PROGNOSIS OF UNI-AXIAL COMPRESSIVE STRENGTH AND STIFFNESS OF ROCKS BASED ON POINT LOAD AND ULTRASONIC TESTS

PROGNOSE DER EINAXIALEN DRUCKFESTIGKEIT UND STEIFIGKEIT VON FESTGESTEINEN AUF DER BASIS VON PUNKTLASTVERSUCHEN UND DURCHSCHALLUNG

PROGNOSTIC DE LA RESISTANCE A LA COMPRESSION UNI-AXIALE ET LA RIGIDITE DE ROCHE A LA BASE D'ESSAIS A CHARGE PONCTUELLE ET A ULTRA-SON

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SUMMARY

The strength- and deformation properties of in total 10 different rock types of South West Germany were investigated by uni-axial compressive tests according to E1-AK 19 (3) and modified point load tests with deformation measurement. Additionally the dynamic characteristics of rock were determind by ultra-sonic measurements.

Within the framework of test evaluations the measuring values of static and dynamic modulus of elasticity, of compressive strength and dynamic and static modulus of elasticity and of stiffness in the point load test for the different rock types were correlated.

ZUSAMMENFASSUNG

Die Festigkeits- und Verformungseigenschaften von insgesamt zehn verschiedenen Festgesteinsarten Südwestdeutschlands wurden mittels einaxialer Zylinderdruckversuche gem. E1-AK 19 (3) und mittels modifizierter Punktlastversuche mit Verformungsmessung untersucht. Zusätzlich wurden die dynamischen Gesteinskenngrößen mit Hilfe von Ultraschallmessungen bestimmt.

Im Rahmen der Versuchsauswertungen wurden die Meßwerte von statischem und dynamischem E-Modul, von Zylinderdruckfestigkeit und dynamischem E-Modul und von statischem E-Modul und der Steifigkeit im Punktlastversuch für die verschiedenen Gesteinsarten korreliert.

RESUME

Les propriétes de réstistance et déformation de, au total, 10 types différents de roche d'Allemagne de Sud-Ouest ont été investigées par essais de compression uni-axiaux selon E1-AK 19 (3) et par essais à charge ponctuelle modifiés avec mesure de déformation. En outre les caractéristiques dynamiques de roche ont été déterminées par mesures à ultra-son.

Dans le cadre des évaluations d'essai les valeurs mesurées du module d'élasticité statique et dynamique, de réstistance à la compression et module d'élasticité dynamique et de module d'élasticité statique et de la rigidité dans l'essai à charge ponctuelle de différents types de roche ont été correlées.

KEYWORDS: Strength of rock types of South West Germany, dynamic characteristics of rock types of South West Germany, point load test with deformation measurement for rock specimen, stiffness of rock in point load test, correlation of rock characteristics.

1. INTRODUCTION

For construction works in rock formations the uni-axial compressive strength is often used as one of the criteria for reimbursement. As a basis, the classification schemes in DIN 18301, Bohrarbeiten, (5) and DIN 18319, Rohrvortriebsarbeiten, (6) should be mentioned. In these, rocks are classified according to uni-axial compressive strength and fissuring.

Because of the low costs and speed at which the results are available, index tests for indirectly determining the uni-axial compressive strength are important. For these reasons tests such as the point load test and sometimes ultrasonic testing are quite often used by contractors and consulting engineers.

On large projects such as traffic tunnels and pipe jacking work rock samples are taken on a routine basis from different sections for stength testing. Thus it is possible to check the prognosticated strength of the rock and determine any deviations that could lead to change in the remuneration for the work carried out. Often the first checks are carried out using index tests.

The correlation factor with which the uni-axial compressive strength is calculated from the strength index is dependent on the rock type (13), (14) and should in order to obtain absolutely correct results be determined by reference tests in advance. In practice however an average correlation factor of $\alpha = 24$ which is recommended in E5-AK 19, (4) is often used with no differentiation of rock type. Recent tests (1), (11), (12) however show that the deviation of the correlation factors for different rock types from the combined average value can be so large that an exact determination for the purpose of fixing the remuneration of the construction work can be important. This is especially important when differences of opinion occur in border line cases.

Obtaining and preparation of rock cores for uni-axial compression tests is however often very expensive. In order to obtain more precise values for the correlation factors for the point load test two theses (11), (12) were carried out at the FMPA. In these theses strength tests on ten different rock types in South West Germany were carried out. The rock types include both sedimentary as well as igneous rocks. Similar tests with partly different aims have been carried out at Graz university in Austria (1) on alpine rocks.

The tests carried out in (11) and (12) were also used to correlate between:

- static modulus of elasticity and dynamic modulus of elasticity
- uni-axial compressive strength and dynamic modulus of elasticity
- static modulus of elasticity and stiffness in point load test.

