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Chapter 50

Comparison of Hydraulic and Conventional Tensile Strength Tests

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Abstract

Tensile strength is paramount for reliable simulation of hydraulic fracturing experiments on all scales. Tensile strength values depend strongly on the test method. Three different laboratory tests for tensile strength of rocks are compared. Test methods employed are the Brazilian disc test (BDT), modified tension test (MTT) and hydraulic fracturing experiments with hollow cylinders (MF = Mini Frac). Lithologies tested are a micritic limestone, a coarse-grained marble, a fine-grained Ruhrsandstone, a medium-grained rhyolite, a medium- /coarse-grained andesite and a medium grained sandstone. Test results reveal a relationship between the area under tensile stress at failure and the measured tensile strength. This relationship becomes visible when the area under tensile strength ranges over one order of magnitude from 450 to 4624 mm^2. This observation becomes relevant when selecting the tensile strength values of lithologies.

Keywords: hydraulic fracturing, Brazilian Disc test, Modified Tension Test, Acoustic Emission, numerical simulation

1. Introduction

Tensile strength tests are widely applied in rock mechanics to obtain input parameters for planning of hydraulic fracturing on all scales. In literature only few experimental data sets are published dealing with samples size effects on tensile strength tests [1,2] or the comparison of different tensile tests in general [1,3]. Usually, results of laboratory tensile

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tests are taken to be size independent when used as input parameter for numerical studies at different spatial sizes.

We compare the results of 3 different, easily applicable laboratory tests for tensile strength of rocks. The sample set comprises a micritic limestone, a coarse-grained marble, a fine-grained Ruhr-Sandstone, a medium-grained rhyolite, a medium- /coarse-grained andesite and a medium grained sandstone. All tested rocks were characterized petrographically as well as by ultrasonic velocities, density, porosity, permeability, static, dynamic elastic moduli and compressive strength. In order to determine the effects of specimen size on test results, we carried out BDT according to ISRM [4] with disc diameters of 30, 40, 50, 62, 75 and 84 mm, respectively. The recently presented MTT [5] was used as a tensile strength test with an approximately uniform tensile stress distribution. Hydraulic tensile strength was evaluated by MF experiments (core diameter 40 and 62 mm; borehole/diameter ratio 1:10) under uniaxial compression [6]. MF pressurization was performed with a constant fluid volume rate of 0.1 ml/s representing a stress rate of 0.3 MPa/s. In all tests relevant acoustic emission (AE) values have been evaluated to get additional information on the failure processes.

2. Materials and methods

2.1. Sample material

To investigate the influence of rock properties on tensile test methods, six different rock types were tested. Bebertal sandstone, a medium grained Permian sandstone from a quarry near Magdeburg, Germany. Ruhrsandstone, a fine-grained and massive Carboniferous arcose from the Ruhr area in Germany. A medium to coarse grained, jointed Permian andesite from the Doenstedt Eiche quarry near Doenstedt, Germany. A medium grained, highly jointed Permian rhyolite from the Holzmuehlental quarry near Flechtingen, Germany. A micritic Jurassic limestone from a quarry near Treuchtlingen, Germany and a coarse grained marble from Carrara, Italy. The rocks' petrophysical properties, namely bulk density, grain density, compressional wave speed, porosity, permeability, cohesion and friction angle are listed in Table 1.

2.2. Petrophysical characterization

Dry densities are calculated geometrically based on geometrical properties, grain densities are measured according to DIN 18124. Compressional wave velocities are measured at each core with a Geotron USG 40/UST 50-12 at room temperature and in dry condition. Porosities are derived from the difference between grain density and geometrical density of the oven-dried samples. Permeabilities are evaluated via a constant head test on the hollow cylinder samples used for the MF tests [7]. Bebertal-sandstones are permeable enough to use a simple axial flow-through test with a maximum pressure difference of up to 3 bars. The samples are sealed off with rubber jackets to minimize water-flow along the sample surface. Unconfined compressive strengths and static moduli of elasticity are measured by uniaxial compressive tests [8].

