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The failure process and the acoustic emission of brittle rock under compression

Processus de rupture et émissions acoustiques dans les roches fragiles en compression

Der bruchsprozess und die acustische emission der spröden gesteine unter belastung

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ABSTRACT: A systematic experimental study has been performed in order to increase the understanding of the micromechanical behavior during the failure process in rock. Strain gauges were used to determine elastic properties. Core based rock samples were uniaxially loaded to four different stress levels, and then unloaded. Acoustic emissions were recorded during the loading period. Thin sections were prepared with a flourescent epoxy and microcracks were mapped using UV-light in an optical microscope. This paper describes the results of the granite, diabase, limestone and quartzite, tested. Both the igneous rock types and the sedimentary (metamorphic) rock types show differences in microcrack propagation, acoustic emission and elastic properties. While there are a large number of AE-events in granite and quartzite there are very few events in diabase and limestone. Each rock type has its own microcrack pattern, both in virgin samples and during loading. The failure process seems to be highly influenced by the microcrack pattern and rock genesis.

RÉSUMÉR: Une étude expérimentale systématique a été menée afin d'augmenter la compréhension du comportement micromécanique durant le processus de ruture dans les roches. Des jauges de tensions ont été utilisées pour déterminer les propriétés élastiques. Des échantillons de carottes de roches ont été chargés uniaxiallement à quatre niveaux de stress différents puis déchargés. Les émissions accoustiques ont été enregistrées durant la période de chargement. Des lames minces ont été préparées avec de l'époxy fluorescent et les microfractures ont été cartographiées en utilisant de la lumière ulta-violette dans un microscope optique. Cet article decrit les résultats des tests conduits sur du granite, de la diabase, du calcaire et de la quartzite. Les roches ignées et les roches sédimantaires (métamorphiques) présentent des différences sur la propagation des microfractures, les emissions acoustiques et les propriétées élastiques. Alors que le nombre de coups enregistrés est élevé dans le granite et la quartzite, il y en a peu dans la diabase et le calcaire. Chaque type de roches a ses propres motifs de microfractures, que ce soit sur l'échantillon originel ou durant le chargement. Le processus de rupture semble être largement influencé par les motifs des microfractures et la génèse de la roches.

ZUSAMMENFASSUNG: Ein systematisches experimentelles Studium wurde unternommen um ein besseres verstehen von mikromechanischem Verlauf während des Bruchprocesses in Gestein zu bekommen. Drahtdehnungsgeber wurden verwendet um die elastische Eigenschaften zu bestimmen. Kernproben aus dem Gestein wurden einachsig belastet zu vier verschiedene Spannungsnivean und danach entlastet. Die akustische Emission wurde gemessen während der Belastungsperiode. Dünne Gesteinssektionen wurden prepariert mit eine fluoricierenden Epoxi und die Mikrorisse wurden kartographisch aufgenommen durch benutzung von UV-Licht in einem optischen Mikroskop. Dieser Artikel beschreibt die Resultaten von getestetem Granit, Diabas, Kalkstein und Quarzit. Sowohl die vulkanische Gesteinsarten als die sedimentäre und metamorphische Gesteinsarten zeigen unterschiedliche Mikrorissausbreitung, akustische Emission und elastische Eigenschaften. Weil es eine grosse Menge von AE-Treffen in Granit und Kvartzit sind, ist es sehr wenig Treffen in Diabas und Kalkstein. Jeder Gesteinsart hat ihre eigene Mikrorissmuster, sowohl in jungfräulichen Proben als während der Belastung. Der Bruchprocess ist wahrscheinlich sehr influiert bei der Mikrorissmuster und der Gesteinsgenesis.

1 INTRODUCTION

In an earlier study, Li, (1993) showed that the Acoustic Emission (AE) and the Kaiser effect characteristics were different in different rock types subjected to compression. These differences depend on the micromechanical behavior and the fracturing process in the rock. Mineral contents, grain size and shape, size and shape of the initial microcracks and the rock genesis are believed to influence the failure process of brittle rock.

To improve the understanding of the micro mechanical behavior and the difference in Acoustic Emission signature of different rock types a systematic experimental study was initiated. The study employs uniaxial compression tests, acoustic emission monitoring and optical microscope studies. The objective was to study initiation, propagation and coalescence of microcracks, failure pattern and macroscopic failure.

In this investigation the failure mechanisms of some common Swedish rock types have been studied. The rock types were primarily chosen on the basis of previous work done at the Rock Mechanics Division at the Luleå University of Technology.

