Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0334

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Classification of the weathering-dependent disintegration behaviour of weak rocks

Classification du comportement de désintégration des roches faibles en fonction de l'altération par les intempéries

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ABSTRACT: Weak rocks lose their strength within a short time when dehydration and rewetting occur. Knowledge about the disintegration behaviour of weak rocks is important for geotechnical engineering and construction. In the past, conceptions for disintegration tests on weak rocks have been proposed in the literature and there are also classification approaches for the disintegration of rocks, but these are only of limited use for the investigation of weathering-dependent tendency to disintegrate. The aim of the presented research work is therefore to develop a new approach that allows a exact, understandable classification of the disintegration behaviour. For more precise determination of the disintegration behaviour, drying-wetting-cycles were carried out on differently weathered Keuper Marls at the Institute for Geotechnical Engineering at the University of Stuttgart. On the basis of investigations, a new evaluation scheme for the assessment of the durability of weak rocks is derived and the applicability for the classification of the weather-dependent disintegration tendency is verified. It could be shown that the classification test, as proposed in the code EN ISO 14689, underestimates considerably the disintegration tendency of weak rocks. It is therefore recommended that the investigation and classification methods presented in this paper be used to reliably assess the durability tendency of weak rocks.

RÉSUMÉ: Les roches faibles perdent leur résistance en peu de temps lorsque la déshydratation et le ré-humidification se produisent. La connaissance du comportement de décomposition des roches faibles est importante pour le génie géotechnique et la construction. Dans le passé, des conceptions d'essais de désintégration sur les roches faibles ont été proposées dans la littérature et il existe également des approches de classification pour la désintégration des roches, mais elles ne sont que d'une utilité limitée pour l'étude de la tendance à la désintégration . L'objectif des travaux de recherche présentés est donc de développer une nouvelle approche permettant une classification claire du comportement de décomposition. Pour une détermination plus précise du comportement de désintégration, des changements de mouillage-séchage ont été effectués sur des marnes de Keuper soumises à l'Institut d'ingénierie géotechnique de l'Université de Stuttgart. Sur la base de ces recherches, un nouveau schéma d'évaluation de la durabilité des roches faibles est élaboré et l'applicabilité pour la classification de la tendance à la dégradation en fonction de effritement est vérifiée. Il a pu être démontré que l'essai de classification, tel que proposé dans la norme EN ISO 14689, sous-estime considérablement la tendance à la dégradation des roches faibles. Il est donc recommandé d'utiliser les méthodes d'étude et de classification présentées dans le présent document pour évaluer de façon fiable la tendance à la durabilité des roches faibles.

Keywords: weak rocks, weathering-dependent disintegration behaviour, drying-wetting-cycles

1 INTRODURCTION

Weak rocks are susceptible to weathering and disintegrate during drying and rewetting. Already one drying-wetting-cycle might be sufficient to irreversibly weaken the rock formation. These rocks are usually first classified according to the degree of weathering, i.e. the current visually recognisable state of softening, and according to the degree of disintegration tendency, i.e. the property of potentially changing under environmental influences in future.

Worldwide weak rocks can be found close to the surface (Figure 1). It is of great relevance for building practice to recognise how strongly a rock can disintegrate. A strong tendency to disintegration can limit the re-use of soils in earthworks and accordingly requires expensive soil improvement. The knowledge of the disintegration tendency of weak rocks is also of great importance for the assessment of the stability of embankments or for evaluation of the rock solvability. During soil investigation, a suitable drilling procedure and sample treatment has to be selected considering the sensible structure of soft rocks. An inappropriate extraction of samples for laboratory tests can lead to a misinterpretation of the geomechanical parameters.

Figure 1. Weathered Keuper Marls in a quarry near Vellberg in Germany.

In German practice, only simple slake tests with one cycle of wetting according to the code EN ISO 14689 are usually carried out to classify the disintegration behaviour, but the test does not adequately reflect the natural conditions. From literature some procedures with combined drying-wetting-cycles for classification of the disintegration behaviour are known (Nickmann et al, 2006), (Bönsch, 2006) but these are often not applicable (Knopp & Moormann, 2018), therefore a new procedure needs to be developed. The investigations for the development of a new approach for the classification of the disintegration behaviour of weak rocks have been carried out for Keuper Marls, but might be applied also to other types of rock.

