Geotech Geol Eng
https://doi.org/10.1007/s10706-022-02217-3

ORIGINAL PAPER

Influence of Weathering on Pore Size Distribution of Soft Rocks

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Received: 5 December 2021 / Accepted: 27 May 2022

Abstract Soft rocks can weather and lose their structure within a short time due to drying out and rewetting. Thus they are very sensitive to weathering. Since these rocks are often found in the shallow subsurface, they are of great practical relevance in the foundation of constructions. The rock properties change during the weathering process. Particularly relevant is the softening of the material and the decrease of its mechanical properties, which are determined typically using mechanical laboratory or field tests. The objective of this study is to examine in more detail how the microstructure of rocks changes over the course of weathering, which results in a decrease in mechanical properties. Sulfate rocks of the Grabfeld-Formation in Stuttgart, Germany were investigated. Using XRD analyses it was revealed that initially a chemical weathering processes occurs whereby the rocks leach out, followed by a physical weathering process. Investigations with a mercury porosimeter showed that during chemical weathering the intraaggregate pore content greatly increases, whereas the proportion of interaggregate pores only slightly increases.

Keywords Soft rocks · Grabfeld-Formation · Chemical weathering · Pore size distribution

1 Introduction

Soft rocks occupy a large part of the near-surface subsoil and are therefore important for the foundation of construction however they are sensitive to weathering. Their chemical,-mineralogical and mechanical properties change the structure of the soft rock during the weathering process. Examples for rocks that undergo this change are marls, shales, claystones, mudstones, siltstones and stiff clays e.g. Chandler (1969), Pineda et al. (2014). For construction practice, it is important to recognize how severely weathered a rock is. It is also important to understand how the weathering process and the associated structural changes influence the mechanical properties. A strong tendency to decay can limit the reuse of soils in earthworks and accordingly necessitate costly soil improvement or soil replacement measures. Knowledge of weathered rocks is also of great practical importance when assessing the stability of slopes, constructions or in

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questions of solubility. Even during exploration, if an unsuitable drilling method and an inadequate sample treatment is chosen, the resulting extraction of samples for laboratory tests can lead to a misinterpretation of the geomechanical parameters.

Several investigators have studied the effect of weathering on the engineering properties of soft rocks e.g. Alonso and Pineda (2006), Chandler (1969). Changes of the mechanical properties during weathering are caused by changes of physical rock properties such as pore characteristics. In sedimentary rocks, all strength properties decrease with increasing porosity (Dick and Shakoor 1992; Koncagül and Santi 1999; Price 1960), since a high porosity favors a cross-linking of stress-induced microcracks (Howarth and Rowlands 1986). However, it has not yet been investigated which pore sizes significantly affect the decrease of mechanical properties. Thus, the question arises whether the increase of macropores influences a change of the mechanical parameters more strongly than micropores.

Other studies have investigated the disintegration process in more detail. In general, material with a higher porosity tends to be more disintegrated than material with a lower porosity. The disintegration behaviour of soft rocks is strongly influenced by the pore characteristics (Hudec 1998), because all strength properties decrease with increasing porosity in sedimentary rocks (Koncagül and Santi 1999; Price 1960). Furthermore, the influence of the degree of natural weathering on the disintegration process was investigated in a previous study by Knopp and Moormann (2018). Rocks react more sensitively to the disintegration processes with an increasing degree of weathering, which is probably caused by changes in pore space. Nevertheless, the impact of the pore size distribution on the rock's tendency to disintegrate has not yet been investigated.

The objective of this study is to investigate the influence of the natural weathering conditions on the pore size distribution of the Keuper Marls in Germany to better understand the weathering process of these rocks. Therefore, the soft rocks were investigated using XRD analyses to assess chemical weathering. Hence, a mercury intrusion porosimeter (MIP) was used to investigate the pore size distribution of the differently weathered Keuper marls. In addition, the influence of changes in pore space during weathering on behavior and disintegration behavior was investigated using uniaxial compression tests and water storage tests. The results are related to changes in mineralogy and mechanical behavior during weathering. Furthermore, the results of the study serve as a basis for the development of a classification scheme (Knopp 2020) and derivation of the mechanical parameters on the basis of changes in the pore space.