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Rock type (location)	ρ_d [g/cm^3]	ρ_s [g/cm^3]	vp [m/s]	Φ [%]	k [m^2]	c [MPa]	φ [°]
Marble (Carrara)	2.71 ±0.002	2.721 ±0.003	5.67 ±0.06	0.40	1E-19	29	22
Limestone (Treuchtlingen)	2.56 ±0.008	2.713 ±0.002	5.59 ±0.05	5.64	1E-18	27	53
Ruhrsandstone (Ruhr area)	2.57 ±0.006	2.688 ±0.008	4.61 ±0.13	4.39	8E-18	36	50
Rhyolite (Flechtingen)	2.63 ±0.015	2.657 ±0.011	5.39 ±0.34	1.02	9E-19	20-36	55
Andesite (Dönstedt)	2.72 ±0.023	2.734 ±0.006	5.26 ±0.28	0.51	-	20-41	50
Sandstone (Bebertal)	2.66 ±0.061	2.44 ±0.059	3.61 ±0.61	8.27	11E-15	15	45

Table 1. Averaged values of petrophysical properties of the rock samples. ρ_d dry bulk density, ρ_s grain density, vp compressional wave velocity, Φ porosity, k permeability, c cohesion, φ friction angle.

2.3. Testing procedure of the tensile strength tests

All experiments are performed in a stiff servo-hydraulic loading frame from Material Testing Systems (MTS) with a load capacity of 4000 kN. For further details on the technical specifications see Table 2.

Device (manufacturer) name	max. capacity	accuracy	BDT	MTT	MF
Axial load cell (Althen) CPA-50	500 KN	± 100 N	x	x	x
Axial displ. transducer (Scheavitz) MHR 250 LVDT 1 & 2	6.3 mm	± 1•10^{-4} mm	x	x	x
Displ. transducer at pressure intensifier (HBM) WA 100 mm LVDT 3	100 mm	± 1•10^{-3} mm			x
Load cell for Hoek Cell					
Load cell for pressure intensifier (Burster) 8219R-3000	300 MPa	± 0,03 MPa			x

Table 2. Technical specifications of the measurement system.

Acoustic Emission (AE) signals are acquired with an AMSY-5 Acoustic Emission Measurement System (Vallen Systeme GmbH, Germany) equipped with up to 6 Sensors of type VS150-M. The Sensors are sensitive in a frequency range of 100-450 kHz with a resonance frequency of 150 kHz and a preamplification of 34 dB_{AE}. Due to machine noise in the range below 100 kHz incoming signals are filtered by a digital bandpass-filter in a frequency range of 95-850 kHz.

AE data are sampled by a sampling rate of 10 kHz. The sensors are fixed using hot-melt adhesive to ensure best coupling characteristics. Pencil-break tests (Hsu-Nielsen source) and sensor pulsing runs (active acoustic emission by one sensor) are used to ensure good sensor coupling of the sensor on the sample.

2.3.1. Hydraulic fracturing core experiments (MF) procedure

Minifrac experiments are carried out mainly on 40 mm cores with a borehole diameter of 4mm. Furthermore some 62 mm cores with a borehole of 6 mm diameter are tested. The samples are loaded axially up to 5 MPa to ensure that the packer mechanism is tight and seals off the borehole openings at the top and at the bottom. The borehole pressure was raised servo controlled with a fixed volume rate of 0.1 ml/s that results in a pressure rate of approximately 0.3 MPa/s. All MF tests are monitored by Acoustic Emissions with four sensors glued directly to the samples and a fifth sensor placed at the incoming hydraulic line.

2.3.2. Brazilian Disc Tests (BDT) procedure

All Brazilian disc tests are carried out following the ISRM suggested method [4] at a load rate of 200 N/s. Disc diameters used are 30, 40, 50, 62, 75 and 84 mm, whereas the length to diameter ratio (L/D) was constant at 0.5. All tests are monitored by one AE-sensor glued directly in the middle of the disc specimen. The size dependency is tested with discs from Ruhrsandstone, marble, rhyolite and limestone.

