Engineering geological classification of weak rocks

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Abstract: Although weak rocks (meaning the domain of hard soil/soft rock) occur frequently in construction projects all over the world, only few, and mostly unsatisfactory, durability testing methods exist. In various construction projects it became evident that especially slake durability of weak rocks varies strongly from spontaneous decay to slow degradation in months to years.

The conducted investigations have shown, that the usually performed testing methods, as stipulated in national standards (e.g. DIN, Ö-Norm, ASTM) or suggested methods (e.g. IAEG, ISRM), are not suitable to cover the immediate response and long-term behaviour of weak rock in construction practice. A wrong assessment of the durability however can lead to significant problems with the stability, excavatability, transport or reassembly of the excavated material.

In this study, 40 different rock types (sandstone, mudstone/clay-siltstone and marl) of 7 different locations were tested. Not only the behaviour of the rock in simple and cyclic slake tests, but also many other rock parameters as e.g. pore volume, carbonate content, grain size distribution and compressive strength were determined.

A classification based on the rock behaviour in a cyclic slake test lead to the definition of five categories of durability. Thereby the variable durability is not dependent on a single rock parameter, but on a combination of several parameters as e.g. compressive strength (expression of the bond strength of the matrix), grain size distribution (content of clay minerals susceptible to water) and pore volume (degree of the water conductivity). This so-called "structural strength" makes the border established between weak rocks and solid rocks, on the one hand, and soil, on the other hand, more accurate.

Résumé: Bienqu'on puisse trouver des roches faibles souvent dans de nombreux projets de construction, il y a seulement quelques procédés d'investigation concernant la durabilité, ceux-ci souvent n'étant pas satisfaisants. Plusieurs projets ont montré clairement que la durabilité des roches peut varier d'une désagregation spontanée à une désintégration lente pendant des mois à années.

Les tests effectués ont montré que les procédés habituels inclus dans les normes internationales (DIN, Ö-Norm, ASTM) ou d'autres méthodes proposées ne sont pas complètement appropriés à décrire le comportement immédiat et à long terme des roches faibles en pratique. Une evaluation incorrecte peut causer des problèmes importants en ce qui concerne la stabilité, l'excavation, le transport et la réutilisation du matériel excavé.

Par l'étude présente 40 types différents de roches (grès, argilolites, marne) de 7 locations ont été examinés. Ce n'est pas seulement le comportement des roches dans les tests simples et cycliques de la durabilite qui était défini mais aussi beaucoup de paramètres différents de roches comme par ex. le volume poreuxle contenu du carbonate, la distribution de la grandeur de la graine et la résistance compressive.

Une classification dépendant du comportement dans un test modifié et cyclique de la durabilite a eu pour résultat la définition de 5 catégories de durabilité. Selon cette définition la durabilité variable ne dépend pas d'un seul paramètre, mais d'une combinaison de plusieurs paramètres, par ex. la résistance compressive (l'expression pour la résistance de la matrice), la distribution de la grandeur de la graine (contenu de minéral argileux susceptible de l'eau) et le volume poreux (degré de la conductibilité de l'eau). Cette résistance appelée «résistance structurelle» rend le limite entre les roches faibles et les roches résistantes d'une côté et le sol d'autre côté plus précis.

Keywords: weak rocks, durability, laboratory tests, classification, compressive strength, porosity

INTRODUCTION

Weak rocks often form up a big part of the shallow stratums all over the world. Therefore they build up the foundation ground of many construction projects as e.g. deep construction pits, tunnel excavations and open cast mines. However, the extent for investigating the behaviour of these rock types in building projects rarely corresponds to their frequency and to the engineering geological problems they cause. One reason may be the difficulty to apply the testing methods from rock mechanic and soil mechanic on these rock types. Thus an assumed knowledge of the rock behaviour is more often the basis for estimation of the rock properties than the determination in laboratory tests. But although the classification of weak rocks and its separation from (cohesive) soils and hard rocks may be very difficult, they are very important in the phases of planning and construction and for the building contract. A wrong estimation of the rock behaviour often means an increase of time and costs during the construction phase as well as a decrease of the quality of the building. Therefore the behaviour of weak rocks was investigated in a Ph.D.-thesis in order to develop a practicable method for testing and classifying weak rocks and to make the separation of these rock types from the soft soils on the one hand and the hard rocks on the other hand more evident.

