Influence of rock’s structure at grain-scale on rockburst proneness

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Abstract. As projects advance to deeper areas, rockbursts occur more frequently. This failure mode is particularly problematic, as the rock mass fails abruptly, releasing high amounts of energy, endangering the life of workers and damaging equipment. The hazard mode is highly influenced by the grain-level structure of the rock. The authors demonstrate this by comparing the grain-level structure of different rocks to their failure mechanism. For this an extensive laboratory program was performed, including uniaxial compression tests (incl. post-failure tests to evaluate the failure energy), acoustic emission testing (to monitor the cracking activity) and Object Based Image Analysis (OBIA) to analyze rock’s structure at grain scale using thin sections taken before and after the compression test. The results allow a better understanding of the underlying mechanism and emphasize the usefulness of petrographic information within rockburst risk analysis.

1. Introduction

Modern tunnelling and mining projects are exploring deeper areas than ever before, greatly increasing the likelihood of rockburst. This failure is extremely dangerous as it occurs very suddenly and is capable of releasing high amounts of energy. This poses a high risk to the life of workers and equipment used. Therefore, it is very important to fully understand rockbursts and develop methods to predict them. Laboratory tests and observations in tunnels and mines with high overburden have shown that certain rock types have a high potential for storing elastic energy and are hence more susceptible to rockburst. Although rockburst has been studied extensively in the past, the details of the failure mechanisms, including the fracture initiation, propagation and coalescence, are not yet fully understood. Many researchers (e.g. [1, 2]) suspect that rock’s structure at grain-scale plays an important role in this failure mode.

As part of a research project funded by the Austrian Research Promotion Agency (FFG) the Graz University of Technology, the University of Salzburg, the RHI AG and the University of Texas at Austin investigated the influence of rock’s (micro-) structure on the failure mechanism “rockburst” within a multidisciplinary study. For this study, different up-to-date methods were used, such as Object-Based Image Analysis (OBIA), Micro Computer Tomography (µCT) and Acoustic Emission Testing (AET), and combined with state-of-the-art rock mechanical laboratory tests [3].
2. Rock material

Rock mechanical tests on various rock types have shown that the highest potential for rockburst is found in samples with a rather uniform mineralogical composition and a high compressive strength. Therefore, rock types with these properties were selected for testing. In addition, a literature study was conducted on rock types mentioned in connection with highly brittle failure behaviour and rockburst. The result of this was also taken into account in the selection process. Another criterion was the accessibility to rock blocks of these rock types. Due to the cooperation with RHI AG numerous magnesites and dolomites could be tested. Table 1 lists the rock blocks together with a short geological description. The blocks originate from different areas in Italy, Greece and Austria.

Table 1. Geological description of tested rock blocks.

| Label | Rock type |
|-------|-----------|
| BR    | The samples containing the token “BR” (BR2/BR3/BR4/BR5) are magnesites. They come from one of the RHI AG mines in Breitenau (Austria). In thin-sections they show subhedral to euhedral carbonate grains of different sizes up to some mm with no clear structure in distribution. Some of the grain borders show appearances of resolution. |
| HF    | The samples labeled “HF” come from an underground mine in Hochfilzen (Austria) operated by RHI AG. The samples “HF1” and “HF3” are dolomites. The sample “HF2” consists of spar magnesite. All “HF” thin-sections show subhedral grains up to some mm in size. In sample “HF3” appearances of grain border resolution can be observed. |
| MA    | Samples containing the tokens “MA” are marbles. In thin sections they show idiomorphic crystals of different sizes. The crystals possess common cleavage and common twin growth. |
| GL    | The samples with the token “GL” are amphibolites, which show clear parallel structures consisting of changing amphibol-rich and feldspar-rich layers. Hence, in the investigation the parallel structure had to be considered. The rock material originates from the tunnel project “Gleinalmtunnel” in Austria. At the site indications of rockburst occurred. |
| SG    | “SG1” is a limestone. “SG5” a marble, which shows in thin sections idiomorphic crystals of different sizes up to mm scale. |

3. Laboratory test program

3.1. Overview

The test program consisted of various laboratory tests to describe the mechanical behavior of the samples. In addition to uniaxial compression tests, splitting tensile tests and ultrasonic P-wave velocity measurements were carried out. Due to the page limitations, only the results of the uniaxial compression tests are discussed in this paper. To better capture the failure process, many of the uniaxial compression tests were combined with AE-testing (see next chapter).