2 Material and Methods

2.1 Sample Material

As sample materials greatly differ, weathered rocks from the layers 'Bochinger Horizont (BH)', 'Dunkelroter Mergel (DRM)' (Fig. 1) and 'Mittlerer Gipshorizont (MGH)' of the Grabfeld-Formation (middle Keuper) from various construction sites in the city of Stuttgart, Germany, were used (Fig. 2). The investigated Keuper rocks are sulfate-bearing in their unweathered original state. Hence, the data determined here should not be transferred to other non-sulfate-bearing rock formations without further investigations.

The rocks of the southwest german Grabfeld-Formation, consist of clay rocks with single carbonatic, mostly dolomitic banks and sulphate rocks (Ufrecht 2015). The rocks of the 'Bochinger Horizont' are fine layered, grey-green to black-grey dolomitic claystones with individual thin sulfate banks. The rocks of the 'Dunkelroter Mergel' are reddish brown to violet and depending on the sulphate content, whitish clay stones. The anhydrite in the sulphate bearing rocks appeared as fine layers alternating with the clay stones. The rocks of the 'Mittlerer Gipshorizont' are red-grey to light olive-green. The fractured surfaces of all weathered rocks are mostly yellowish and brownish.

The materials were divided into the weathering classes according to Wallrauch (1969). In practice for the upper triassic rocks found in Southern Germany, the classification of the degree of weathering according to Wallrauch is frequently used. This classification system is similar to that described in EN ISO 14689 (2018). Thereby rocks are qualitatively subdivided into weathering classes according to visual criteria. Often the water content as well as the strength, estimated using EN ISO 14689 (2018) are also considered. The visual classification criteria, natural water content and the estimated uniaxial compressive strengths (UCS) for the sample materials used according to EN ISO 14689 (2018), are given in Table 1. It is already known from the literature for various formations in southwest Germany, such as the Opalinusclay formation, that the water content depends on the degree of weathering (e.g. Wallrauch 1969; Baradar-Razizadeh 1980). Empirical values for a weathering dependence on the water content exist for rocks from the Grabfeld-Formation (Fig. 3; Knopp and Moormann 2018). This dependence was validated on the basis of a detailed series of laboratory tests. The water content of the rocks investigated almost increases linearly with the degree of weathering. During weathering, the rock structure and the diagenetic grain bonds are loosened, enabling water to accumulate. Thus, the water content increases with the degree of weathering.

2.2 Structure of Keuper Marls

In the examined Keuper Marls of the Grabfeld-Formation, an aggregate structure was formed during diagenesis (Fig. 4). The primary structure of the Keuper Marls deposited during sedimentation was superimposed by the sediments of the Jurassic and younger layers. The primary structure of the sedimented clay was consequently compressed to particles of silt grain size by the increasing pressures. These particles have a high ion density in the interior and 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 1968).

The smallest pores are called nanopores and have diameters < 0.05 µm. Pores with diameters between 0.05 and 100 µm are called micropores or microcapillaries. The largest pores are called macropores or macrocapillaries (100-1000 µm). In addition, inter- and intraaggregate pores are often distinguished. Interaggregate pores are larger pores between aggregates and intraaggregate pores are smaller pores within aggregates.