DEFINITION OF WEAK ROCKS

Position of weak rocks

In the national standards (e.g. DIN 4022 T1, Ö-Norm B 2203 resp. DIN EN 14689-1, ASTM D 4644) weak rocks are a part of the group of rocks, in contradiction to soils. The difference to hard rocks is their nature to disintegrate within a short time period (days to several years) when being exposed to water and climatic changes. This loss of strength is not reversible under normal conditions, whereas in cohesive soils it is possible due to changes in water content.

Due to their geotechnical behaviour, weak rocks constitute an intermediate stage between (cohesive) soils on the one hand and hard rocks on the other hand. These three groups are linked by geological processes, so the borders between them are variable (see Figure 1).

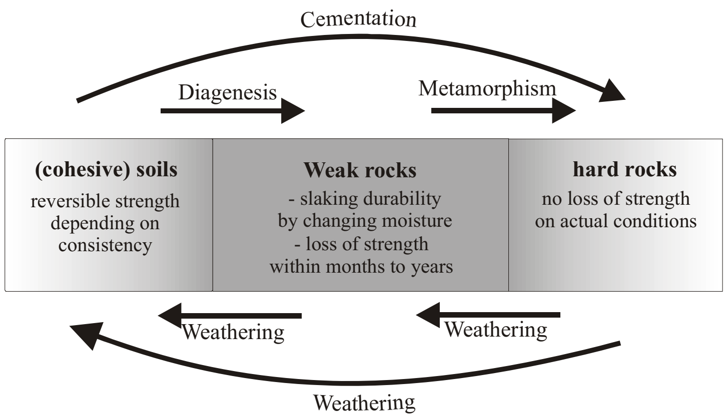

Figure 1. Position of weak rocks between cohesive soils and hard rocks.

Types of slake durability

Within the group of weak rocks there are many different rock types from weak sandstones to claystones and marlstones, all of them showing an extremely different behaviour:

- Spontaneous decay into small fractions (aggregates or grains) right after water supply.
- Decay into aggregates after desiccation and rehydration (e.g. from precipitation) within days to weaks (Figure 5a).
- Slow degradation into aggregates in months to years (Figure 4a).

These different forms of slake durability lead to different effects for the construction cycle concerning excavatability, stability, transport or reassembly of the excavated material.

INVESTIGATED ROCK MATERIAL AND TESTING METHODS

Investigated rock types

For the present investigation weak rocks and soils of a great variety were studied. One main criterion for the selection of samples was to get fresh material to exclude the influence of weathering, so the tested material was taken from current tunnel projects and from quarries under production. Table 1 gives a short view of the studied rock materials and the corresponding projects.

Table 1. View of the investigated rock materials.

Project / Location	Geological formation	Geological Age	Rock /soil types
Tunnel Euerwang, ICE-railway-project Ingolstadt-Nürnberg (D)	„Eisensandstone“, „Ornatenton“, Oxford-marl	Jurassic/Bajoc-Bathon, Jurassic/Callov, Jurassic/Oxford	Sandstones, sand-claystones, marlstones
Tunnel Sandberg, Thüringen (D)	“Buntsandstein”	Trias/Skythian	Sandstones, siltstones, claystones
Tunnel Bramschstrasse Dresden (D)	“Pläner Mergel”	Cretacious/Turonian	Marlstones
Investigation tunnel Achrain, Vorarlberg (A)	“Weissachschichten”, “Tonmergelschichten”	Tertiary/Oligocene	Siltstones, claystones, marlstones
Cement plant Leube, Salzburg (A)	“Schrambachschichten”, “Rossfeldschichten”	Alpine Cretacious/Neocomian	Marlstones, calcareous marlstones, sandy marlstones
Cement plant Rohrdorf (D)	“Stockletten”	Tertiary/Eocene	Marlstones, sandy marlstones
Sand pit Derching/Augsburg (D)	„Obere Süsswasser-molasse (OSM)“	Tertiary/Miocene	Clay, sandy clay (soil)

