single hole ignition or were ignited according to the momentum theory, against the distribution of jointed body sizes of the rock mass (Figure 10).

Figure 10 illustrates that coarser rock body proportions are fragmented more intensely than the finer ones, which is a well-known fact. The main

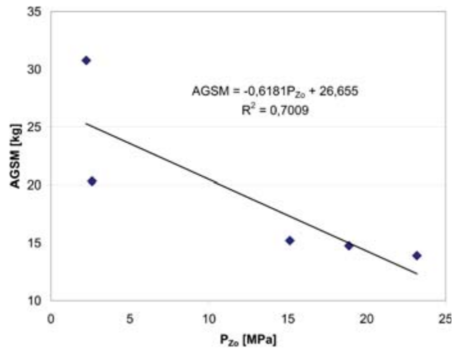


Figure 9. Correlation between the detonation pressure $P_{Zo}$ related to the unit volume $(a_B \cdot w \cdot l_{B0})$ to the Average Grain Size Mass (*AGSM*), which is a product of the spherical volume of the representative grain size ($d = 63.2\%$) in the cumulative curve and the rock density for various muck piles of blasted limestone.

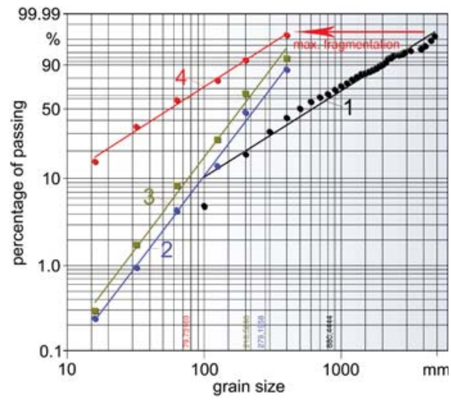


Figure 10. Comparison of grain size distributions of a rock mass (1) and some blastings (2–4) in the Rosin-Rammler-Sperling-Bennet-diagram (RRSB) for one quarry; one single hole fired blast (2) and two blastings with ignition system according to the momentum theory (3, 4).

shift of the cumulative curves of the natural rock fragmentation to the muck pile is obviously in the coarser region of the grain size distribution. In addition, Figure 10 documents the common observation, that the finest fragments of the muck pile are coarser compared to the smallest jointed bodies. It can be concluded that the large inner specific surface of the rock mass cannot be fragmented completely during the blasting.

In order to proof a better energetic reaction of explosives with regard to the fragmentation of the rock mass, the specific surfaces of the muck piles were correlated to the distribution of the jointed body size distribution. Figure 11 shows an exemplary data set for one quarry. The change in grain size distribution was compared with the applied drill and blasting parameters. Main parameters are the average diameter at $d = 63.2\%$ of the cumulative curve and its slope.

The evaluation of the throw-off verifies the physically derived effect of the effective detonation pressure on the loosening of the muck pile (Figure 12). The loosening is defined as the proportion of the muck pile volume to volume of the blast before firing. This correlation implies the possibility to rotate the throw-off direction perpendicular to the simultaneously fired borehole row using an ignition sequence according to the momentum theory (Figure 6). The loosening and the throw-off of the muck pile are caused and influenced by the volume of blasting fumes and the effective detonative pressure of the explosives. Furthermore, a direct correlation between the joint percentage and the kinetic energy of the muck pile can be declared (Table 3).

Therewith the suggestions by Müller (1974) and Heinze (1993) have been confirmed that the distribution of the jointed body sizes has a major

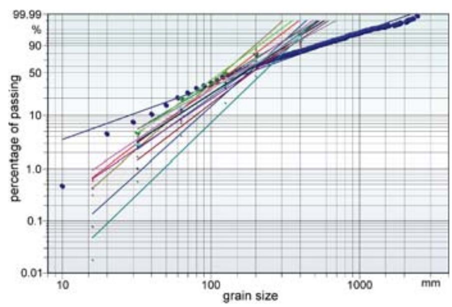


Figure 11. Exemplary analysis in the Rosin-Rammler-Sperling-Bennet-diagram (RRSB) of all muck pile distribution curves of various blasts of the quarry Koschenberg in comparison to the grain size distribution of the natural rock mass (dots).

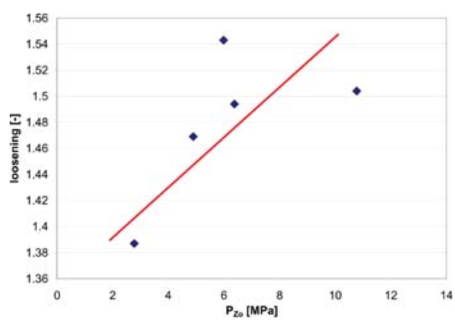


Figure 12. Influence to the muck pile loosening due to the value of detonation pressure per unit volume; the loosening can be defined as the proportion of the muck pile volume to the volume of the blast before firing.

influence on the fragmented size as well as the throw-off of the muck-pile.