2. SELECTION OF ROCK TYPES AND BLOCKS FOR THE INVESTIGATION

The sedimentary and igneous rocks investigated represent a group which is also important outside the borders of Baden-Württemberg as a raw material and thus important in construction works. The size of the blocks of rock taken from the various locations was so selected that the cores with a diameter d of 74 mm and a length l at least equal to the diameter $l/d > 1$, ideally $l/d \geq 2$ could be taken.

	sedimentary rock	
1	Katzenkopf	Stubensandstein
2	Ostfildern	Angulatensandstein
3	Dietersweiler	Plattensandstein
4	Dotternhausen	Oxfordkalk
5	Enzberg	Nodosuskalk
	igneous rock	
6	Detzeln	Paragneisanatexit
7	Bötzingen	Phonolith
8	Tegernau	Granit
9	Ottenhöfen	Quarzporphyr
10	Hohenstoffeln	Olivin-Nephelinit

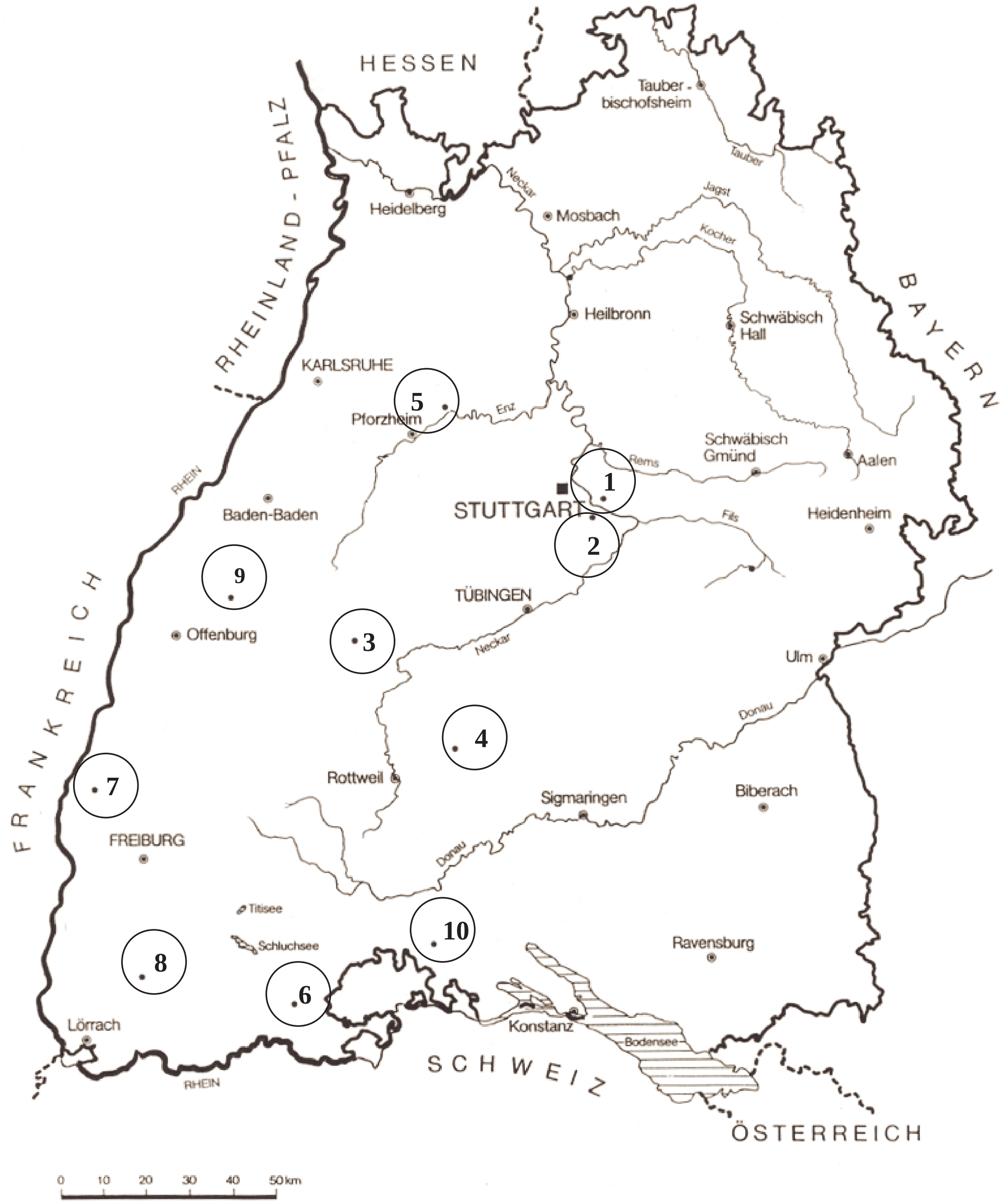

fig. 1: *Locations of the rock types investigated*

3. DESCRIPTION OF TEST PROCEDURES

3.1 Ultrasonic measurements

The dynamic rock properties are determined by sending sound waves through the sample. The speed of ultrasonic longitudinal waves as well as the density of the sample are used to determine the dynamic modulus of elasticity.

$$E_{dyn} = \rho \cdot \mathrm{v}_{ul}^{\;2} \quad \text{(MPa)}$$

Th ultrasonic measurements in the test were carried out on rock cores.

3.2 Uni-axial compression test

The uni-axial compression test (3) is used to determine the compressive strength as well as the deformation characteristics of a rock sample under a one dimensional stress state in the laboratory. The compressive stress is the quotient of the uni-axial test load F and the area of the sample A

$$\sigma = \frac{F}{A} \quad \text{(MPa)}$$

The strain is the quotient of the sample deformation Δl and the original length of the sample l.

$$\varepsilon = \frac{\Delta l}{l} \quad (\;)$$

The static modulus of elasticity is determined in the linear part of the load deformation curve.

3.3 Modified point load test

In the point load test (4) a strength index I_s is determined which allows the uni-axial compressive strength to be estimated. The rock sample is placed between two cone shaped loading points and the load is increased until failure occurs.