2 LABORATORY TESTING OF FOUR ROCK TYPES

2.1 *Tested rock types*

In this study four different rock types were tested. Two of these are igneous rocks, granite from Kuru, Finland and diabase from, Gudmundberget, Sweden. The other two are sedimentary rocks, limestone and sandstone(or sub-arkose of low to medium metamorphic grade, from now on called quartzite). The granite is gray, medium grained (1-5mm) and massive with main minerals quartz, feldspar and mica. The diabase is a fine to medium grained hypabyssal rock where oblong plagioclase grains form a, so-called, ophitic structure. Other minerals are pyroxene and opaque. The limestone is gray and has very fine carbonaceous grains of organic materials. The quartzite originates from fine grained quartz sandstone with a slight banded structure consisting of coarser feldspar grains.

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2.2 *Methods and experimental setup*

Rock core specimens (∅=42mm, L=105 mm) were drilled from carefully sawn-out blocks collected in Swedish and Finish quarries except for the diabase cores, which came from an investigation core.

The uniaxial compressive strength σ_c was determined, (Brown, 1981) using at least five specimens. Elastic properties such as Young's modulus E and Poisson's ratio ν, were determined using two opposite pairs of axial and tangential standard strain gauges. Volumetric strain ε_v

$$\varepsilon_v = \varepsilon_{axial} + 2\varepsilon_{lateral} \quad (1)$$

crack volumetric strain ε_{cv}

$$\varepsilon_{cv} = \varepsilon_V - \varepsilon_{Velastic} \quad (2)$$

where

$$\varepsilon_{Velastic} = \frac{1-2\nu}{E}\sigma_{axial} \quad (3)$$

were then calculated.

Groups of four core samples of each rock type were prepared for testing. The core samples of each group were uniaxially loaded to a predestinated stress level, and then unloaded. The first group was loaded to 60% of the uniaxial compressive strength., the second to 70%, the third group to 80% and finally the fourth group to 90% of σ_c. The maximum load for limestone was 80 % of its σ_c. The loading rate was 1 kN/s or 0.72 MPa/s. The tests were performed in the servo-hydraulic 4500 kN testing rig at the Rock Test Laboratory of Luleå University of Technology.

Acoustic emission was monitored during the loading period with a PAC Locan 8900 system. A piezoelectric WD 100-1200 MHz wide band transducer was used together with a steel waveguide to improve AE detection. The waveguide presents a concave face towards the rock core matching the core radius. An AE amplitude threshold was set to 50 dB to filter out background noise. As couplant between the transducer, waveguide and rock core ultrasonic liquid was used. AE quantities such as events, counts, amplitude, AE-energy, duration and rise time were analyzed

Thin sections (50mm×42mm×30 μm) were prepared with a flourescent epoxy of both four virgin samples and of three to four of the tested rock cores of each loading level. The thin sections were studied in an optical microscope at 50 times magnification. Microcracks were systematically mapped for each loading level using line mapping on two vertical and four horizontal lines. Fracture length, fracture orientation and type of fracture, along grain boundaries or through grains, were investigated.

3 RESULTS

3.1 *Rock properties*

The physical properties of the four rock types are shown in Table 1.

Table 1 Physical properties of the four tested rock types.

Rock type	σ_c [MPa]	E_{50}[GPa]	ν_{50}	ρ[kg/m^3]
Diabase,	370	89	0.30	2954
Granite,	278	69	0.38	2622
Quartzite	239	67	0.34	2772
Limestone	205	61	0.29	2661

All values are average values

In Figures 2a-d examples of the axial stress-strain curves, total volumetric strain and crack volumetric strain curves together with acoustic emission counts, are shown for each of the tested rock types respectively.