Table 1 Criteria for the visual classification of the degree of weathering, mean values of water contents and the estimated compressive strength according to EN ISO 14689 (2018) (Knopp and Moormann 2018) with water content $\overline{w}$, estimated uniaxial compressive strength $\overline{q_u}$

Degree of weathering		Visual description	$\overline{w}$ (%)	$\overline{q_u}$ (MPa)
W0	Unweathered	No visible weathering	1.1	High: 50–100
W1	Slightly weathered	Beginning of color changes of the jointed faces; sharp edges	3.6	Moderately high: 25–50
W2	Moderately weathered	Loosened, but not friable; surface of the jointed rock bodies oxidized and marginal plasticized	9.7	Low: 5–25
W3	Weathered	Loosened up; weathering has reached the total interface structure	12.0	Very low: 1–5
W4	Completely weathered	Weathered to soil; the interface structure is still recognizable; hand-crumbled	16.5	Extremely low: < 1
W5	Eesidual soil	No structure recognizable; kneadable or rollable	22.8	Extremely low: < 1

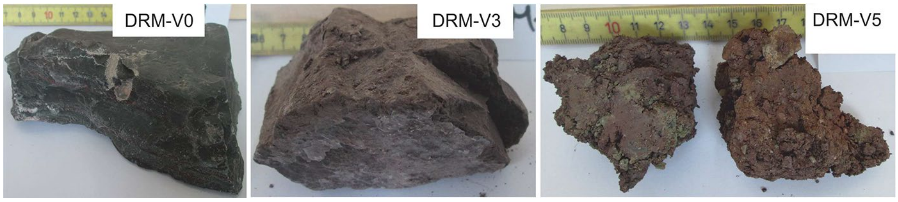


Fig. 1 Different weathered Marls from 'Dunkelroter Mergel', Grabfeld-Formation (Knopp and Moormann 2018)