2.3.3. Modified Tension Test (MTT) procedure

The MTT tests are driven load controlled at a rate of 200 N/s that corresponds to a stress rate of 0.02 MPa/s. The axial force is applied from the top (Figure 1). MTT test samples are observed by up to 6 AE-Sensors glued directly to the specimen. The samples were overcored with 62 mm and 30 mm diameters where the overlapping height is 1/3 of the total sample height (Figure 1). The centralizing of the drills was achieved by using a former plate to adjust the sample before drilling. Despite assiduously arrangement the eccentricity of the overcoring was in the range of up to 3 mm due to the imprecise vertical guidance of a standard drilling machine. In order to test the influence of eccentricity we also prepared samples with an eccentricity of 14 mm.

3. Experimental results

3.1. Brazilian disc test size dependency

The size dependency of the absolute size of the Brazilian disc test discs on the tensile strength is shown in Figure 2. Overall 138 Brazilian disc tests are undertaken for up to 6 sizes and four lithologies. The disc diameters, ranging from 30-84 mm, represent the sizes that are mostly tested in laboratories to determine the BDT tensile strength of rock samples. The results of the size dependency tests show no significant relationship between the sizes of the tested disc to

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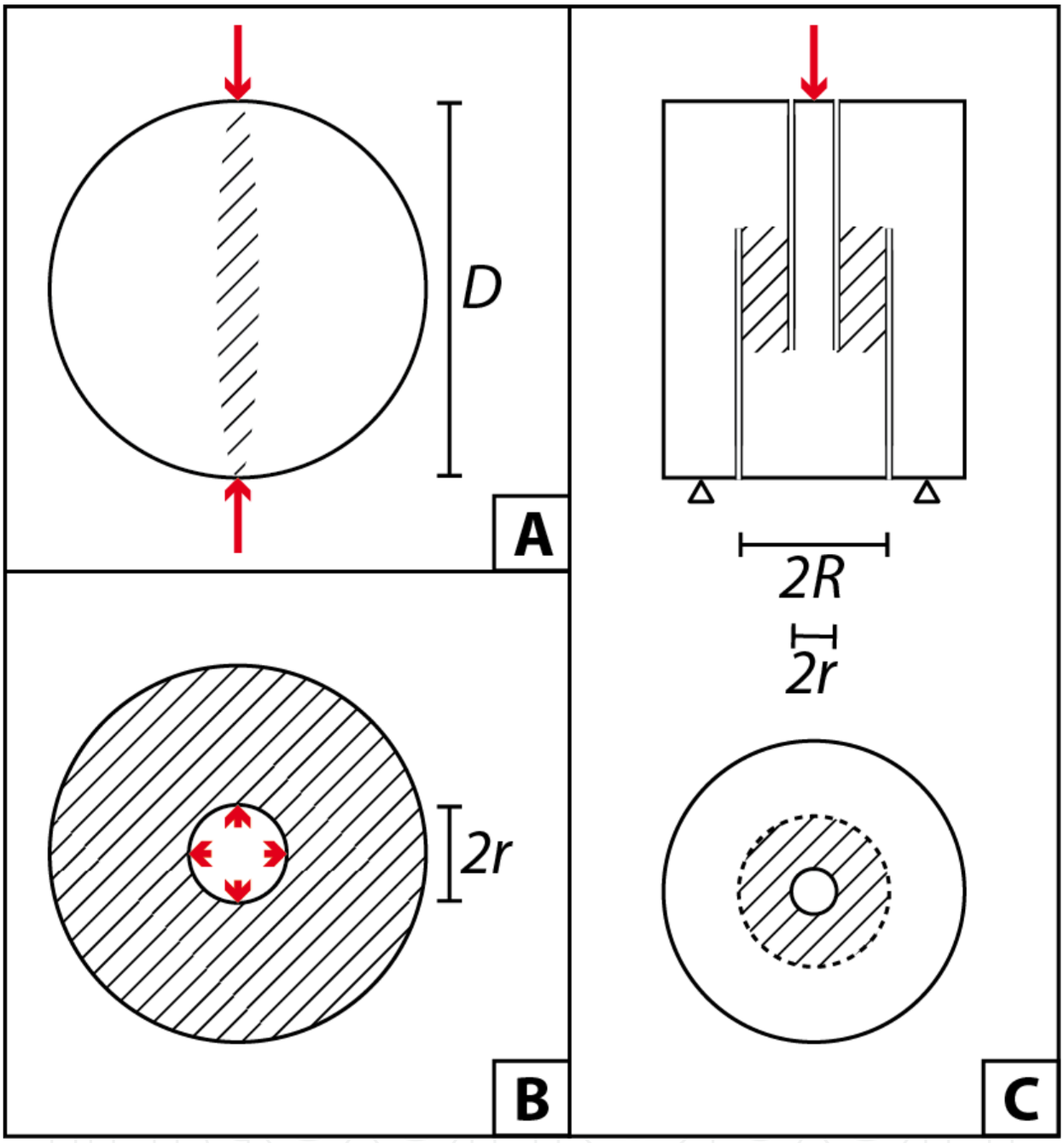