3.2. Uniaxial compression tests

The uniaxial compression tests were carried out in a standard servo-controlled testing machine and comply with ASTM-standards “D7012” [4] and “D4543” [5]. Strain gauges measured the longitudinal and lateral deformation during loading. Unloading/reloading loops were performed to determine the Young’s modulus and some of the most common rockburst parameters (e.g. Strain Energy Storage Index $W_{ET}$ [6, 7, 8], Potential Energy of Elastic Strain PES [7], Brittleness Index Modified BIM [9]). After the last loop, a constant circumferential displacement rate was used to control the loading for the sequence. Thus, post-failure behavior could also be obtained for class II rocks [10, 11] and various energy values determined.

3.3. Mechanical properties

Figure 1 shows the energy at peak in relation to the uniaxial compressive strength for the rock types tested. The designation consists of the label of the rock block and the internal laboratory test number of
the sample. In the course of the study, various other parameters (e.g. Young’s Modulus, Deformation Modulus) were also determined, which are not presented here due to page limitations. Decisive for assessing the rockburst susceptibility of a rock are its ability to store energy and its type of release. The ability to store energy is highly dependent on the uniaxial compressive strength (UCS).

The dolomite samples (HF1 and HF3) show the highest peak energy with values between 335 KJ/m³ and 385 KJ/m³. The magnesite samples “BR4” and “HF2” are in a similar range. The marbles (MA5, MA8, MA9 and SG5) have the lowest peak energy with a mean value of 120 KJ/m³.

![UCS vs. Energy 100%](image)

**Figure 1.** Uniaxial Compressive Strength versus energy at peak.

4. Acoustic Emission Testing
Acoustic Emission Testing (AET) is a passive, non-destructive testing method. The acoustic emissions of a solid material provide information about the initiation and propagation of (micro-) cracks and the deformation behavior in general, which gives an idea about the rock behavior under certain stress conditions [12, 13].

4.1. Test set up and evaluation
Six piezoelectric acoustic sensors (PAC Nano30) were attached to the sample in an isosceles triangular arrangement to record the quality and quantity of acoustic signals (Figure 2). The acoustic signals were then pre-amplified and processed further at the Micro-II Digital AE System using the real-time data acquisition and replay software AEwin (Mistras Group Hellas). For post processing, the software Noesis (Mistras Group Hellas) was also used. Both software packages are signal based analysis tools.

In the post-processing phase, primarily the raw data was cleaned with regard to detached sensors or external ambient noise. In the process, doubtful data for the intervals in question was filtered out. Based on the adjusted data several evaluations were done and summarized in a clear form in an AE-post processing data-sheet for each sample. In addition to the typical parametrical analysis, the 3D-Location of AE events was assessed (Figure 2). The AE-parameters were calculated for each sensor and then
averaged. In addition, the individual AE-parameters were also assigned to the different deformation phases (crack closure phase, elastic deformation phase, steady crack growth phase and unsteady crack growth phase). The phases were determined using three different methods (deformation strain analysis [14], analysis of the cumulative AE-energy release and pattern recognition of AE-data).

4.2. AE Results

Figure 3 shows the relative amount of released energy determined by AE during the deformation phases. Additionally, the total amount of released energy is presented for each sample.

![Energy Release in the Deformation Phases](image)

**Figure 3.** Normalized released energy grouped after the different deformation phases and total released energy.
To observe the average energy release per hit, the released energy is divided by the number of hits. Figure 4 shows the released energy per hit on a logarithmic scale grouped after the different deformation phases.

![Figure 4](image)

**Figure 4.** Released absolute energy per hit grouped after the different deformation phases.

The relative limits of the deformation phases are very similar for the investigated rocks. The transition between the crack closure phase and the elastic deformation phase is at about 5% of the uniaxial compressive strength. Here, the marble samples show the greatest spread. The subsequent phase, the steady crack growth phase, starts at about 40%. Magnesite samples were closer to 45% and amphibolite samples closer to 35%. The following transition to the unsteady crack growth phase occurred at approximately 75% of the uniaxial compressive strength. Marbles were closer to 70% and amphibolites closer to 80%.