The aim of the investigations presented here are also to take a closer look at the influence of the natural state of weathering on the disintegration behaviour. A rock, which shows only a small disintegration tendency in its unweathered state, can have a considerably stronger disintegration tendency in its weathered initial state. Therefore, the influence of the natural weathering condition on the disintegration behaviour is to be investigated.

2 SAMPLE MATERIAL

The sample materials used were taken from various construction sites in Stuttgart and from a quarry near Vellberg in southwest Germany (see Figure 1) in the form of handpieces. The materials were differently weathered silt and marl stones from the so called „Bochinger Horizont“ (BH) and „Dunkelroter Mergel“ (DRM) of the Grabfeld-Formation (Middle Keuper) (Figure 2). In addition „Untere Bunte Mergel“ (UBM) of the Steigerwald-Formation (Middle Keuper) was investigated. Geographically they originate from similar areas, so that a weathering dependent comparison is possible.

Figure 2. Differently weathered "Dunkelroter Mergel" of Grabfeld-Formation

The materials were divided into weathering classes according to Wallrauch (Wallrauch, 1969). The classification of the degree of weathering according to Wallrauch is frequently used in German practice for silt and clay stones. According to Wallrauch's classification, the rocks are qualitatively divided into weathering classes using visual criterias. Often the natural water content and an estimated strength according to EN ISO 14689 are also taken into account. The visual classification criteria, natural water contents and the estimated uniaxial compressive strengths for the sample materials are given in Table 1.

3 EXPERIMENT TO DETERMINE DISINTEGRATION BEHAVIOUR

The sample is first stored in water for 24 hours and then gently washed through a sieve set with plenty of water. Then the sieves are dried with residue at 50°C in the oven. After oven drying, the sieve set is placed on the sieve shaker for 30 seconds and the sieve residues are determined. A total of five sievings are carried out. It should be noted that the fraction < 0.063 mm is not collected. The fraction < 0.063 mm must be calculated over of the dry mass of the initial sample. For calculation of the dry mass a seperate piece, which is broken off from the initial sample, is used. Since the fraction < 0.063 mm is not collected, it is also not possible to investigate more closely whether changes occur within this fraction during the disintegration test. Keuper Marls consist of an aggregate structure (Davis, 1968). The clay particles of the Keuper Marls deposited during sedimentation, were superimposed by the sediments of the Jurassic and younger layers. The developed high pressures compressed the primary flake structure of the sedimented clay into low-water particles with the size of silt grains. These particles have a high ion density inside and there are stable bonds between the crystal groups so that the particles remain intact during later mechanical stresses. The particles in turn form aggregates with a low pore content. Davis (Davis, 1968) explained that aggregates are crushed during decomposition, but particles can tolerate stresses. This ist due to very stable bonds between the crystal groups. It can therefore be assumed that no significant changes occur during the disintegration tests within the fraction < 0.063 mm.

Table 1. Water content and estimated compression strength of sample materials (DRM = Dunkelrote Mergel, BH = Bochinger Horizont, UBM = Untere Bunte Mergel).

weathering degreee	**material**	$\bar{w}_n$ **[%]**	**estimated** $\overline{q_u}$ **[MN/m²]**
W0 fresh	DRM BH	0.9 0.2	high: 50 – 100 MPa
W1 slightly weathered	BH	3.6	moderately high: 25 – 50 MPa
W2 moderately weathered	DRM	9.4	low: 5 – 25 MPa
W3 highly weathered	DRM UBM	11.7 12.3	very low: 1 – 5 MPa
W4 completely weathered	DRM UBM BH	15.7 16.5 14.4	extremely low: < 1 MPa
W5 Residual soil	DRM BH	17.7 25.8	

4 NEW METHOD FOR EVALUATION OF DISINTEGRATION TESTS

Figure 3 shows an example of the results of a disintegration test on a sample from the Bochinger Horizont (BH) with weathering grade W1.