Figure 1. Sketches of the three tensile test methods. A: BDT side view, B: MF top view, C: MTT side view cross section (upper) and top view (lower).

its calculated tensile strength as long as the length to diameter ratio is held constant as suggested by the ISRM suggested method at a value of 0.5 [4]. There is a marginal tendency for the standard deviation of the tensile strength to decrease with increasing disc size.

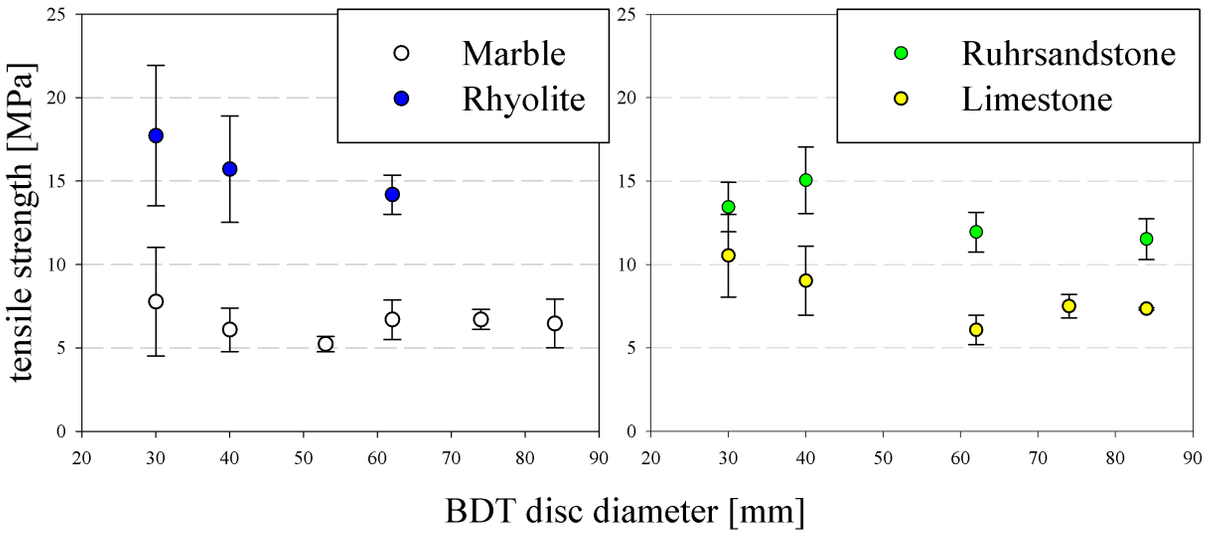


Figure 2. Size dependency of the BDT disc size on the tensile strength for four lithologies. Circles represent the mean values, bars stand for the standard deviation.

3.2. MF, BDT and MTT tensile strength results

Three different methods for the determination of tensile strength are compared regarding their results. 201 Brazilian disc tests, 31 Minifrac tests and 15 Modified tension tests form the basis of the data evaluation, where σ_t^{BDT}, σ_t^{MF} and σ_t^{MTT} are the tensile strengths indexed by the used method. BDT tensile strengths are calculated as follows [4].

$$\text{BDT: } \sigma_t^{BDT} = 2P / \pi Dt \tag{1}$$

Where P is the force at failure, D is the disc diameter and t the disc thickness.