The strength index I_s is the quotient of the failure load F_u and the square of the distance between the two loading points at the start of the test.

$$I_s = \frac{F_u}{a^2} \quad \text{(MPa)}$$

In order to compare results (4) recommends a standard distance between the loading points of a = 50 mm. The standardisation can either be achieved using a nomogramme (4) or with the following formula (11), (12):

$$I_{s(50)} = \left(\frac{14+0.175 \cdot a}{22.75}\right) \cdot I_s \quad \text{(MPa)}$$

The uni-axial compressive strength σ_u is estimated using a correlation factor α which is typical[1)] for the rock type:

$$\sigma_u = \alpha \cdot I_{s(50)} \quad \text{(MPa)}$$

In the standard point load test the deformation of the sample during the test is not measured. In the modified point load test (11) and (12) the deformation during the loading is recorded (see fig.2).

The slope of the deformation curve of a rock from a point load test can be looked upon as the stiffness of the rock. This stiffness is called (11) and (12)

[1)] The correlation factor α can be significantly different for a particular rock type when the samples have different origins (7), (8), (9).

I_s-modulus. This I_s-modulus is calculated from the linear part of the load deformation curve.

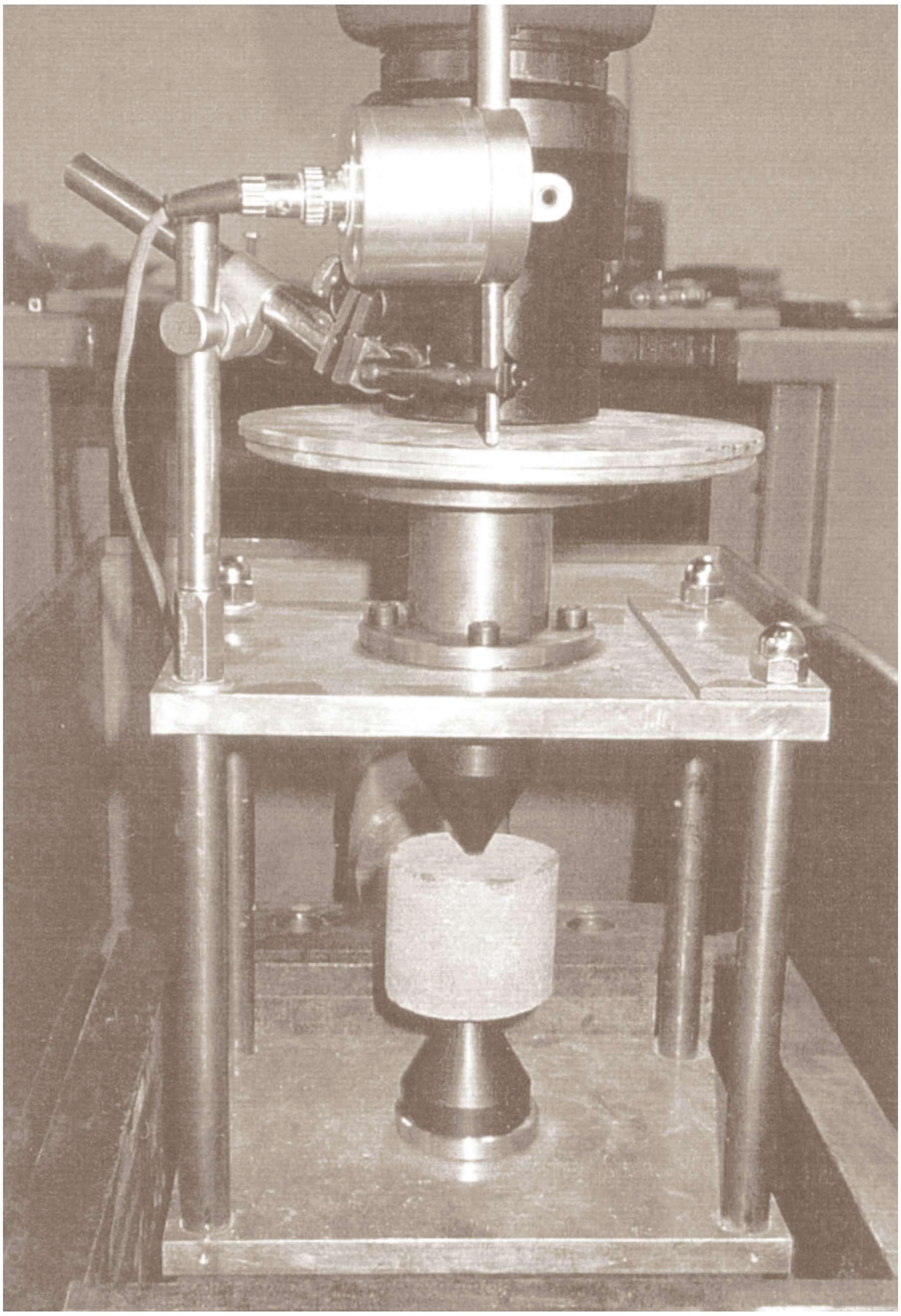

fig. 2: *Modified point load test with measurement of deformation*

The slope of the deformation curve of a rock from a point load test can be looked upon as the stiffness of the rock. This stiffness is called (11) and (12) I_s-modulus. This I_s-modulus is calculated from the linear part of the load deformation curve.

4. TEST RESULTS AND CORRELATIONS

The average values for the density, dynamic elasticity modulus, static elasticity modulus and compressive strength (tables 1 and 2) were calculated from 6 individual values for each rock type. The average of the standardised strength index $I_{s(50)}$ was calculated from 25 - 30 individual values for each rock type.