5. Microstructural thin section analysis using Object Based Image Analysis

5.1. Introduction

Quantitative analysis of petrographic micrographs is a key method within this research. A well-defined workflow involving thin section preparation, micrograph acquisition and Object Based Image Analysis (OBIA) was used [15]. This allowed for automatic extraction of rock fabric features of various samples at different loading stages. OBIA software used was Trimble eCognition 9.2.1. In contrast to pixel-based approaches, OBIA uses spatially contiguous image objects as the building blocks for image analysis. OBIA provides analysis of these image objects beyond their spectral properties: object shape, spatial relationships to other image objects (neighborhoods, distances, shared borders) or spatial hierarchical relationships between image objects (inclusion) are provided. In petrography, OBIA excels at nearly perfect mineral grain identification, shape description and analysis, enabling objective and quantitative extraction of rock fabric features [16].
5.2. Data acquisition and preparation
The petrographic micrographs were taken with a Leica DM LP photomicroscope equipped with a 5-megapixel Olympus DP26 sensor. To maximize photo micrograph information input to OBIA, we combined micrographs acquired at different rotations of the polarization filters [17]. Rotation angles were 0°-180° with an increment of 10°. Images were taken with parallel and crossed polarizers, yielding 36 images per rock thin section. The co-registered image stack was represented as one multilayer image in the OBIA system.

5.3. Object based analysis of thin sections
OBIA abstracts a petrographer’s expert knowledge into rule-sets, which describe the spectral, morphological and topological features of the objects to be extracted from the multilayer image. We used all polarizations and rotation angles with equal weight and took a two-level-segmentation approach to describe mineral grain textures. Figure 5 shows the object boundaries derived from the full OBIA workflow: besides mineral grains, mineral-internal small structures (cleavages, inclusions) and even minute cracks that originate from loading are clearly reproduced.

5.4. Microstructural characterization by OBIA
OBIA rule sets were developed for the main rock types involved in the research project. Respective rule sets were applied to the photo micrographs, ending up with classified images and – most important in the project context - tabular outputs of grain shape parameters per mineral class: length, width, area, border length, asymmetry, border index, compactness, density, elliptic fit, main direction, elliptical fit, rectangular fit, roundness, shape index. We used rose diagrams to convey 2D directional symmetry or asymmetry in rock fabrics and notched box-whisker plots for explorative data analysis (EDA) and quantitative comparison of above-mentioned shape parameters (Software: Golden Software Grapher v.15).

5.5. Representative Results
Below, OBIA results of a marble sample (MA8) and a magnesite sample (HF1) are presented as rose diagrams and notched box-whisker plots. Similar to histograms, rose diagrams display the characteristics of circular distributions. Comparing the rose diagrams of “MA8” and “HF1”; “MA8” shows a pronounced anisotropy with mineral grains mostly elongated in NNE-SSW direction, while HF1 grains can be considered to be about directionally isotropic. This is in accordance with non-directional fabric features that can be read off the respective box-whisker plots (same scaling): for example, as compared to HF1, MA8 has higher medians and larger ranges of length/width, border index, compactness, roundness and shape ratio, which also indicates stronger fabric anisotropy.
Figure 6. Mineral main directions rose diagrams, samples “MA 8” (left) and “HF 1” (right).

Figure 7. Mineral object statistics of samples “MA 8” and “HF 1” (notched box-whisker plots).
6. Discussion and Conclusion

Although the focus in the selection of rock material was set on rock types known to have a high rockburst potential, the results show clear differences. The examined dolomites and magnesites depict a higher potential than for example the marbles. As mentioned above, the ability to store energy and its type of release are decisive in assessing the rockburst susceptibility of a rock.

In laboratory, parameters such as uniaxial compressive strength or energy values represent rock’s ability to store energy. Acoustic Emission Testing can capture the failure mode, which is coherent with energy release, very well. Typical for rockburst prone samples is a high total amount of released energy, which primarily takes place within the last deformation phases. Another characteristic is a high absolute energy per hit within those phases. Samples with those characteristics exhibited in the survey a uniform distribution of AE-events (Figure 2).

In this study rocks potential to rockburst was compared to rock’s structure at grain level. In the following, two representative rock blocks are discussed. Table 2 contrasts the main results of the marble “MA8” with the dolomite “HF1”.