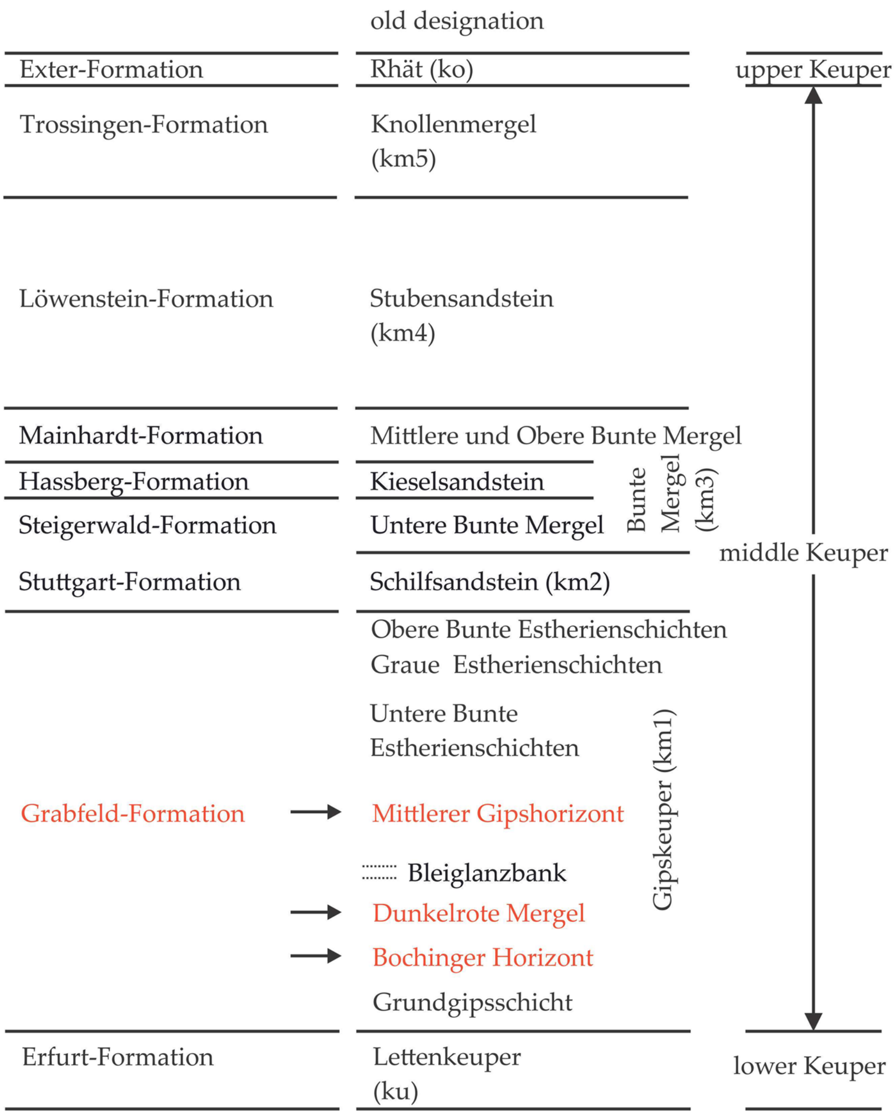


Fig. 2 Stratigraphic overview of the Keuper. The sample material is indicated in red and marked with arrows. Based on Wagenplast (2005) and Knopp (2020)

2.3 Weathering of Sulfate Bearing Keuper Marls

If the superimposed material is removed, the surcharge load will be relieved and the microstructure will be loosened by opening existing and new separating surfaces. The newly formed interfaces create surfaces for physical and chemical processes. Physical weathering leads to destruction without mineralogical changes (Alonso and Pineda 2006). The rock is decomposed purely mechanically, without the chemical state of the rock changing significantly. Chemical weathering means a chemical decomposition of the rock and re-formations or new formations as well as dissolution of minerals.

The initial weathering process of the investigated rocks of the Grabfeld-Formation is chemical, because they are sulphate-bearing clay rocks with anhydrite ($CaSO^4$) in the unweathered initial state. Anhydrite is only stable in the absence of free pore water. Small amounts of water lead to hydration and the anhydrite

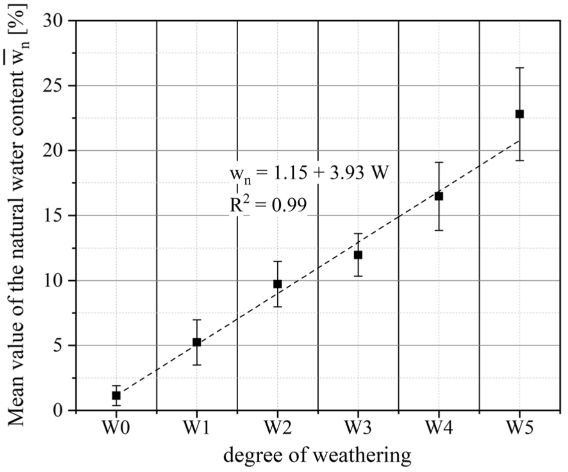


Fig. 3 Mean natural water content $\overline{w}_n$ as a function of the visually determined degree of weathering

is converted into gypsum ($CaSO^4 \cdot H^2O$). The transformation of anhydrite into gypsum is accompanied by an increase in volume of about 61% (Butscher et al. 2016).

Figure 5 shows possible solutions for the anhydrite-gypsum-transformation (Nitsche 1996). In case A, the volume of the rock remains constant. The anhydrite volume can therefore only be replaced by a gypsum volume of the same size and the excess gypsum must dissolve in groundwater. The gypsum structures show no significant expansion compared to the anhydrite structure. In case B, the entire anhydrite is converted into gypsum and in the case that the rock expansion is hindered, pressures between 1.7 and 4.7 MPa are generated. In groundwater the whole gypsum dissolves and is transported away. The gypsum Keuper loses its sulphate related strength and acquires a semi-solid to soft rock character above the leaching front.

2.4 Influence of Weathering on the Mineralogical Composition of Keuper Marls

The mineralogical investigations were carried out using XRD. The results are given in Table 2. The influence of weathering on the sulphate content has been previously analysed by Knopp and Moormann (2018) and Knopp and Moormann (2021).