4.1 Correlation between point load strength and uni-axial compressive strength

The possible error in the calculation of the uni-axial compressive strength from the point load strength using a correlation factor $\alpha = 24$ is given by BIENIAWSKI (2) as 20 %. In table 1 the results of the test on sedimentary rocks carried out by LEHNE (12) are listed. The average values of a vary from a = 17.31 for Angulatensandstein to a =27.09 for Oxfordkalk. The values for igneous rocks tested by KNÖCHEL (11) (see table 2) lie between $\alpha = 9.64$ for Paragneisanatexit and $\alpha = 15.80$ for Olivin-Nephelinit. The quotient of standard deviation to the average values gives some idea of the statistical distribution curve.

tab.1: *Test results (Average) for sedimentary rocks*

Test results for sedimentary rocks						
		Platten-sandstein	**Nodosus-Kalk**	**Stuben-sandstein**	**Angulaten sandstein**	**Oxford-Kalk**
density ρ						
Average	[g/cm³]	2.35	2.64	2.16	2.38	2.56
Variation	[ ]	0.004	0.005	0.022	0.010	0.007
Dyn. E-modulus						
Average	[MPa]	17228	88146	5316	43163	59441
Variation	[ ]	0.049	0.068	0.314	0.046	0.100
Stat. E-modulus						
Average	[MPa]	9195	19773	2592	15169	16058
Variation	[ ]	0.100	0.150	0.214	0.003	0.186
Compressive strength σ_u						
Average	[MPa]	60.48	71.32	11.31	92.24	111.60
Variation	[ ]	0.046	0.087	0.288	0.099	0.083
$I_{s(50)}$						
Average	[MPa]	2.67	4.02	0.42	5.33	4.12
Variation	[ ]	0.128	0.303	0.369	0.399	0.144
I_s-modulus						
Average	[MPa]	80.04	154.29	18.48	126.42	161.02
Variation	[ ]	0.184	0.202	0.204	0.180	0.186
Factor α	[ ]	22.66	17.74	27.05	17.31	27.09

tab.2: *Test results (Average) for igneous rocks*

Test results for igneous rocks						
		Granit	**Paragneis-anatexit**	**Quarz-porphyr**	**Phonolith**	**Olivin-Nephelinit**
density ρ						
Average	[g/cm³]	2.61	2.76	2.52	2.40	3.12
Variation	[ ]	0.010	0.014	0.004	0.021	0.004
Dyn. E-Modul						
Average	[MPa]	64631	70227	57430	62242	137918
Variation	[ ]	0.057	0.080	0.059	0.111	0.040
Stat. E-modulus						
Average	[MPa]	28481	13454	22156	25045	40000
Variation	[ ]	0.041	0.173	0.076	0.090	0.062
Compressive strength σ_u						
Average	[MPa]	154.23	112.42	166.88	198.17	311.97
Variation	[ ]	0.101	0.086	0.114	0.194	0.062
$I_{s(50)}$						
Average	[MPa]	10.62	11.66	12.35	13.62	19.74
Variation	[ ]	0.162	0.267	0.162	0.278	0.163
I_s-modulus						
Average	[MPa]	456	333	580	421	584
Variation	[ ]	0.484	0.319	0.477	0.697	0.288
Factor α	[ ]	14.52	9.64	13.52	14.54	15.80