Table 2. Comparison of two representative rock blocks: Marble “MA8” versus dolomite “HF1”.

| Label | Marble “MA8” | Dolomite “HF1” |
|-------|--------------|----------------|
| **Mechanical Properties** | • Medium peak energy (110–180 kJ/m³);  
  • Medium UCS (120–130 MPa);  
  • Young’s Modulus of 85 GPa;  
  • Slight Class II rock. | • High peak energy (336 kJ/m³);  
  • High UCS (225 MPa);  
  • Young’s Modulus of 100 GPa;  
  • Extreme Class II rock. |
| **AE-Results** | • Medium total amount of released energy (~2.1E+04 aJ);  
  • Energy release distributed over the entire uniaxial compression test;  
  • Low absolute energy per hit (on average 9.6 aJ), which is similar over all deformation phases. | • High total amount of released energy (~2.2E+09 aJ);  
  • Energy release mainly in steady crack growth phase and unsteady crack growth phase;  
  • Absolute energy per hit:  
    o High in steady crack growth phase and unsteady crack growth phase (on average 4.16E+04 aJ);  
    o Low to medium in crack closure phase and elastic deformation phase (on average 35.0 aJ). |
| **OBI-Results** | Heterogeneous microstructure:  
  • The rose diagram, which depicts the mineral main directions, shows a clear directional fabric anisotropy.  
  • The box-whisker plots indicate anisotropy and larger ranges of grain shape parameters. | Homogeneous microstructure:  
  • The rose diagram indicates isotropic fabric.  
  • The box-whisker plots point to diminished grain-shape-parameter scattering. |

Both the mechanical properties and the AE-results show a greater susceptibility to rockburst for “HF1”. The peak energy, for example, is about three times higher than the one of “MA8”. Additionally, “HF1” is characterized as extreme Class II rock, which is also an indicator for rock’s high brittleness [10]. The AE-results portray well the differences regarding the failure mechanism. “HF1” fails very spontaneously releasing a high total amount of energy of about 2.2E+09 aJ. In comparison, the total amount of released energy of “MA8” is about 10^5 times lower. In addition, in the case of “MA8” the energy release is distributed more over the entire loading process. Furthermore, the “energy per hit”-
values show a clear difference regarding the failure behavior of the two rocks (see Figure 4 and Table 2).

The comparison of the failure mode with rock’s structure at grain scale showed a high dependence. The potential for violent, brittle failure, like rockburst, increases with rocks homogeneity. “MA8”, for example, possesses a more heterogeneous microstructure than “HF1”. The evaluation of the mineral main direction yielded a clear directional fabric anisotropy (Figure 6). Additionally the box-whisker plots indicated anisotropy and larger ranges of grain shape parameters (Figure 7).

Summarized, based on the study’s results, the following conclusions are drawn:

- AE-Testing in laboratory is very suitable for determining rock’s proneness to rockburst.
- Rocks structure at grain-scale plays a major role in its failure behaviour.
- The potential for rockburst raises with rocks homogeneity at grain scale.

The study demonstrates the potential of including microstructure analyses in rockburst risk assessment. Especially as in many cases, thin section analyses are already available and cause no further costs.

It is important to keep in mind that this study deals with the proneness of a rock to violent, brittle failure (e.g. rockburst). For a robust rockburst risk assessment at a specific area in-situ conditions (e.g. geological features, overburden, and excavation method) have to be taken into account.

7. Outlook
In order to predict, reduce or avoid the consequences of rockburst, it is essential to understand the failure mechanism well and put the gained knowledge into practice. Therefore, an extension and further development of the current laboratory program is planned. The focus is set on intrinsic properties of rock, which promote its propensity to rockburst, as well as on extending the knowledge in AE-Testing. For the practical side of this research topic, collaboration with sites around the world, such as Alto Maipo (Chile), that have experienced major rockbursts, are in progress or planned. In addition, a more detailed analysis of the evaluated OBIA and AE results in connection with the failure mechanism is planned. Furthermore, the determined rockburst parameters (e.g. Strain Energy Storage Index, Potential Energy of Elastic Strain, Brittleness Index Modified) will be examined for their validity based on this new data. By implementing the gained knowledge into current risk management systems, rockburst predictions will become more accurate and hence, countermeasures can be initiated more precisely. Overall, this research will contribute to reduce the safety risk to workers and equipment in tunnelling and mining.

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