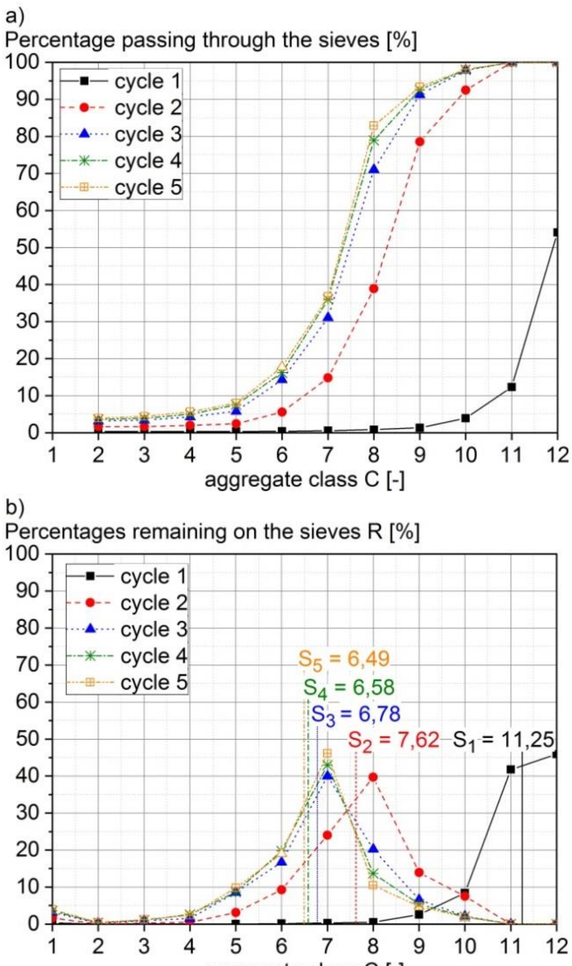

Figure 3. Results of the disintegration test of a sample from the Bochinger Horizont, weathering degree W1. a) Percentage passing through the sieves. b) Percentages remaining on the sieves

The specified aggregate classes are defined according to Table 2. Especially after the first drying (between cycle 1 and 2) a very strong disintegration occurs in the sample. After the third cycle, the sample disintegrates only very slightly.

Table 2. Aggregate classes

Aggregate class Ci [-]	**Sieve fraction [mm]**
1	< 0,063
2	0,063 – 0,125
3	0,125 – 0,25
4	0,25 – 0,5
5	0,5 – 1,0
6	1,0 – 2,0
7	2,0 – 4,0
8	4,0 – 8,0
9	8,0 – 16,0
10	16,0 – 31,5
11	31,5 – 63,0
12	> 63,0

The distribution curve (percentages remaining on the sieves) of the cycle n can be parameterised by the center point of sieve remainings S_n (Eq. 1), whereby C_i indicates the aggregate class i and $R_{i,n}$ the percentage remaining on the sieve of aggregate class i in the drying-wetting-cycle n.

$$S_n = \sum_{i=1}^{12} \left[R_{i,n} \cdot C_i\right] \tag{1}$$

For the sample shown in Figure 3, the center point of sieve remainings of the distribution curve between cycle 1 and 5 is reduced from 11.25 to 6.49. The distribution curve between cycle 1 and 5 is also reduced.

Figure 4 shows the change in the center point of sieve remainings during the five drying-wetting-cycles of all samples examined in this study. In all experiments that are the basis for determining the new classification scheme, specimens with a size of > 63 mm were used for the investigations. A sample of completely weathered material (W5) consist of clayey matrix whose particles are held together by cohesive bonds.

In the initial state (alternating 0), the distribution of the material has the center point 12. The samples with natural water content were stored under water and then sieved wet. The difference between the initial state and cycle 1 shows the reaction of the material to the first wetting cycle without prior drying (immediate reaction).

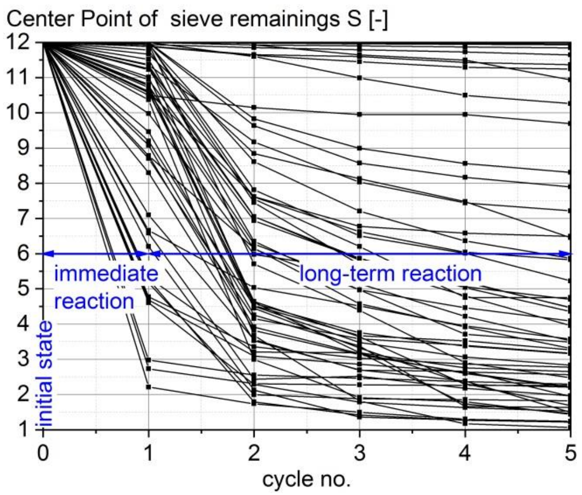

Figure 4. Cycle of the center point of sieve remainings during the five drying-wetting- cycles for all examined samples

After the first wet sieving, the material is dried, rewetted and sieved (cycle 2). The difference between the center point of the distribution curve after cycle 1 and after cycle 2 represents the influence of drying prior to contact with water. In the following three drying-wetting-cycles, the material disintegrates less and less with each cycle, the center points approach an asymptote. In the following, the reaction of the material between cycle 1 and 5 is referred to as long-term reaction.