Results showed that only samples with weathering degree W0 and partly W1 contain relevant amounts of sulphate in the form of anhydrite and gypsum (Fig. 6). For rocks of weathering class W0, it was found that the sulphate is present in the form of anhydrite. Rocks with weathering grade W1 mainly contain gypsum,

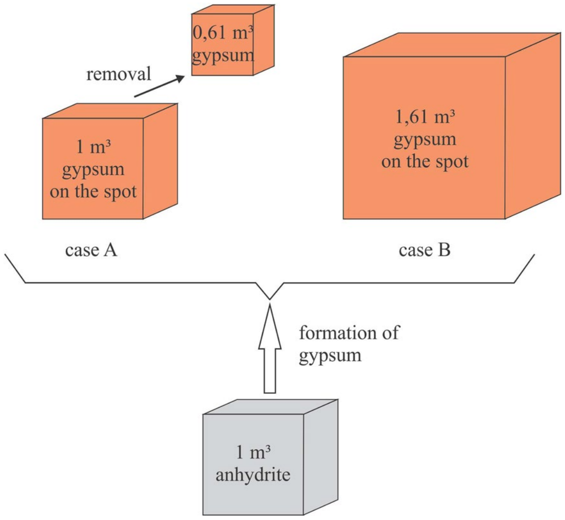


Fig. 5 Formation of secondary gypsum (graphic based on Nitsche 1996; Knopp 2020)

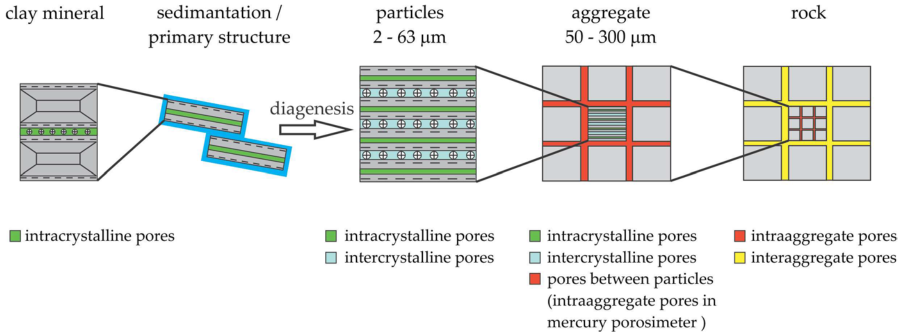


Fig. 4 Structure of Keuper Marls (graphic based on Knopp 2020)

Table 2 Mineralogical composition (Knopp and Moormann 2018)

1	2	3	Data in %																
			Sulphate			Carbonates			Clay minerals					Feldspar			Q	H	R
			A	G	∑	C	D	∑	S	I	Ch	Kao	∑	K−	Na−	∑			
W0	DRM	S1	24	1	25	1	20	21	8	14	15	<0.1	37	9	1	10	6	–	1
		S2	29	1	30	<0.5	15	≈ 15	7	17	13	–	37	10	1	11	7	–	–
	BH	S3	77	8	85	<1	4	≈ 4	3	2	1	–	6	2	<0.5	≈ 2	2	<0.1	–
W1	BH	S4	1	2	3	1	29	30	5	33	9	<0.5	≈ 47	9	<1	≈ 9	10	–	<0.5
		S5	<0.5	9	≈ 9	–	28	28	2	25	7	<0.5	≈ 34	8	<1	≈ 8	7	–	–
W2	DRM	S6	<0.5	<1	<1	–	21	21	8	44	4	1	57	4	<1	≈ 4	15	2	–
		S7	<0.5	<0.1	<0.6	<0.1	26	26	5	47	5	1	58	5	2	7	6	2	<0.5
W3	DRM	S8	<0.5	<0.1	<0.6	6	7	13	8	52	8	1	69	3	4	7	5	3	2
		S9	<0.5	<0.1	<0.6	5	1	6	16	54	8	–	78	5	2	7	4	4	1
W4	BH	S10	<1	<0.5	<1.5	18	3	21	15	32	14	–	61	9	<1	≈ 9	7	–	–
	DRM	S11	1	<1	1–2	<0.5	18	≈ 18	13	46	7	<1	≈ 66	4	2	6	8	–	–
W5	DRM	S12	<0.1	<0.5	<0.6	6	10	16	12	37	8	–	57	7	2	9	15	1	2
		S13	<0.5	<0.5	<1	<1	25	25	12	27	15	1	55	7	3	9	8	1	–