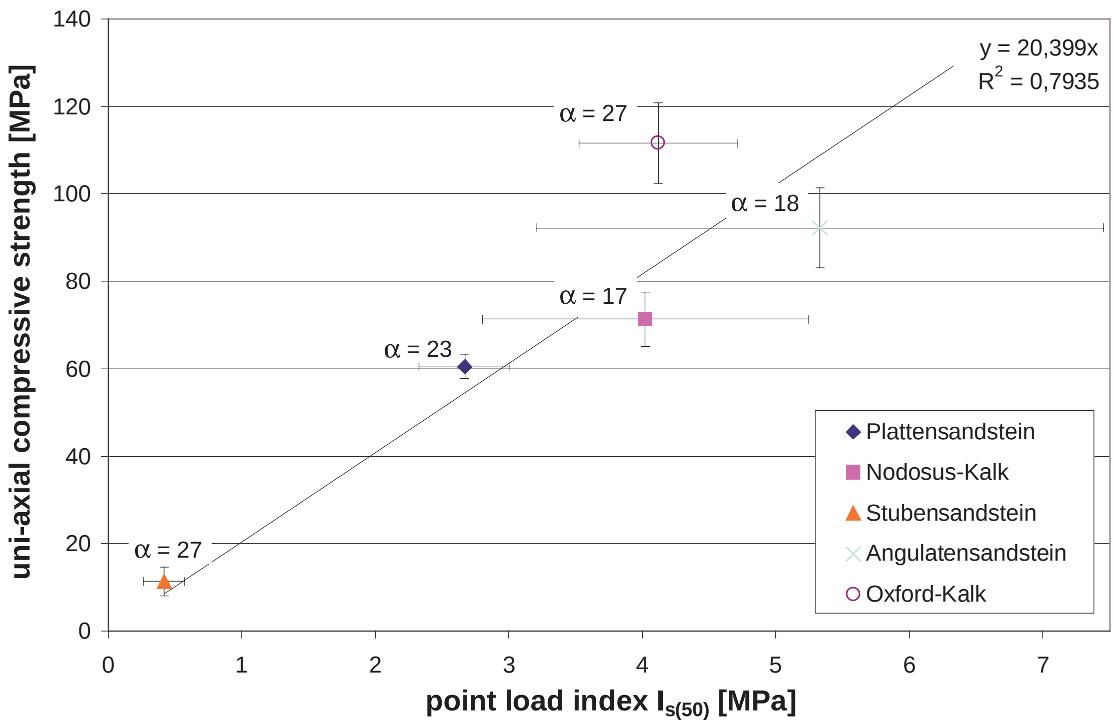

fig. 3: *Correlation factors α for sedimentary rocks*

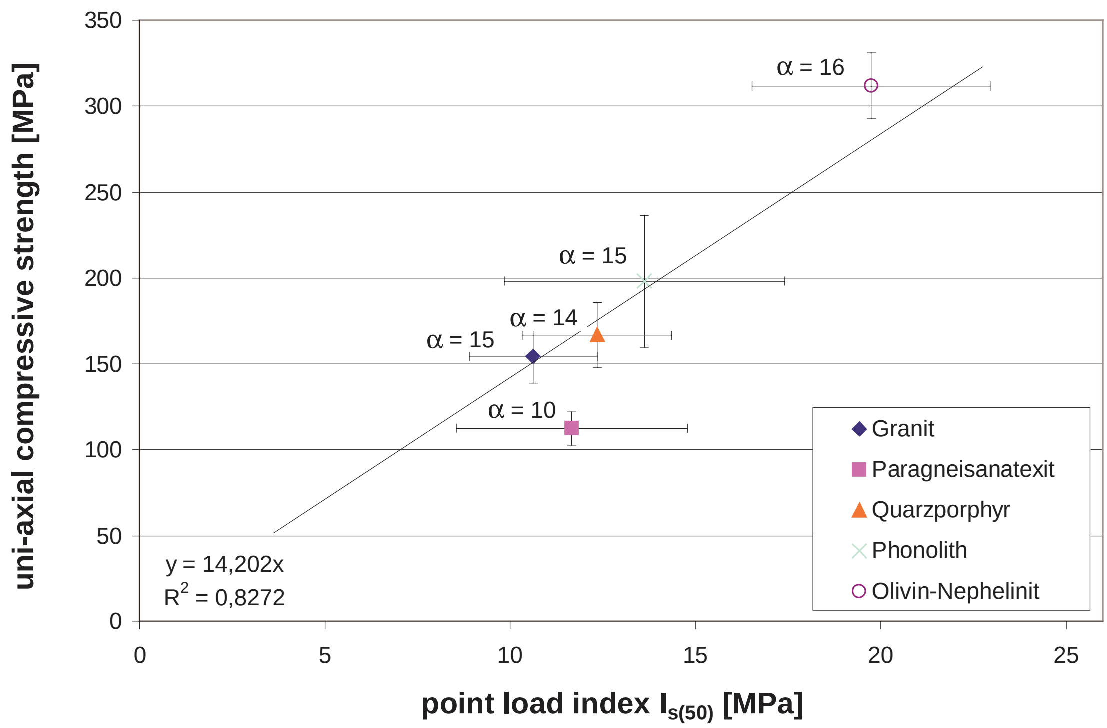

fig. 4: *Correlation factors α for igneous rocks*

4.2 Correlation between dynamic elasticity modulus and static elastictity modulus

The dynamic elasticity modulus is generally higher than the static elasticity modulus. HENKE, GAY, KAISER (1974), (10) showed that for rock types with $E_{dyn} < 50000$ MPa there is a linear correlation with $E_{stat} = 0.7388\ E_{dyn}$. The correlation was for both sedimentary and igneous rocks. The number of samples was however small.

The tests by LEHNE (1998), (12) on sedimentary rocks and by KNÖCHEL (1998), (11) on igneous rocks also show a large number of samples a linear correlation but the correlation factors are much smaller.