Testing methods

The investigation of weak rocks is very difficult because a standardized testing program is missing. Neither the testing methods used in rock mechanics nor those used in soil mechanics are satisfactory and cannot be fully applied on weak rocks. Often special test procedures or a special method for preparing the specimens are necessary, as e.g. a dry preparation of specimens or mild sieving in the slake test. Therefore the test program of this study contains testing methods from the rock mechanics as well as from the soil mechanics domain:

- Testing methods for determining the slake durability: slake tests, wetting-drying tests, crystallization tests.
- Mineralogical and petrographical testing methods: microsection analysis for determining the mineral content and the rock fabric, determination of carbonate content, X-ray spectral analysis, scanning electron microscope analysis (SEM), powder-swelling tests.
- Testing methods for determining petrophysical properties: determination of water content, density, pore volume, grain size distribution.
- Testing methods for determining the strength: uniaxial compression tests, point-load-tests.

EVALUATION OF THE ACTUAL TESTING STANDARDS

For determining and rating the slake durability, the national standards of several countries define different testing methods. The methods of the DIN and the ASTM-Standard are viewed below.

German standard (DIN)

For determining the slake durability, the German standard DIN 4022 T1 resp. DIN EN 14689-1 contains the so called wetting-test (“Wasserlagerungsversuch”): After immersion of the rock material in water for 24 hours the optical assessment of the specimens leads to 5 grades of slake durability. The evaluation of this test showed the following problems:

- The optical rating is partly subjective.
- The natural effect of cyclic wetting and drying is disregarded.
- It is not possible to distinguish between weak and hard rocks, because the loading is too low. Hard rocks and many of the weak rocks come under grade 1.
- It is not possible to distingish between weak rocks and soils, because some soils (e.g. overconsolidated clays) behave like weak rocks in this test.
- A rough classification in grade 1 may result in a too optimistic rating of the rock material.

Altogether it is evident that the wetting test is not suitable to determine the behaviour of weak rocks.

ASTM-Standard

The ASTM-Standard D 4644 uses the slake durability test (according to ISRM 1979) to determine the durability of weak rocks. The main problem, besides the relativly high technical effort, is that the test works with oven-dried material, so it does not simulate natural conditions. Especially the immediate response from rock materials with low durability under natural conditions is not recognized.

A NEW CALSSIFICATION OF WEAK ROCKS

The modified testing method of durability

A modified wetting test

This study introduces a new classification to give a better distinction between the different categories of weak rocks. It works on the basis of a 3-cyclic wetting-drying-test according to the investigations of RUCH (1985):

For the first wetting a fresh sample with natural water content is immersed into water for 24 hours. Both the immediate response and the shape after the test are documented. To get quantitative results for decay, a mild sieving of the remaining material is performed for determining the grain size distribution of aggregates and grains. After oven-drying at 50°C two additional cycles of wetting, sieving and drying are carried out.

The diagram of Figure 2 shows the mass fraction of the biggest remaining piece of each sample after the different cycles. Corresponding to the course of disintegration it is possible to distinguish between 5 categories of durability.

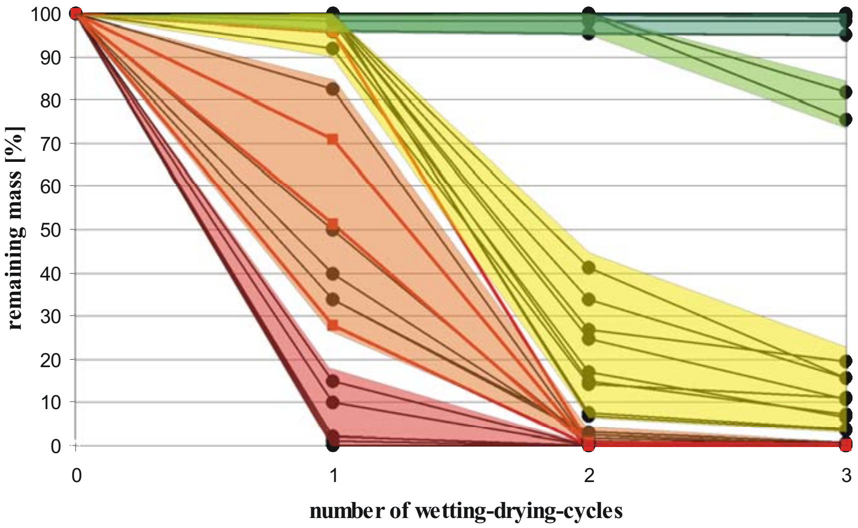

Figure 2. Course of disintegration in a 3 cyclic wetting-drying test. It is possible to distinguish between 5 categories of durabiliy. Angular red points are soils.