1 degree of weathering, *2* type of rock, *3* sample identification, *A* anhydrite, *G* gypsum, *C* calcite, *D* dolomite, *S* smectite, *I* illite, *Ch* chlorite, *Kao* kaolinite, *K−* potassium feldspar, *Na−* sodium feldspar, *Q* quartz, *H* haematite, *R* rutile, *DRM* Dunkelroter Mergel, *BH* Bochinger Horizont

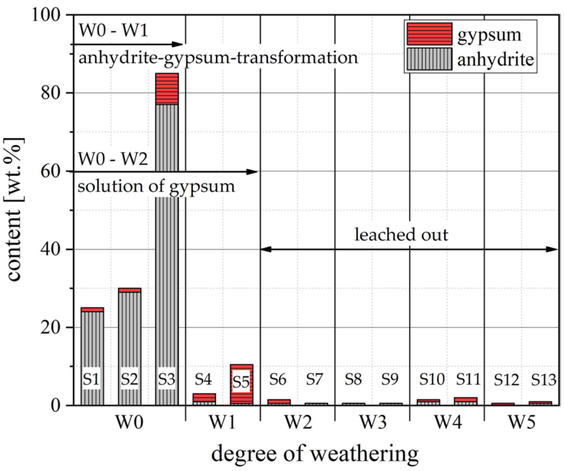


Fig. 6 Sulphate content depending on the degree of weathering. Each bar corresponds to one examined sample (Knopp and Moormann 2021)

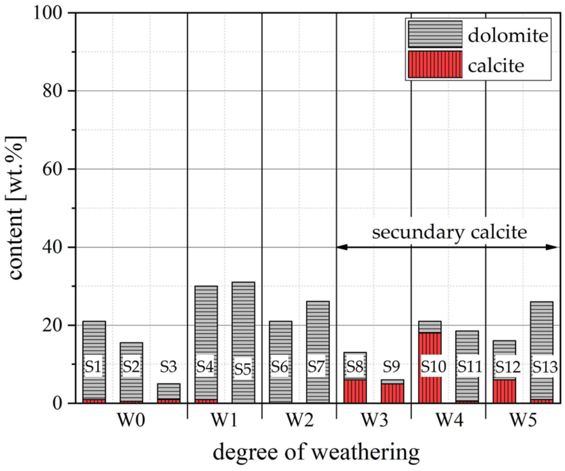


Fig. 7 Carbonate content depending on degree of weathering. Each bar corresponds to one examined sample

and from weathering grade W2 onwards hardly any sulphate is present, thus the sulphate is leached out of the rock. The total sulphate content is already reduced at W1 showing that gypsum has already dissolved between grades W0 and W1.

Carbonate is contained in the investigated rocks in the form of dolomite and calcite (Fig. 7). The mineral contents are highly variable and presumably strongly influenced by the randomness of the sampling site. Up to weathering degree W3 the samples contain mainly dolomite, from W3 mainly calcite.

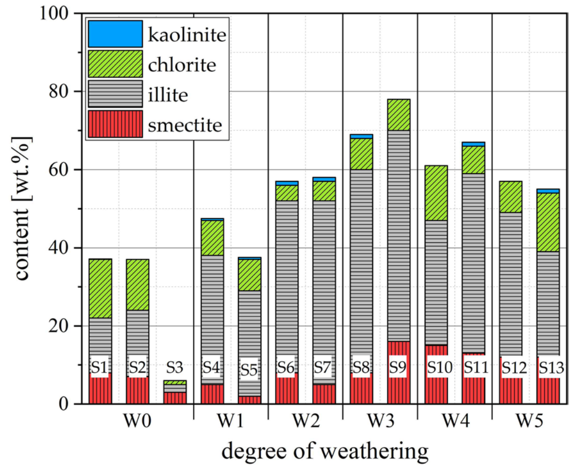


Fig. 8 Clay mineralogical composition. Each bar corresponds to one examined sample