Sedimentary rocks: $0.224 < E_{stat}/E_{dyn} < 0.534$, Average = 0.373

Igneous rocks: $0.290 < E_{stat}/E_{dyn} < 0.441$, Average = 0.341

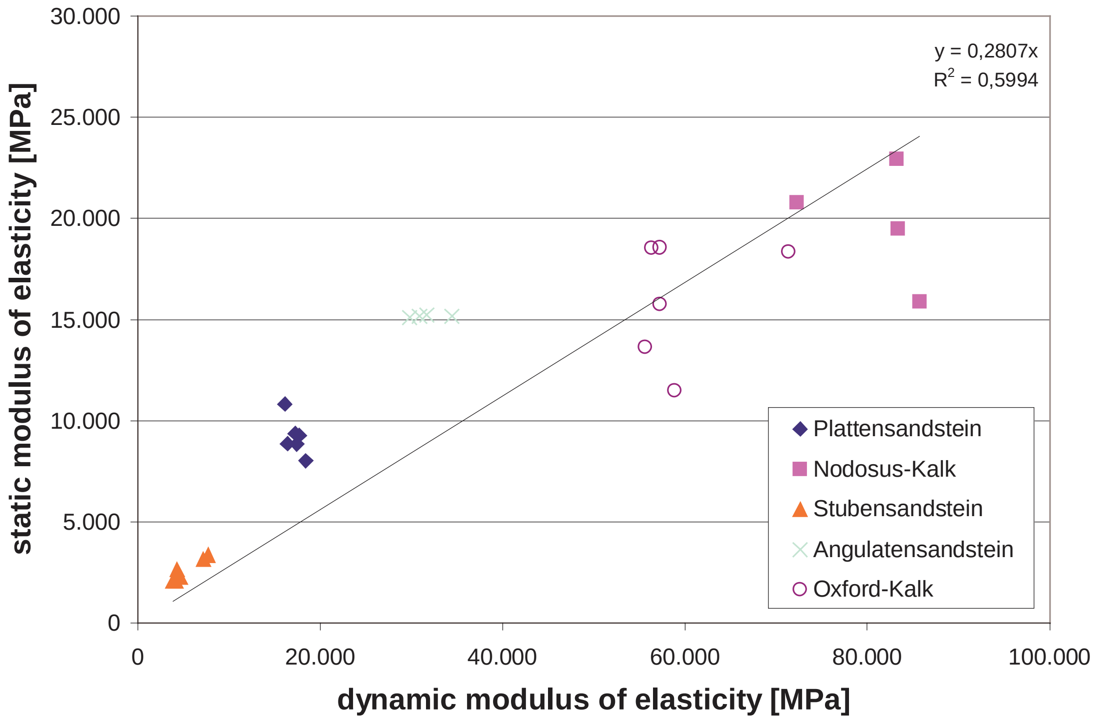

fig. 5: *Correlation between dynamic modulus of elasticity and static modulus of elasticity for sedimentary rocks*

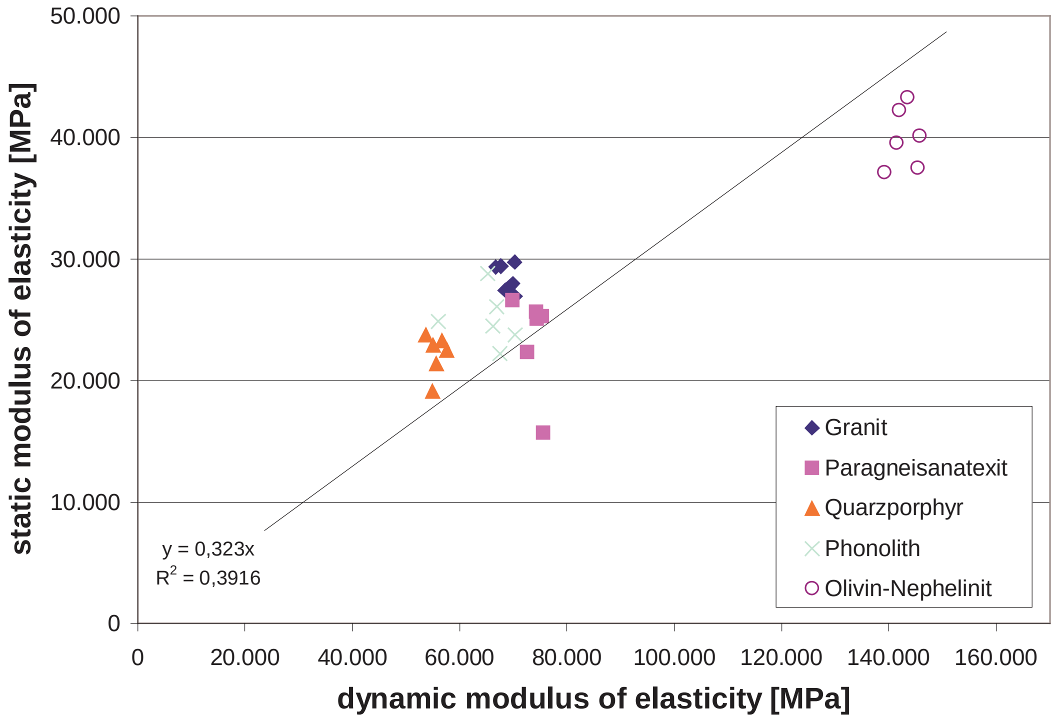

fig. 6: *Correlation between dynamic modulus of elasticity and static modulus of elasticity for igneous rocks*

4.3 Correlation between dynamic elasticity modulus and uni-axial compressive strength

The ultrasonic waves run predominantly through the dense rock matrix. Any cavities are circumvented using rock bridges. Dense rock matrices have high ultrasonic wave speeds. The dynamic E-modulus depends on the square of the ultrasonic wave speed and so dense rock matrices have high dynamic elasticity moduli. With regard to the compressive strength, any cavities have a negative influence since the area of the cavities have to be subtracted from the total area of the test sample.