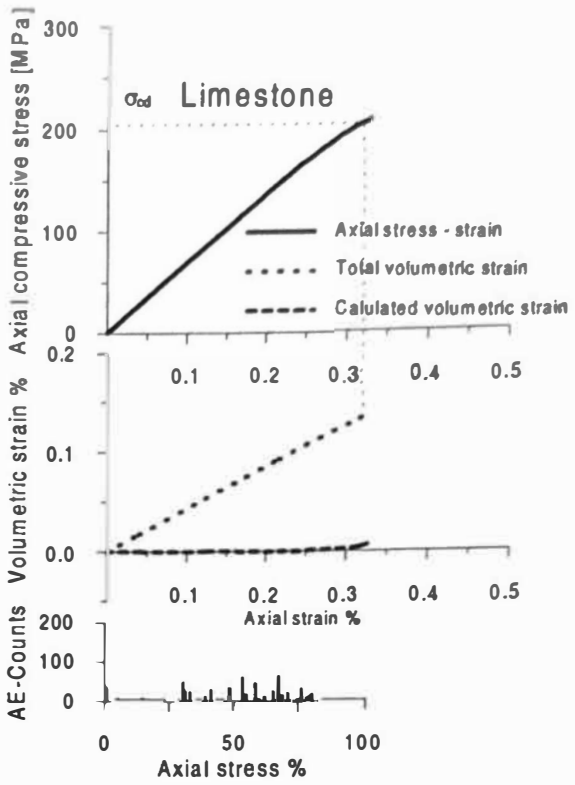

Figure 2a. Stress-strain, volumetric strain curves and AE-counts of limestone.

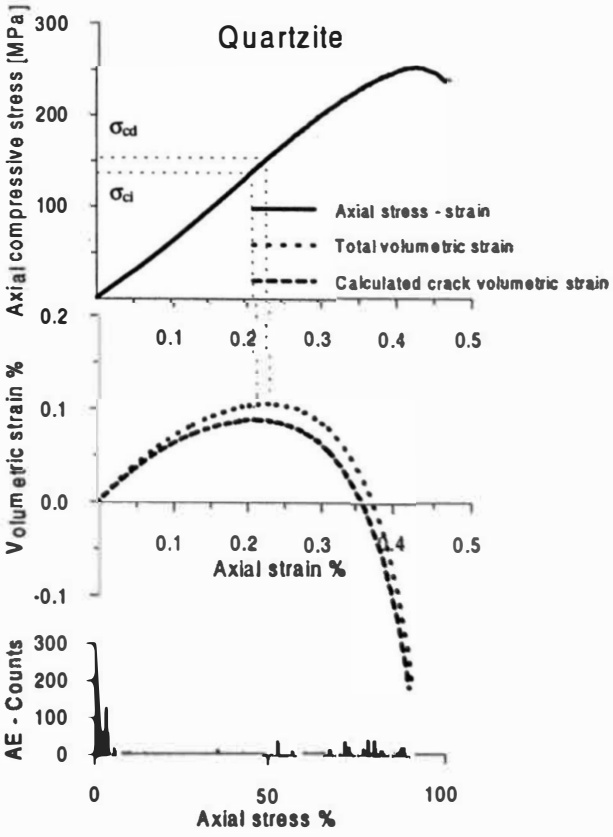

Figure 2b. Stress-strain, volumetric strain curves and AE-counts of quartzite.

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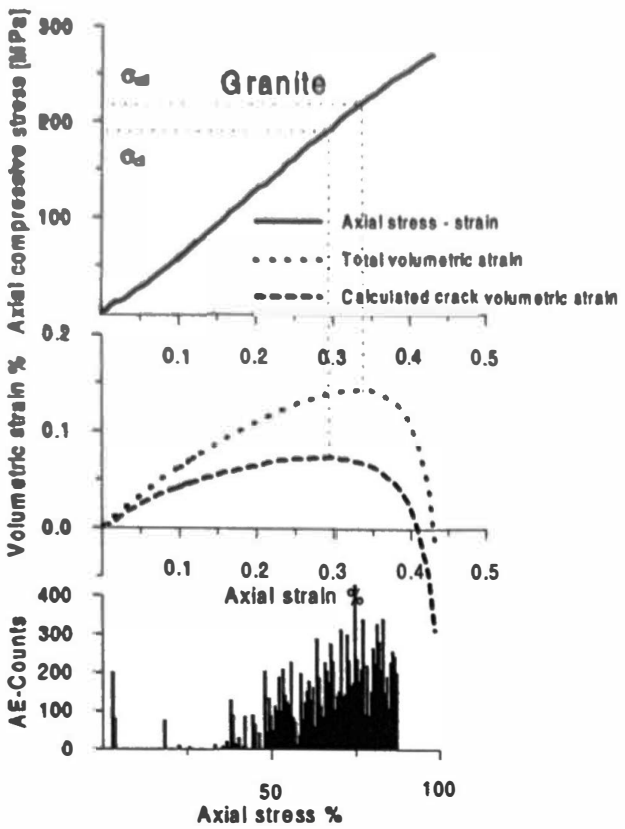