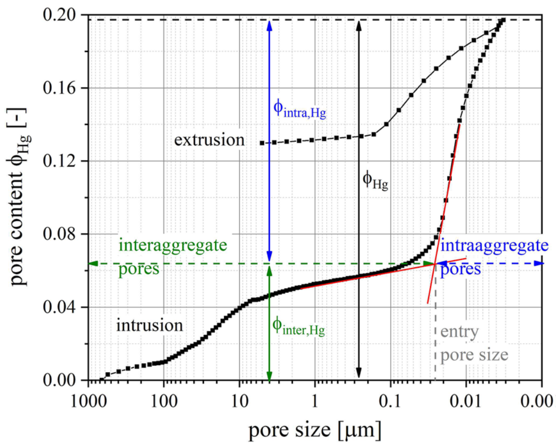


Fig. 9 Proportion of pores filled with mercury and determination of the inter- and intraaggregate pore volume. Based on Birle (2011)

The predominant clay mineral is illite (Fig. 8), however smectite and chlorite are also present, while kaolinite is almost absent. Up to weathering degree W2, the absolute clay mineral content increases. Between the weathering degree W2 and W5, when no sulphate is present, the absolute clay content is influenced by the presence of other minerals, e.g. the carbonate content. A clear link to the degree of weathering could not be established.

When evaluating the feldspar, quartz, hematite and rutile contents, no correlation to the degree of weathering was found. The data are included in Table 2, but are not considered further here.

In conclusion, it was found that sulfate leaching is the first stage of weathering. No clear influence on the mineralogical composition was found in the further course of weathering. However it was observed that the clay mineral content increases up to weathering grade W3, which is clearly dependent on the decreasing carbonate or sulfate content.

2.5 Experimental Studies

The focus of the investigation presented here was to determine the influence of the degree of weathering on pore space. In addition to the total porosity investigated with immersion weighing, the pore size distribution is of particular interest as it strongly influences the weathering behaviour.

A mercury intrusion porosimeter (MIP) from micrometrics, type AutoPore IV 9520 (pore size 360–0.003 µm; pressure 410 MPa), which was provided by the Institute of Applied Geology (AGW), Karlsruhe Institute of Technology (KIT), was used to investigate the pore size distribution of the differently weathered Keuper Marls.

By means of MIP, the pore size distribution can be determined especially in the macro- and mesopore range of a dry sample (Diamond 2000). As an example of weathering degree W3 as a sum curve from the Grabfeld-Formation, Fig. 9 shows the mercury-filled pore fraction as a function of the respective pore diameter. A subdivision into inter- and intraaggregate pores is possible via the gradient of the intrusion curve. First, the larger pores between the aggregates (interaggregate pores) are filled with mercury in the course of the intrusion. Before the pore content rises sharply again, the curve visibly flattens out. The beginning of the filling of the intraaggregate pores is recognizable by a strong increase of the curve and can be determined by tangents (Birle 2011).

Before examination, the rocks were crushed into small pieces with a diameter of about 0.5–1 cm. Afterwards they were freeze-dried. Freeze-drying does not disturb the rock structure significantly. Due to the low temperature of the liquid nitrogen, the rock is frozen so quickly that the formation of crystalline ice during the natural freezing process and the associated increase in volume is largely prevented (Birle

2011). Subsequently, the frozen water is sublimated by reducing the pressure.

Knowledge of the grain density is necessary for the evaluation of the MIP, because the maximum pressure during the measurement is 410 MPa and Hg is a non-wetting liquid. The dry density ρ^d was determined by immersion weighing and measuring methods according to EN ISO 17892-2 (2014) and the grain density according to DIN 18124 (2019) with the capillary pycnometer method. To determine the grain density, the rocks were ground to powders with grain sizes < 0,25 mm.

For correlation the changes of the pore space during weathering with the mechanical behaviour and the disintegration behaviour, uniaxial compression tests (EN ISO 17892-7 2017) and water storage tests (EN ISO 14689 2018) were carried out at the Institute for Geotechnical Engineering at the University of Stuttgart (IGS). The results are already analysed by Knopp and Moormann (2021).