Figure 2 shows that the behaviour in the first wetting as well as the decay up to the third cycle are important parameters to describe the categories. By plotting these two results onto a diagram, the 5 categories of durability can be distinguished clearly (Figure 3).

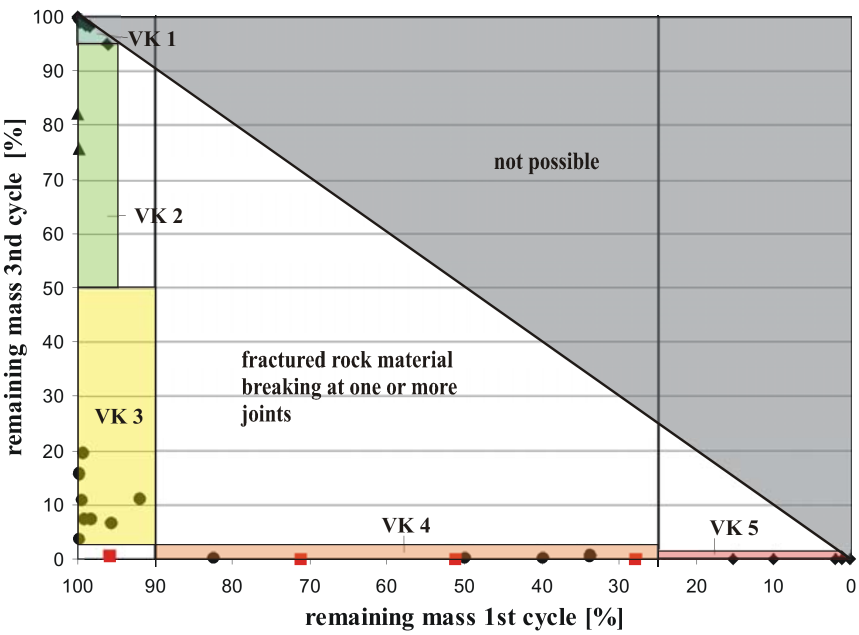

Figure 3. Separation of 5 categories of durability by means of the remaining mass (residual I and III) from Figure 2. Angular red points are soils.

The additional crystallization test for separation of hard rocks

To distinguish between weak rocks and hard rocks the 3-cyclic wetting-drying test is not sufficient because the loading in this test also is too low. Therefore the crystallization test after DIN 52111 was carried out on the rock materials from category VK 1 as an additional test. Material surviving this test without waste can be rated as hard rock.

Development of a classification system

Based on these results a more detailed classification system of slake durability can be set up, consisting of 6 categories of durability ("VK") from VK 0 to VK 5. To quantify the categories, an index, called "*Index of slake durability"* ("Veränderlichkeitsindex" I_V) is introduced. It is defined as follows:

I_V = residual I + residual III + residual $_{ct10}$

where I_V is the *Index of slake durability*, residual I and III are the mass fraction of the biggest remaining piece after the 1st and the 3rd wetting-drying-cycle, residual_{ct10} is the mass fraction of the biggest remaining piece after a 10 cycle crystallisation test.

Table 2 shows the new classification system.

Table 2. Classification of weak rocks based on the behaviour in the 3-cyclic wetting-drying-test and the crystallization test.