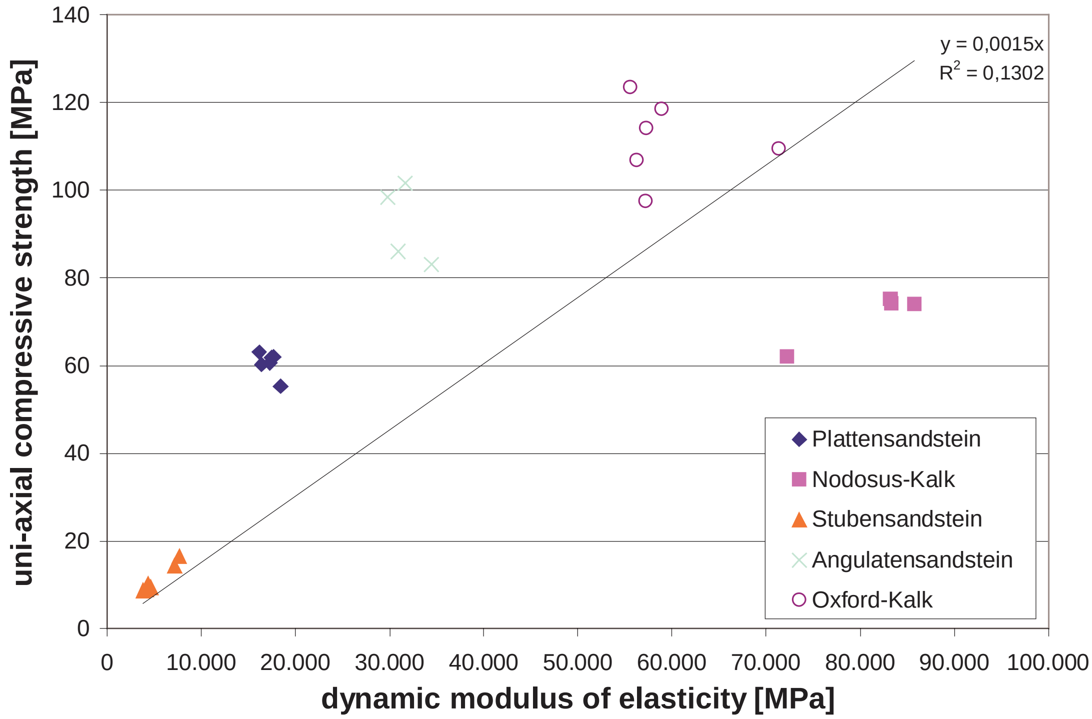

fig. 7: *Correlation between dynamic modulus of elasticity and uni-axial compressive strength of sedimentary rocks*

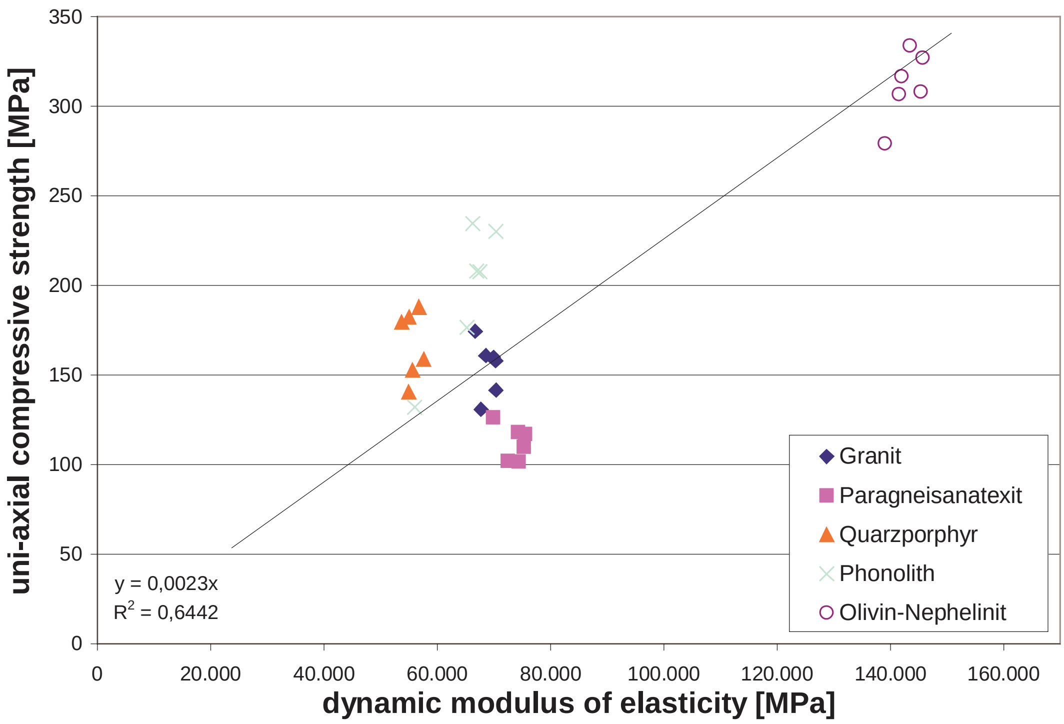

fig. 8: *Correlation between dynamic modulus of elasticity and uni-axial compressive strength of igneous rocks*

4.4 Correlation between I_s-modulus and static elasticity modulus

A comparison of the load deformation properties of rock samples in the uni-axial compression test and the point load test shows that for sedimentary rocks a good linear correlation exists (12) p. 50. On the other hand the results of the tests on igneous rocks did not show a very good correlation (11) p. 63.