The disintegration tendency D (Eq. 2) can be described by the difference between the center point of the distribution function in the initial state and the center point of the distribution function in the final state.

$$D = S_0 - S_5 = 12 - \sum_{i=1}^{12} \left[R_{i,5} \cdot C_i\right] \quad (2)$$

It is often of great interest in construction practice if a initial contact with water leads to large changes of the sample or if drying and rewetting are important for the disintegration behaviour of the sample. Therefore, the immediate reaction D_I (Eq. 3) and the long-term reaction D_L (Eq. 4) should be considered separately.

Table 3. Variability classes

Variability classes VCi		**Disintegration tendency D**
VC 1	invariable	$D \leq 0{,}5$
VC 2	slightly variable	$0{,}5 < D \leq 3$
VC 3	moderately variable	$3 < D \leq 5$
VC 4	highly variable	$5 < D \leq 7$
VC 5	very highly variable	$7 < D \leq 9$
VC 6	extremely variable	$9 < D \leq 11$

$$D_I = S_0 - S_1 = 12 - \sum_{i=1}^{12} \left[R_{i,1} \cdot C_i\right] \quad (3)$$

$$D_L = S_1 - S_5 \quad (4)$$

$$= \sum_{i=1}^{12} \left[R_{i,1} \cdot C_i\right] - \sum_{i=1}^{12} \left[R_{i,5} \cdot C_i\right]$$

Six variability classes are distinguished on the basis of the disintegration tendency D, as defined in Table 3. The parameter D can be determined for classification either according to Eq. 2 or as the sum of the two parameters D_I and D_L. For a better knowledge of the investigated materials, it is recommended to subdivide disintegration tendency into immediate and long-term reactions.

Figure 5 shows the two parameters D_I and D_L describing the disintegration for all investigated samples and the six classes of variability from Table 3. It can clearly be seen that a large number of the samples examined hardly reacted to contact with water in the inital state, but then reacted strongly when dried out. A few rocks only reacted very strongly in the initial state.

Figure 6 shows examples of the distribution of a Bochinger Horizont sample, weathering degree W1 (Figure 6a) and a Dunkelroter

Mergel sample, weathering degree W3 (Figure 6b).

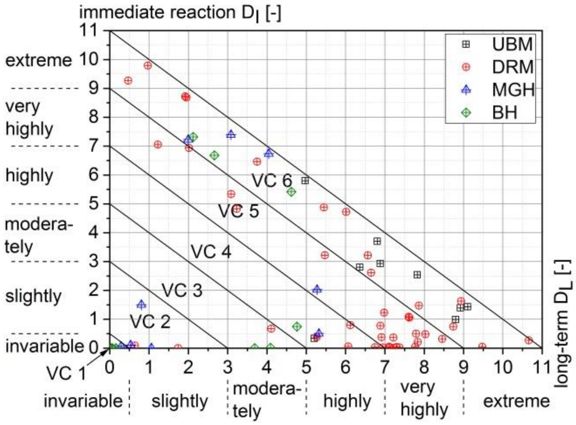

Figure 5. Classification into durability classes on the basis of the two parameters D_I and D_L describing the disintegration

The two curves describing the final state (cycle 5) have almost the same center point of sieve remainings S_5. For the sample shown in Figure 6a the disintegration tendency is D = 5.51 and for the sample shown in Figure 6b D = 4.78. The disintegration tendency is very similiar. However, the two samples are very different in the type of disintegration. While the sample shown in Figure 6a breaks mainly into aggregates in the size range 0.5 to 8 mm (C_i = 5-8), in the sample shown in Figure 6b part of the sample is dispersed into particles < 0.063 mm (C_i = 1), while the other part of the sample does not change within the five drying-wetting-cycles. This different behaviour can be described with the standard deviation σ_n (Eq. 5).

$$\sigma_n = \sqrt{\sum_{i=1}^{12}\left[R_{i,n} \cdot \left(C_i - S_n\right)^2\right]} \tag{5}$$

The standard deviation of the distribution after five drying-wetting-cycles for the sample shown in Figure 6a is σ_n = 1.65 and for the sample shown in Figure 6b is σ_n = 5.23. The standard deviation σ_n describes the variation of the percentages in the different aggregate classes. Thus it can be determined whether the aggregates of the samples after five drying-wetting-cycles are close to the centre point or widely distributed.