VK	I_v	class	Description
VK 0	285-300	Hard rock	No change up to the 3rd wetting-drying-cycle, maybe small losses because of loosened aggregates during sample preparation (< 5 %), no reaction in the crystallisation test (loss < 10 %)
VK 1	195-285	Low slake durability	No change up to the 3rd wetting-drying-cycle, maybe small losses because of loosened aggregates during sample preparation (< 5 %), losses in the crystallisation test > 10%
VK 2	145-195	Slow slake durability	No reaction during 1st wetting, up to the 3rd cycle cracking and /or beginning of decay up to 50 % of the original mass
VK 3	92,5-145	Medium slake durability	During 1st wetting cracking or loss of smaller aggregates (max. 10 % of mass), but the sample remains preserved. Up to the 3rd cycle decay into aggregates > 2,5 % of the original mass
VK 4	27,5-92,5	Rapid and high slake durability	During 1st wetting disintegration up to 75 %, up to the 3rd cycle decay into aggregates < 2,5 % of the original mass
VK 5	< 27,5	Immediate and very high slake durability	Spontaneous decay into aggregates < 25 % during 1st wetting, up to the 3rd cycle into flakes < 0,1 %

Besides a good division of weak rocks, the new classification gives the possibility to separate the hard rocks. On the other side it is not possible to distinguish between weak rocks and soils. For example, the tested OSM-soils, which are overconsolidated clays, behave in a very similar way as the weak rocks of category 4 with only low reaction in the first wetting and decay into small aggragates up to the third cycle. This means that for questions of rock behaviour as e.g. excavatability, stability or transport these soils will be treated as rocks. If the distinction is necessary, e.g. for questions of nomenclature or the building contract, other methods shown in the next chapter, will be necessary.

Figures 4 and 5 show that the behaviour of the rock material during the test can be compared with its behaviour under natural conditions.

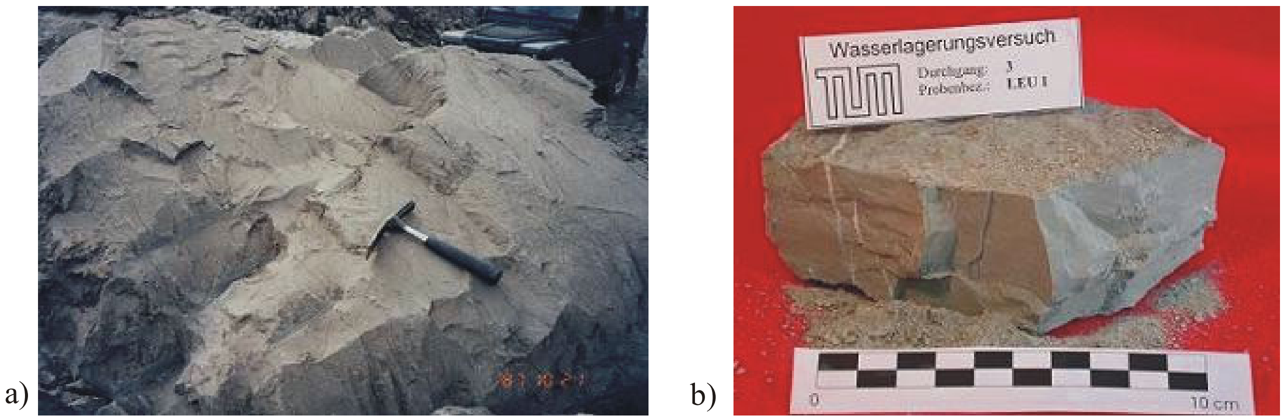

Figure 4. Calcareous marlstone from "Schrambachschichten", category VK 1. a) First cracks formed after 2 weeks, quarry "Leube". b) In the laboratory test beginning of disintegration after the 3rd wetting-drying-cycle.