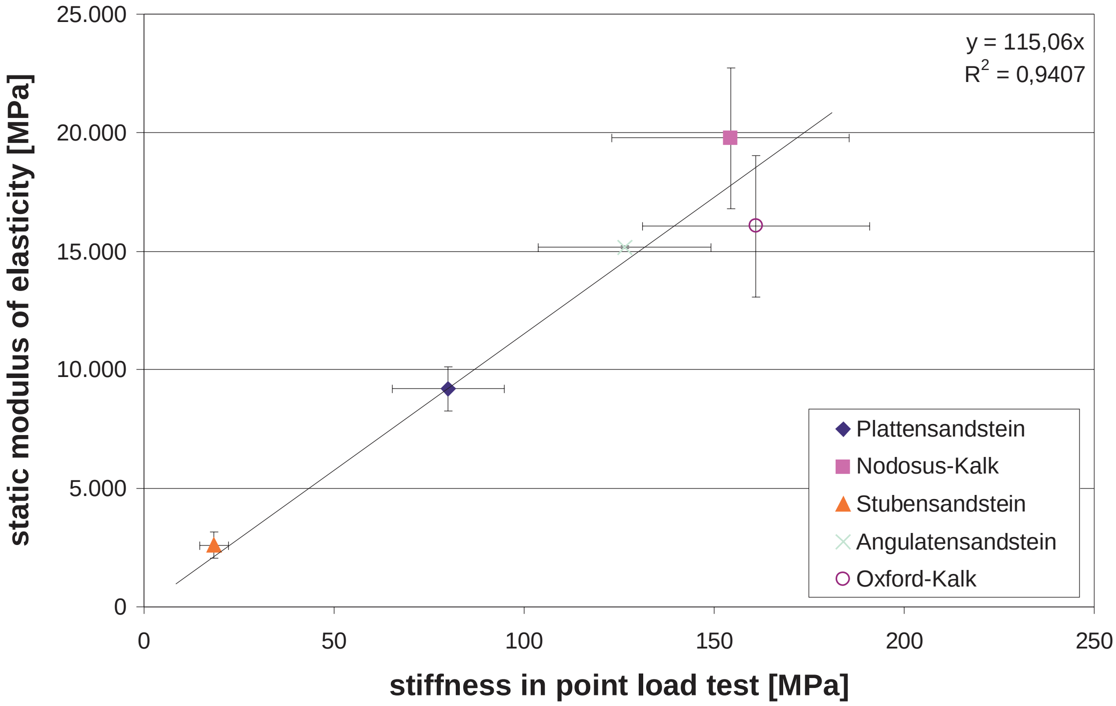

fig. 9: *Correlation between I_s-modulus and static modulus of elasticity for sedimentary rocks*

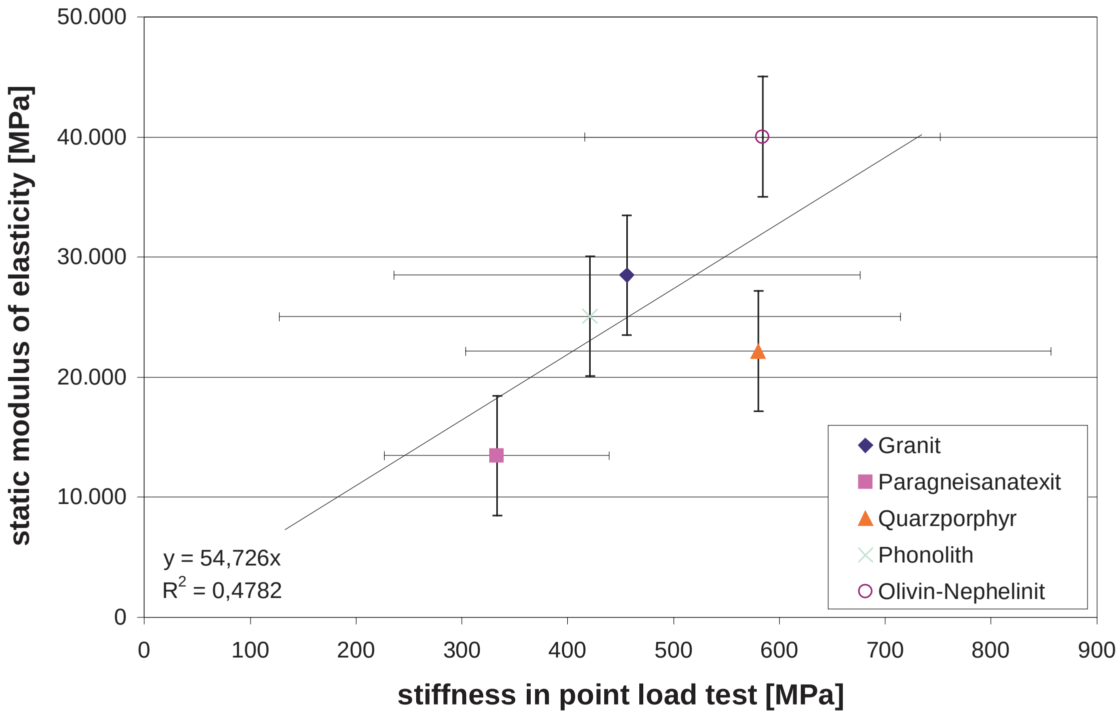

fig. 10: *Correlation between I_s-modulus and static modulus of elasticity for igneous rocks*

5. ASSESSMENT OF TEST RESULTS AND NOTES FOR THE PRACTICAL USE

It is usual in the geotechnique to use the results of more economic index tests to serve as a correlation basis for rock parameters whose direct determination are both time consuming and expensive. In proven cases it is also a suitable method of determining the magnitude of individual rock parameters.

The work of KNÖCHEL (11) and LEHNE (12) show that general correlations exist between uni-axial compressive strength and point load strength, between static modulus of elasticity and dynamic modulus of elasticity as well as between uni-axial compressive strength and dynamic modulus of elasticity. For example (11) and (12) showed that a schematic use of a correlation factor $\alpha = 24$ for calculation the uni-axial compressive strength from the point load strength leads to on average to uni-axial compressive strength which is 13 % too low for Oxford-Kalk and 250 % too high for Paragneisanatexit.

Fortunately it seems that in practical cases – especially in questions of classification – the realisation that a testing of the validity and applicability of a correlation for a particular rock can be worthwhile. For construction works with large excavation masses in linear structures such as tunnels etc. it is worthwhile thinking over whether a correlation for a particular job should be set up.

Further systematic testing in addition to that in (11) and (12) is required in order to assess whether a general correlation exists between static E-modulus and I_s-modulus.

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