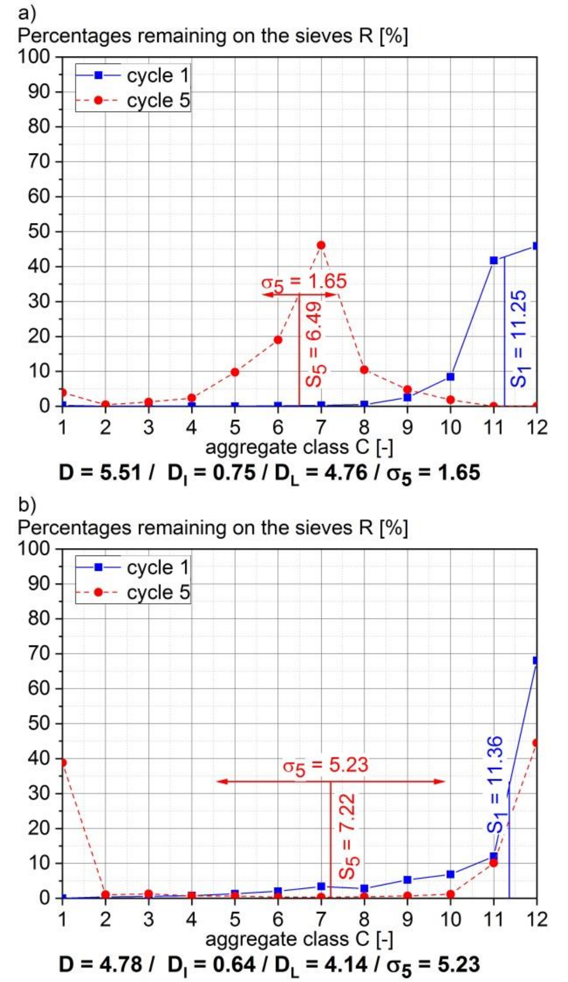

Figure 6. Percentages of the aggregate classes of material BH, weathering class V1 (a) and material DRM, weathering class V2 (b). Almost equal disintegration indices, but different standard deviations.

5 WEATHER-DEPENDENT DISINTEGRATION TENDENCY

Across all materials for each degree of weathering an average value was formed from the results for each of the three parameters D, D_I and D_L. Figure 7 shows the mean values and the deviations. The disintegration tendency D, which indicates the total disintegration of a sample, increases monotonously with increasing

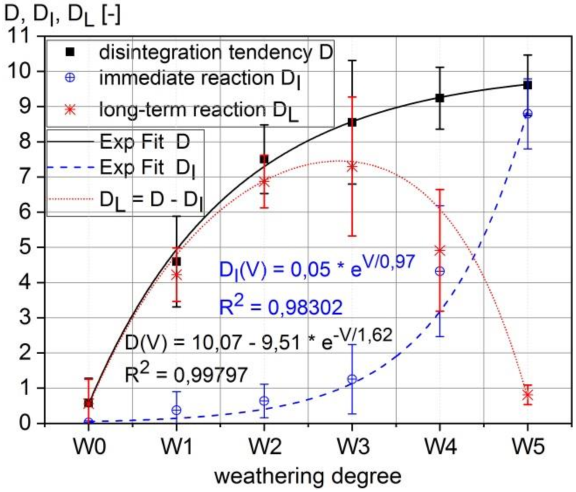

Figure 7. Disintegration indices D, D_I and D_L as a function of the degree of weathering for the examined materials. Represented are the mean values of all samples associated with a degree of weathering.

weathering degree of the investigated Keuper Marls. Until weathering degree W3 the increase of the disintegration tendency is high. The influence of weather-dependent changing rock parameters is considerable. This influence decreases with more heavily weathered materials (W4 and W5). Between materials with a weathering degree of W3 and W5, there is only a slight difference in the disintegration tendency.