For the MF tests, assuming the rocks to be nearly impermeable and therefore neglecting a relevant pore pressure influence the tensile strength is given directly by the breakdown pressure P_b [9].

$$\text{MF: } \sigma_t^{MF} = P_b \tag{2}$$

MTT tensile strengths are evaluated by the formula given by [5].

$$\text{MTT: } \sigma_t^{MTT} = F_{max} / A_{TZ} = F_{max} / \left(R^2\pi - r^2\pi\right) \tag{3}$$

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Where R^2 and r^2 are the outer and inner radius, respectively (Figure 1). Mean values, standard deviations and total number of tests for all three testmethods can be found in Table 3.

Lithology	Test method	Mean [MPa]	Std. dev. [MPa]	N [-]
Ruhrsandstone	BDT	13.2	2.1	32
	MF	19.0	3.0	10
	MTT	5.8	1.0	3
rhyolite	BDT	15.8	3.2	39
	MF	20.1	5.5	5
	MTT	4.9	1.4	2
limestone	BDT	8.2	2.2	36
	MF	10.2	1.7	5
	MTT	4.8	1.0	2
marble	BDT	6.4	1.5	32
	MF	7.8	1.3	4
	MTT	4.3	1.2	2
andesite	BDT	14.6	4.5	23
	MF	14.4	5.1	4
	MTT	8.7	4.4	3
Bebertal sandstone	BDT	4.1	1.2	39
	MF	4.3	2.0	3
	MTT	2.4	-	1
	MTT eccentric	1.0	5E-3	2

Table 3. Comparison of tensile strength out of three test methods.

One of the main observations is the very low tensile strength measured with the Modified Tension Test method. The MTT results mean values are in the range of 66 % down to 31 % of those obtained with the BDT. In addition to the low tensile strengths obtained by the MTT an eccentricity of the overcoring yields to an additional underestimation of the tensile strength values. The BDT and MF results seem to be more similar. The BDT results lie in the range of 70 % to 100 % of the MF tensile strength, so the MF test yields the highest tensile strengths and also to the highest standard deviations. All measurements are visualized in Figure 3. Doenstedt andesite and Flechtingen rhyolite tensile strengths have the highest standard deviations of the tested rock types. This variance is due to the high amount of natural joints that are assumed to have a different tensile strength with respect to the intact parts. Therefore the tensile strength scattering is the result of the material heterogeneity itself.