The great relevance of the explosive density and detonation velocity initiated an appropriate re-evaluation of data previously published by different authors and the explosive producers, and of own measurements. Figure 13 gives an idea of the emerged, statistically proved relation between the explosive density and the detonation velocity of a number of commercial explosives. Using this regressive correlation, it is possible to calculate the detonation velocity out of the explosive density and vice versa (Figure 13).

As a result of the evaluation and analysis of the most important drilling, blasting and ignition parameters and the statistical correlations of the energetic values and the effective detonation pressure in the blasting system the following conclusions for blast dimensioning can be drawn:

- The rock fragmentation process appears successively from the maximum grain size to the finer grain size, whereas the larger grain aggregates are stronger affected than the finer ones.
- The demand of blasting energy increases with increasing joint distances and higher requests for lowering the fragmented size of the muck pile.

Table 3. Kinetic energy of the muck pile and the average joint percentage/joint distances of the rock masses.

| Quarry/rock mass composition | Kinetic energy $E_{kinM}$ of the muck pile (MJ) | Joint percentage/ ∅ joint distances of the rock mass (m) |
|---|---|---|
| Elbingerode/ limestone | 1,15–4,74 ∅ 2,525 | 0,804 |
| Lueptitz/ rhyolite | 0,437–2,48 ∅ 1,876 | 0,414 |
| Koschenberg/ metagreywacke | 0,216–2,0 ∅ 0,8672 | 0,255 |

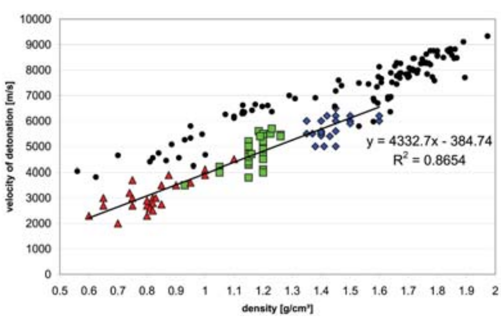


Figure 13. Coherencies between the explosive density and the detonation velocity of commercial explosives (data by Cooper 1996, Heinze 1993, Persson et al. 1994 and own measurements).

- The influence and relevance of the joint system to the kinetic energy of the moved muck pile becomes more important with an increase of the grain size variation as well as larger joint distances. A muck pile with small fragmented size can be thrown-off more easier than those with coarse fragmented size.
- The fragmented size of the muck pile can be improved by changing the ignition sequence according to the momentum theory, without increasing the amount of explosives. The effect can be achieved by improved ingnition techniques and an increase of the effective detonation pressure.
- Based on the established relationships of the fragmentation of the rock mass, the fragmented size of the muck pile can be controlled by the blast design. The design has to be based on the quantitatively determined distribution of the joint body sizes of the particular rock mass and the acoustic impedance of the rocks.

The following drilling, blasting and ignition parameters increase the rock fragmentation:

- reduction of the blasted burden $w'$
- extension of the spacing (13)

$$\lambda_s = \frac{a_B'}{w'} \quad (-) \tag{13}$$

- configuration of the ignition sequence according to the momentum theory
- increasing of the specific charge of the explosives
- utilisation of high density explosives with a high velocity of detonation.

The throw-off can be improved by:

- increasing the effective detonation pressure per unit volume due to ignition according to the momentum theory
- coarser sized muck pile
- rotation of the throw-off direction perpendicular to the simultaneously ignited borehole row using an ignition sequence according to the momentum theory.

The establishment of a general energetic balance of a production blast is currently not possible due to the following reasons:

- The proportions of the dynamic energies (Edyn) are distributed heterogeneously during fragmentation and the throw-off according to the acoustic impedance of the rocks and the joint body composition of the rock mass.
- The value of the quasi static energy proportion (Eqstat) and its effect on the throw-off changes with the grain size distribution of the muck pile and is influenced by the effective detona-

tion pressure. The precise proportion of the gas pressure during the throw-off is not detectable by the radar measurements.
- Chemical reactions, heat development and induced air pressure during the detonative reaction of explosives cause an energy loss, which is not measurable with the applied methods.

## 5 OUTLOOK

The primary aim of the research study, to produce an improved energetic utilisation of the used explosives has been achieved. The study improves the physical understanding of the blasting process in general. The effects are physically explainable and the blasting is technically configurable. Furthermore, the study will significantly increase the acceptance of side effects affecting residents in the surroundings of active quarries. There is no doubt that not all energetic coherencies and correlations were found. Further research is required in order to identify additional physical relationships and laws of observed effects and phenomenon, such as the time delay.

## ACKNOWLEDGEMENTS

At this point the authors would like to thank the blasting companies Dexplo GmbH, Orica Germany GmbH, Maxam Deutschland GmbH and the quarries Koschenberg, Lueptitz, Winterberg, Elbingerode, Leukersdorf and Goersdorf for support and constructive cooperation.

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