The reaction of rocks to wetting without previous drying is called immediate reaction D_I. Up to the degree of weathering W2/W3 this reaction is very low. The diagenetic bonds are very strong and cannot be destroyed only by contact with water. The tendency to disintegrate already with a simple water contact increases very strongly by the degree of weathering. The cause therefor is probably the weather-dependet increasing number of cracks, over which water can get into the rock. For materials with a weathering degree W5, the final value of the disintegration tendency D is already reached with one wetting cycle.

In the long-term reaction D_L, the unweathered rocks (W0) and the completely weathered rocks (W5) hardly react. In the case of weathering grade W0 this is due to the fact the sample do not react and in the case of rocks with a weathering grade W5, the entire material disintegrate during the first wetting cycle (immediate reaction). Rocks with a degree of weathering between W1 and W4 react very strongly to cycles in drying and rewetting. The strongest reaction have rocks with a weathering degrees W3. The long-term reaction D_L can be determined as the difference between the disintegration tendency D and the immediate reaction D_I. Except for rocks with weathering degree W5, the simple slake test according to the code EN ISO 14689 considerably underestimates the disintegration tendency. For completely weathered materials (W5), it should be noted that some materials require a minimum water content in the area of the lower plastic limit for dissolving during the first wetting cycle. If the same materials have a semi-solid or solid consistency, the cohesive bonds between the particles are very strong and the sample cannot dissolved alone by wetting. So it is also possible, that materials with a weathering degree W5 show no reactions during the first wetting cycle and the simple slake test with one cycle of wetting underestimates the tendency to disintegrate.

6 SUMMARY

Weak rocks are sensitive to weathering and disintegrate under environmental influences. These rocks are classified according to the degree of weathering and the degree of disintegration. For example for soil investigation, it is very important to determine the correct disintegration tendency for selection of the right process techniques for sampling and storage. However, the simple slake test with one cycle of wetting according to the code EN ISO 14689, which is frequently used in practice, is not sufficient to estimate the disintegration tendency. However, the improved methods proposed in the literature are only applicable to a limited extent.

Therefore, a new classification system for weak rocks was developed in a first step with the aim of classifying rocks with different initial states according to their disintegration tendency on the basis of unambiguous characteristic values. It is proposed to perform drying-wetting-cycles combined with wet sievings. After the test, the total disintegration tendency D (Eq. 2), the immediate raction D_I (Eq. 3) and the long-term reaction D_L (Eq. 4) can be determined and a classification into the durability classes given in Table 3 or Figure 5 can be made. By calculating the standard deviation σ_n (Eq. 5), it is also possible to check how widely distributed the aggregate sizes of the material are after the drying-wetting-cycles.

Compared to the simple slake test, the new method is considerably more laborious. But the certainty of assessment and the associated planning certainty for structural applications justify the additional effort. Specially since it could be shown that in a procedure according to the code EN ISO 14689 the durability of the investigated Keuper Marls was considerably underestimated.

The aim of the investigations presented here was also to investigate the influence of the initial state (degree of weathering) of a rock on its disintegration behaviour. It was found that the disintegration tendency D of the examined Keuper Marls increases monotonously with increasing degree of weathering (Figure 7). Up to the weathering degree W3 the disintegration tendency D increases strongly. Between materials with a weathering degree W3 and W5, there is only a slight difference in the disintegration tendency D. Even when considering the immediate and long-term reaction, a weathering dependent behavior was observed. Up to the weathering degree W2 the Keuper Marls only disintegrate when they are exposed to combined drying and wetting cycles, because up to the weathering degree W2 there is hardly any reaction of the rocks to a simple wetting cycle ($D_I \approx 0$). Keuper Marls with a degree of weathering greater than W2 already react to simple water contact, but drying and wetting cycles are necessary to determine the total possible disintegration tendency. For rocks with weathering grade W4/W5, the strength of the reaction to a wetting cycle without previous drying is equal to the strength of the reaction to drying-wetting- cycles ($D_I = D_L$). Rocks with a weathering degree of W5 usually disintegrate completely with simple contact with water ($D_L \approx 0$). It should be noted that this does not apply to materials in which the cohesive bonds between the particles are so strong that they cannot be dissolved by a wetting cycle without prior drying.

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