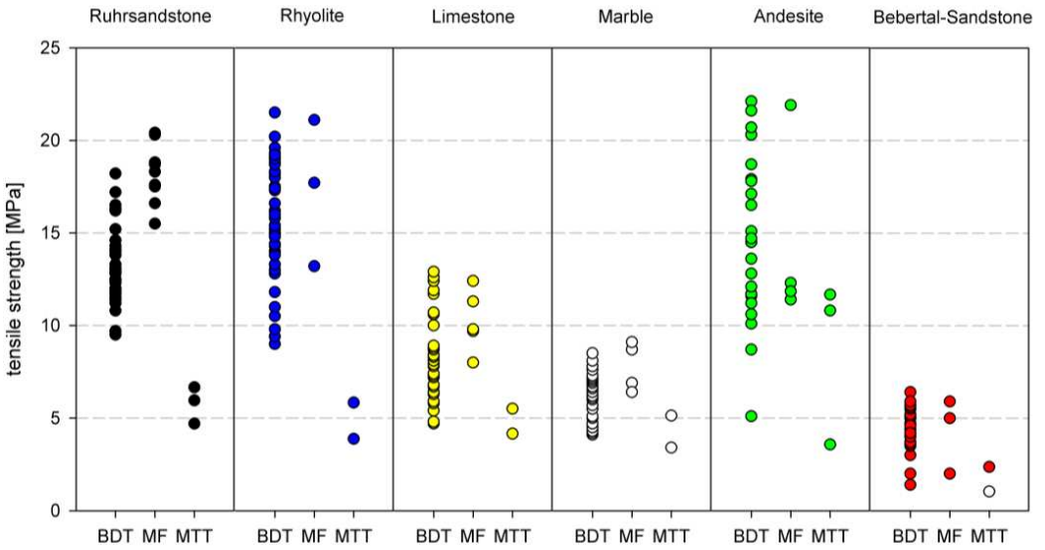


Figure 3. Results of all tensile strength test. BDT: Brazilian Disc Test, MF: Minifrac, MTT: Modified Tension Test. Hollow circle in Bebertal sandstone MTT tests represents two results of the highly eccentrical MTT tests.

3.3. Acoustic Emissions results

Acoustic emission data obtained during the tests give rough insights into the failure processes. It is obvious that all tests end with a spalling of the specimens in parts due to a complete tensile failure. Simple AE count analysis show that the BDT is accompanied with an immense hit-rate long before total failure in comparison to the relatively quiet pre-failure phases of the MF and MTT tests. In good agreement with theoretical considerations of the stress distribution in the Brazil disc [1] these events are most likely due to compressional failure at the top and bottom of the disc, accompanied with crack propagation and coalescence before peak load (Figure 4).

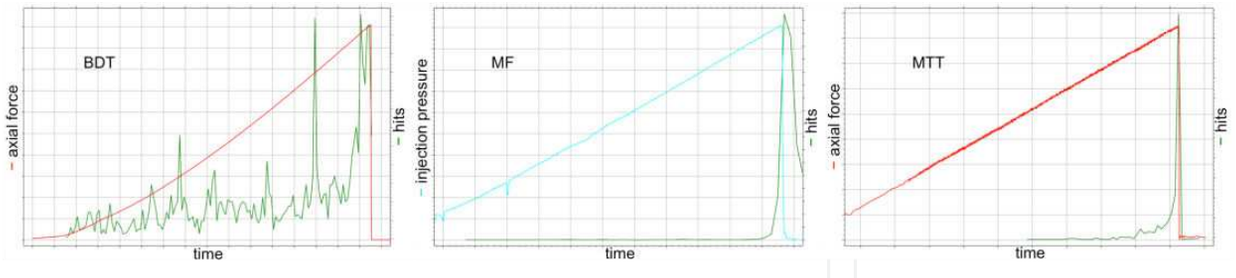


Figure 4. AE hits per 0.5 sec., BDT left, MF middle and MTT right showing the huge difference in AE hits before total failure of the sample.

4. Numerical model

We investigate the effect of eccentricity of the overcoring for the MTT samples by a numerical simulation. A finite element study that has been performed by Plinninger et al. [10] that shows

http://dx.doi.org/10.5772/56300

a uniform tensile stress distribution in the annulus of the test samples. It is arguably if this model is the right tool for modeling a tensile stress distribution in rock samples prior to failure. A simple linear elastic 3D FEM model reveals tensile stress concentrations at the edges of the rims in the sample (Figure 5). Fractures may be initiate there at relative low axial forces.

During preparation of the samples it becomes obvious that exact centralization of the inner overcoring is not always given. Two Bebertal sandstone samples were prepared with a eccentricity of 14 mm resulting in a minimum rim width of 2 mm instead of 16 mm for a perfectly centralized sample. The average eccentricity of our samples is in the range of up to 3 mm. Tensile stress redistribution due to eccentricity is modeled as well and can easily double the tensile stress in the thinner rim of the annulus (Figure 5).