Figure 2c. Stress-strain, volumetric strain curves and AE-counts of granite

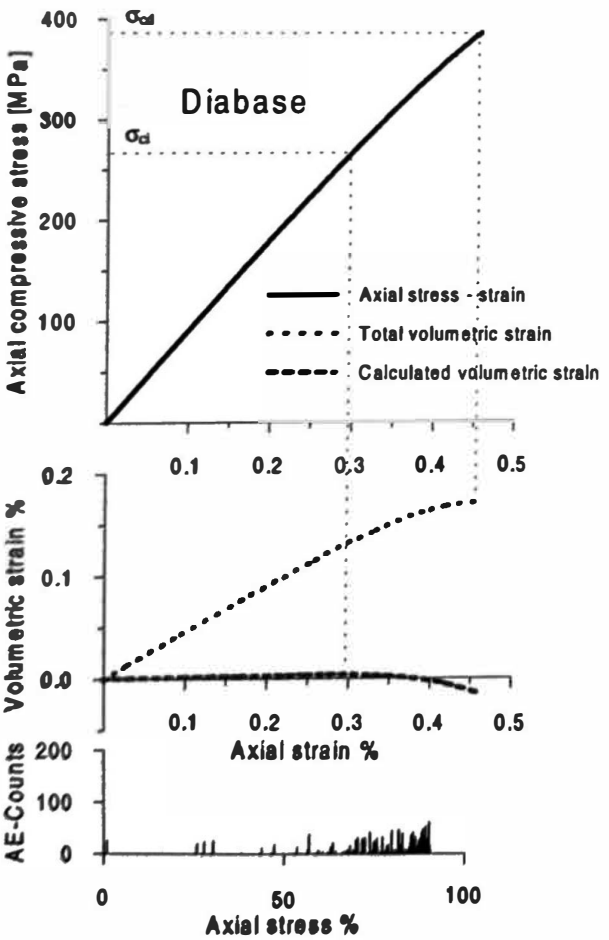

Figure 2d. Stress-strain, volumetric strain curves and AE-counts of diabase

Martin & Chandler (1994) first demonstrated the method of calculating the volumetric strains to improve the determination of the different phases of the failure process in rock by defining the crack closure stress σ_{cc}, the crack initiation stress σ_{ci} and the crack damage stress σ_{cd}. This method have been used by several others, see for instance Hakala(1996) and Eberhardt et. al (1998).

3.2 *Acoustic emission*

In Figures 2a-d typical acoustic emission count patterns for each rock type are plotted. All samples shown in Figures 2a-d are loaded up to 90 % of the uniaxial strength except limestone. Some notable differences can be seen between the tested rock types.

The granite obviously shows high AE-activity. The average number of events was over 4500 for the four samples tested up to 90 % of the uniaxial compressive strength. After some noise or crack closure in beginning of the loading period and some random events the onset of acoustic emission generally starts at 40-60 %

Diabase in general shows very few events. The average of the samples tested up to 90 % was approximately 500 while the number of events in the 80 % samples averaged below 10.

In the quartzite the AE-activity vary more. Two of the 90 % samples have almost 2000 events, while the other two just have some 400 events. The 80 % samples are in the range of 300-350 events with one exception that has almost 1000 events. Generally most of the emission occur in the beginning of the loading period.

The limestone shows very little AE at all loading levels. The range of events for five 80 % loading samples is between 31 and 51 with one exception that had 170 events. That particular sample failed at 80 %. The AE-activity occur randomly for some samples but generally, the AE occurs in the beginning and the end of the loading period.

3.3 *Microcrack mapping*

The microcrack mapping showed totally different patterns for all rock type.

The thin sections from the virgin samples of limestone have few microcracks, although some voids can be seen. In the loaded samples a few long irregular macrocracks have developed. Those are often but not always parallel or sub-parallel to the main loading direction and can be seen for all loading levels above 70 % of σ_c and in some of the 60 % samples.

In the quartzite samples a fine mesh of weak grain contacts or intergranular cracks around the fine quartz grains was observed at all loading levels, also in the virgin samples. In some of the thin sections the mesh is more apparent at higher loading levels. The banded structure consists of more coarse feldspar grains. These grains often include long straight microcracks through the whole grain and the orientation tends to align parallel to that of the bands, at all loading levels. There are also a great number of pores in the quartzite.

In the diabase the microcracks primarily follow the grain boundaries of the plagioclase grains and are often very straight. Though, some transgranular cracks across plagioclase and other grains are observed. The microcracks increase by number rather then by length as the load increases. Almost all microcracks are shorter than 0.5 mm at all loading levels. The propagation rate increases evidently above 70 % of σ_c. The direction of microcracks seems to be randomly distributed at loading levels below 80 % and just vaguely tend to become parallel to the main loading level for higher stress levels.