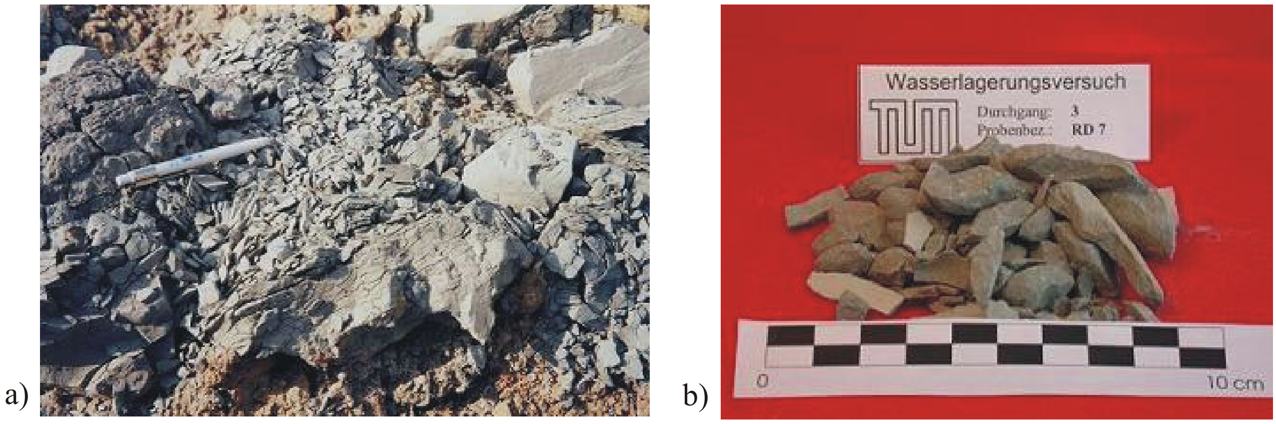

Figure 5. Marlstone from "Stockletten", category VK 4. a) Strong disintegration after only a few days, quarry "Rohrdorf". b) In the laboratory test decay to small lumps until the 3rd wetting-drying-cycle.

THE CAUSES OF SLAKE DURABILITY

To investigate the causes of slake durability, the relations between the categories of durability and many other rock and soil parameters were tested. The evaluation showed that the durability depends on a variety of parameters, shown in Figure 6.

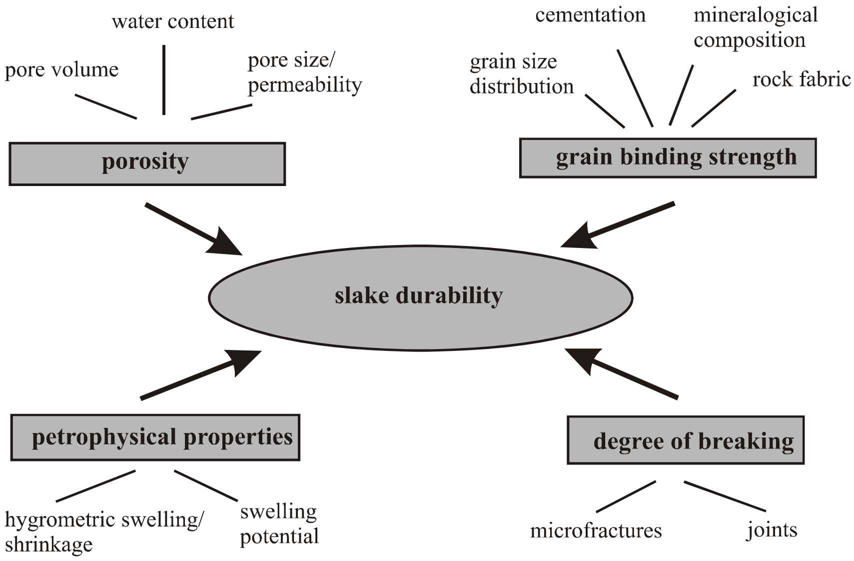

Figure 6. Summary of the parameters influencing durability.

Decisive parameters

Some of these parameters show a great influence on durability and therefore may be referred to as decisive.

Porosity

The porostiy can be described by means of the pore volume. On the one hand it affects the durability by controlling the water seepage through the rock material and hydraulic parameters and thus is a measure of the wetting rate and the percolation volume. On the other hand a high total pore volume stands for a fine-grained material with a high fraction of silt and clay, which show a relativly high slake durability. The correlation in the curve of Figure 7 only shows an intermediate fit, caused by a great span of rock types tested. Sandstones e.g. often have a high pore volume but a low slake durability.

However, the curve shows that the pore volume could be a value suitable to distinguish weak rocks and soils. Indeed all tested soils showed much higher pore content than the rocks.