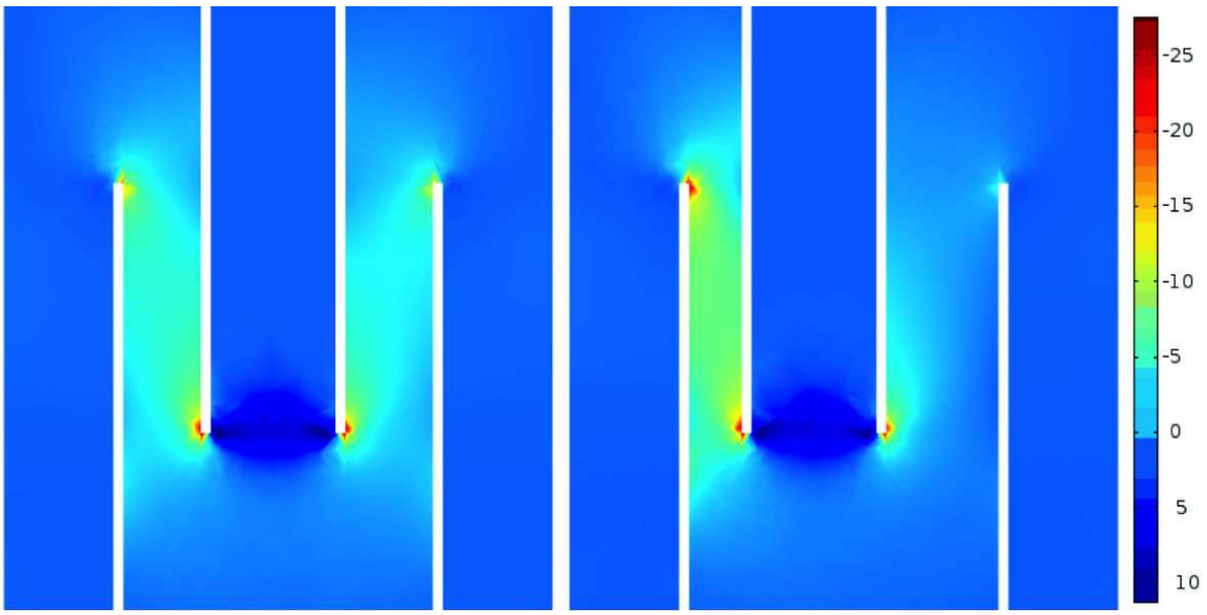


Figure 5. Slice through a linear elastic 3D FEM model of MTT tensile test. Values of axial stress are given in MPa where negative values stand for tensile stress. Left model represents a perfectly centralized sample. Right model shows the stress distribution for a eccentricity of 6 mm towards the left edge.

5. Discussion

247 tensile strength test results of BDT, MF and MTT tests vary considerable within one lithology (Figure 6). Therefore it is not trivial to give a reliable prediction of the tensile strength parameter. Results of the BDT tests show no significant variation with respect to the specimen size, as long as the aspect ratio is held constant. Nevertheless the tensile strength data scattering is high, so that it may obscure existing trends. Acoustic Emission evaluation shows that during the BDT multiple fracturing mechanisms are present. Before total fracturing of the sample by a tensile rupture there is a high amount of AE activity that is most likely related to compressional failure at the top and bottom of the disc. Beside this, compressional stress concentrations and the inhomogeneous tensile stress distribution may lead to tensile cracks before peak load.

MF results lead to the highest tensile strengths in this comparison where there seem to be no differences in tensile strength when using a 4 mm or a 6 m borehole for pressurization. Again one has to take into account that the high amount of tensile strength scattering for these tests inhibits a statement regarding a borehole size dependency.

The results of the MTT tests give the lowest tensile strengths and very low standard deviations. Latter may be related to the small amount of testes MTT per lithology. Furthermore all MTT are prepared using the same sample sizes. A major problem of the MTT experiments is the centralization of the boreholes. An eccentricity yields to a significant inhomogeneity of the tensile stress distribution in the sample (Figure 5). Numerical simulations of the MTT eccentricity effect together with the two eccentric MTT samples (Figure 3) show that the calculated tensile strength may be underestimated massively. One reason for the apparently lower tensile strength measured using the MMT might be the applicability of Equation (3). In deriving the equation, it was assumed that, when the peak load is approached, the tensile stress distribution is almost uniform in the area defined as A_{TZ} [5]. This may only be true if the material is highly ductile. However, for brittle rocks, especially for highly fractured rocks, fracture propagation may occur and lead to ultimate failure at a much lower load as suggested by Equation (3) due to stress concentration (Figure 5).