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In the granite the number of microcracks increases up to 70% of σ_c and tends be almost constant at higher levels. From that stress level one can assume that the microcrack length increases. The orientation is principally parallel to the main loading direction from 60 % and higher. The percentage of transgranular cracks seems to decrease above 80 % and crack propagation apparently follows the boundaries.

4 DISCUSSION

4.1 *Failure processes of the tested rocks*

The failure process of brittle rock is evidently very different depending on the rock fabric, rock genesis and microcrack pattern.

The acoustic emission and microcrack mapping together with the strain curves show that the failure process in the limestone is ruled by a few long microcracks. Dilation of the limestone seems to be controlled mainly by the rock matrix.

The volume increase in quartzite is obvious at approximately 50 % of σ_c. One can observe from the crack volumetric strain curve, that the failure of quartzite is dominated of the weak grain boundaries and the large number of pores, since the elastic strain is small. The lack of acoustic emission and the microcrack mapping indicates little evidence of coalescence leading to dilation.

The strain curves of the granite resembles that of the quartzite. The failure process in granite is possibly more dominated by crack propagation through grains. The grain boundaries are probably stronger and the acoustic emission rate is higher. The microcrack mapping results show that the number of new cracks initiated decrease as the load increases above the 60 % loading level. The orientation of microcracks become evidently more parallel to the loading direction. This is the evidence of coalescence and axial splitting.

The microcrack mapping together with the volumetric strain curves, the crack volumetric strain curve and the acoustic emission indicate that the coalescence of cracks starts just at the final failure in diabase. The interlocking of the fine and irregular grains prevents the cracks from coalescence. Since the crack lengths are kept small they cannot open and the volume does not increase before final failure.

Although the strain curves of limestone and diabase resembles the failure processes are completely different. Therefore the elastic properties cannot solely describe the failure processes.

4.2 *The microcrack mapping method*

The line mapping used, is of course a simplification of the microcrack patterns in the rock cores. A certain amount of subjective errors cannot be eliminated since the method is manual.

4.3 *Influence of Poisson's ratio on the crack volumetric strain*

The crack closure stress σ_{cc} and the crack initiation stress σ_{ci} are both highly dependent on the Poisson's ratio chosen. Since ν has to be kept constant (here ν_{50}, representing the rock matrix) in the equation (2) to create a reasonable crack volumetric strain curve, one has to be somewhat cautious making conclusions.

In Figure 3, a moving point regression analysis of the variation in Poisson's ratio ν is plotted for each of the tested rock types. For the particular quartzite sample plotted in Figure 2c and 3 the Poisson's ratioν =0.46, while the average ν= 0.34 in quartzite

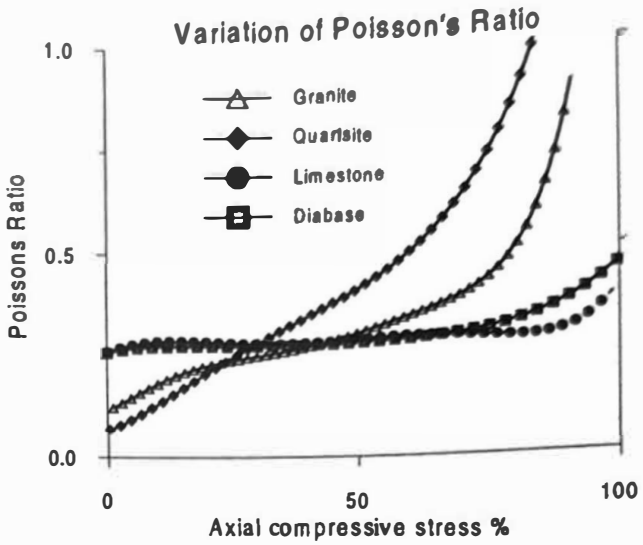

Figure 3. The variation of Poisson's ratio with increasing axial stress in % of σ_c. of the tested rock types.

Both the variation of ν_{50} between different rock samples and the variation of ν with increasing stress make the determination of stress thresholds uncertain for this type of rock.

5 CONCLUDING REMARKS

The failure processes of brittle rock are different in different rock types, depending on the rock genesis, the microcrack propagation pattern and the rock matrix.

The conclusions of the different phases of the failure process in rock cannot be based only on strain curves. Additional investigations including acoustic emission and microcrack studies should be used to better understand the "soul" of every rock type.

One has to be cautious when determining stress thresholds from calculated crack volumetric strain curves as the variation of the elastic properties vary during loading. The method may not be suitable to all types of rock.

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