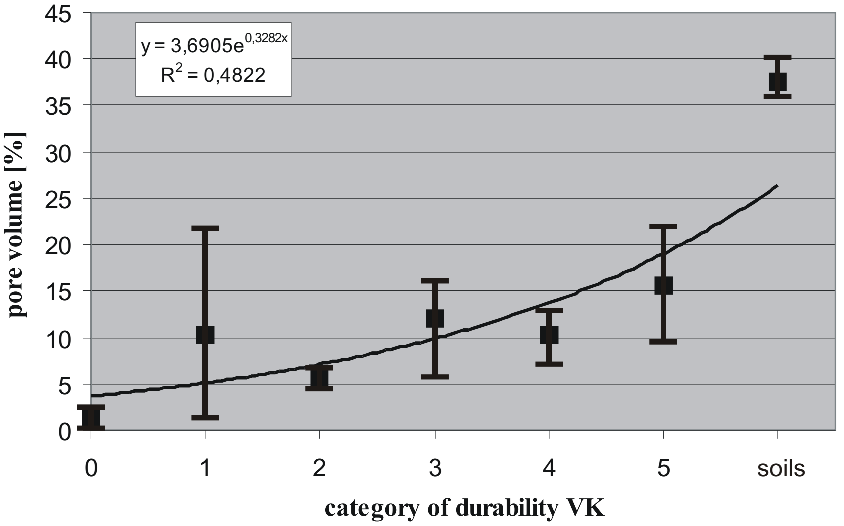

Figure 7. Relation between category of durability and pore volume.

Grain binding strength

The parameter of grain binding strength means the cohesion of the single grains of a rock material. It depends on the rock building minerals, their grain sizes and the amount and type of potential cement. An indirect value of the grain binding strength could be the uniaxial compressive strength, i.e. the stress needed to destroy this cohesion.

In Figure 8 the relation between the category of durability and the uniaxial compressive strength shows a good correlation, but the variation mainly in the low categories of durability is evident.

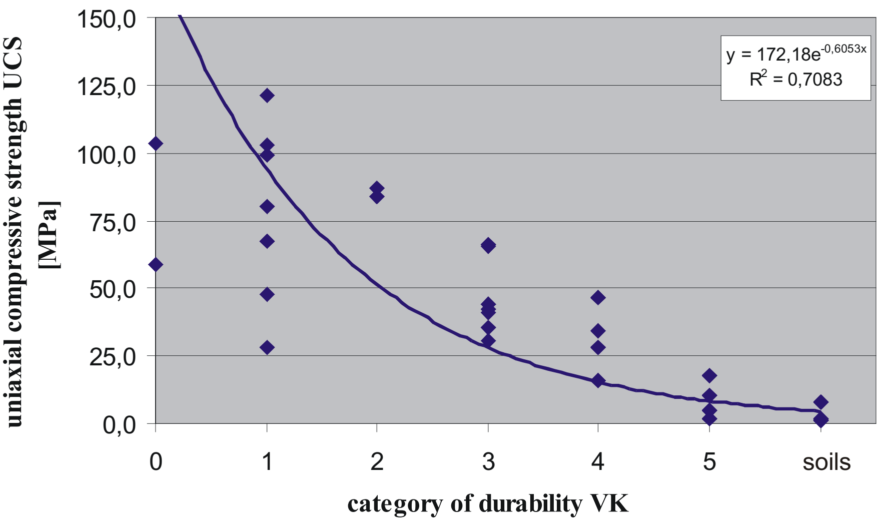

Figure 8. Relation between category of durability and uniaxial compressive strength (UCS).

Physical properties

Especially in fine grained rock materials, namely claystones, the existence of swelling clay minerals is an important parameter for the swelling potential of the rock and a cause of the strong decay of these materials.

Degree of breaking

As the actual tests were carried out mainly on fresh and undisturbed rock material without evident macroscopic cracks, the influence of small fissures can only be estimated. Probably very fractured rocks will show a rapid decay on existing cracks or joints in the beginning. During the following wetting cycles the decay slows down considerably depending on the rock type. Such rock materials can be addressed to form a special part in the diagram of decay and to constitute a special class of slake durability (see Figure 3).

Collective parameter "structural strength"

The previous considerations lead to a collective parameter causing the slake durability, the so-called "structural strength". It is defined by the following equation:

G = UCS² x KV / PV x Q

where G is the structual strength, UCS is the uniaxial compressive strength in MPa, KV is the median grain size in mm, PV is the pore volume [-] and Q is the swelling potential in the powder swelling test (after Thuro 1993) in %.