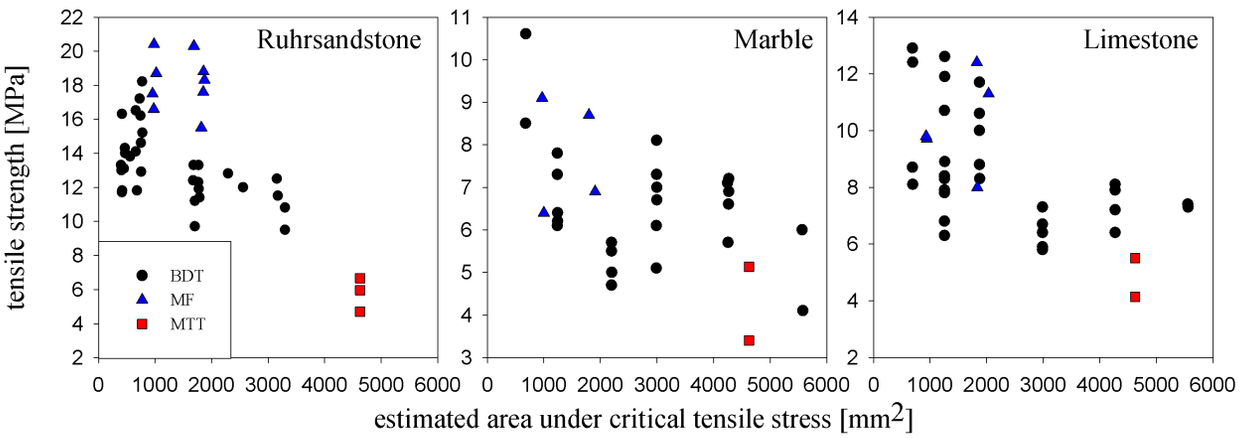


Figure 6. Tensile strength results plotted against the assumed area under tension. BDT: diameter x thickness, MF: surface area of the borehole and MTT: twice the surface area between the outer and inner borehole, upper and lower.

Testmethod	BDT	MF	MTT
Area under 1,51,5	450-3400 mm²	1005-3393 mm²	4624 mm²
Calculation	$D \cdot t$	$2 \cdot \pi \cdot rbh \cdot l$	$2 \cdot (\pi \cdot (R^2 - r^2))$

Table 4. Estimated area subjected to tensile stress for the different tensile tests. *D*: BDT disc diameter, *t*: BDT disc thickness, *rbh* : MF borehole radius, *l*: MF sample height, *R*: MTT outer borehole radius, *r*: MTT inner borehole radius.

Main difference in all experiments and the reason for choosing these are the areas that are under tensile stress at the point of failure. The calculated tensile strengths compared to the area perpendicular to the maximum tensile stress show a negative trend for the tensile strength

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with increasing area being set under tensile stress. That is reasonable in terms of the statistical theory of strength. Especially for the igneous rocks it seems evident, that the probability to set a healed joint under a critical tension rises with the size of the sample volume that is under tensional stress. For the selection of the tensile strength test one should keep in mind that depending on the lithology the apparent tensile strength appears to be a function of the area, or more exact of the volume under tensile stress. Thus, for a relative homogeneous rock a less severe reduction of the measured tensile strength with size will be visible as it will be at the highly fractured igneous rocks tested in this study.

It is arguable and may not be appropriate to study the effect of area/volume under tensile stress on the measured tensile strength using the combined results from different types of tests, especially if the different tests tend to give different average measured tensile strengths. Furthermore the negative trend of tensile strength with respect to the stressed area/volume is not that obvious for the single test methods. Especially the assumption of uniform tensile stress distribution close to peak load in the annulus [5] for the MTT samples seems not to be comprehensible. It may hold for ductile materials but not for brittle ones. Therefore the validity of equation (3) for the calculation of the tensile strength is questionable. Nevertheless the resulting tensile strengths are treated as the same rock property when used as input parameters for calculations. This is very problematic due to its huge variation as shown in the tests. The correlation of the calculated tensile strength with the stressed area/volume is one possible approach to account for the decreasing apparent tensile strength behavior.

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