The correlation between the new defined structural strength and the category of durability in Figure 9 shows a good correlation, that means the structural strength is a good measure of durability.

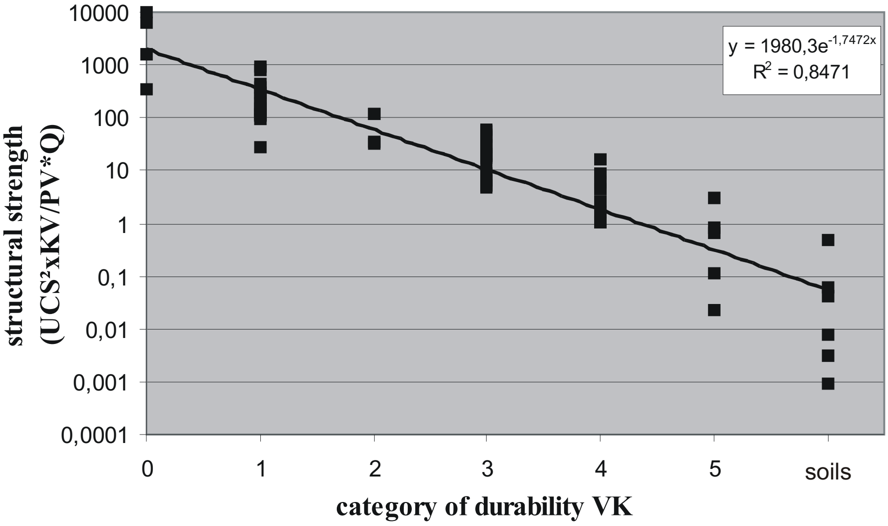

Figure 9. Relation between the category of durability and structural strength.

Considering the parameters defining the structural strength, the following principles are evident:

Rocks with a high stability combine high compressive strength with small pore volumes. Water seepage in these rocks happens to be slow and on a small scale. Thus the rock structure can only be broken slowly in a large number of wetting drying cycles. The bigger the pore volume the better is the hydraulic conductivity and the faster the water is able to percolate and weaken the rock material. In fine-grained materials an additional pore water pressure may develop, resulting in the spontaneous decay of the rock.

Rock materials of a medium compressive strength but coarser grain size and larger pore volume, e.g. sandstones, are durable as well. Since water seepage is much faster in those rocks, a pore water pressure is unlikely to develop, and doesn't exceed the grain binding strength.

CONCLUSIONS

In summary the new classification system of weak rocks gives a good instrument to test and classify the durability of rock materials. Simple tests common in preliminary site investigations give a considerably better idea of the rock behaviour under the influence of water. The course of testing procedures realized during such site investigations and drawn conclusions are shown in Figure 10.

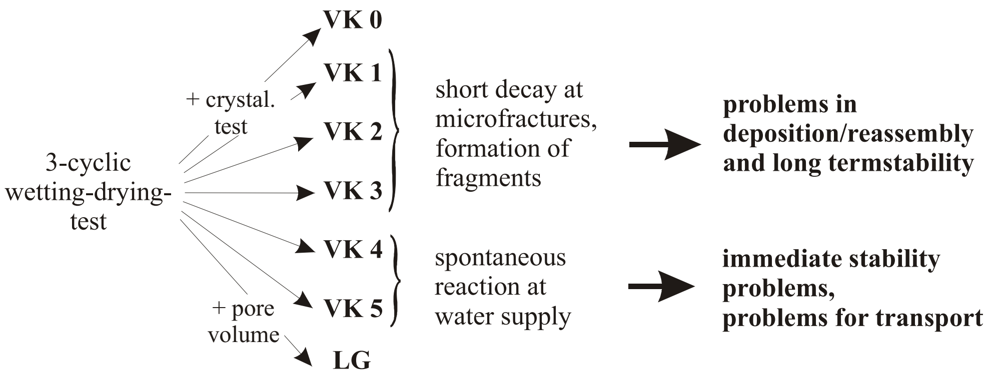

Figure 10. Testing procedures for the classification of durability and conclusions drawn.

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