3 Results and Discussion

3.1 Total Porosity

The total porosity ϕ is the fraction of the total soil volume that is taken up by the pore volume and can be calculated from the density of the rock (grain density) ρ^s and the density of the porous body ρ^d.

Figure 10 shows the determined grain densities of some rocks of the Grabfeld-Formation investigated here as a function of the degree of weathering. It should be noted that the grain density ρ_s according to DIN 18124 is defined as the bulk density of the solid individual components (grains) of the soil including closed pores within the grain. To determine the grain density, the rock has to be crushed into grains. Individual particles with closed pores should not be destroyed. Due to the aggregation during diagenesis, a clear definition of the so-called grain is practically impossible in the rocks investigated here. It was therefore difficult to determine reproducible or comparable grain densities. Thus, the decrease in grain size may be related to the decreasing density of the ground grains during weathering. Additionally, mineralogical changes can also lead to a decrease in grain density in the course of weathering. The dissolution of anhydrite, for example, leads to a decrease in grain density. The high dolomite content of the W1 and W2 samples examined here, however, prevents a further strong decrease.

Figure 11 shows the pore proportions determined as a function of the visually determined degree of weathering. Between the chemical weathering (W0 to W2), the pore content is not constant. The pore content rises between W0 and W1 slightly and between W1 and W2 sharply. Between the physical weathering (W2 to W5), the pore content grows linearly,

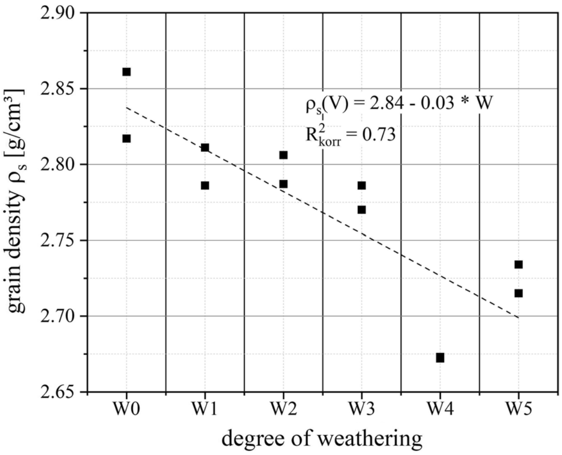


Fig. 10 Grain densities as a function of the visually determined degree of weathering

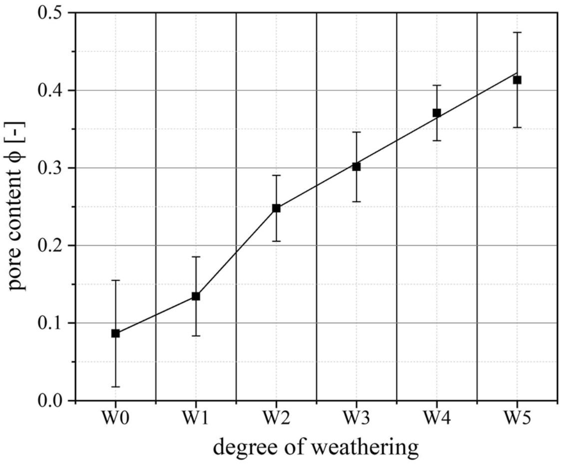


Fig. 11 Porosity as a function of the visually determined degree of weathering

which was previously demonstrated for the southwest German Opalinus Clay (Baradar-Razizadeh 1980).

The pore size distribution should be used to take a closer look at which pores cause the abrupt increase between W1 and W2.

3.2 Pore Size Distribution

Figure 12 shows the density functions of the studied samples. All investigated samples have a significant peak in the nanopore range, which increases up to the weathering degree W3 and is lower at the weathering degrees W4 and W5. In the weathering classes W2 and W3, there are samples that show a peak in the nanopore range and another peak in the transition to the micropore range. In the micropore range the samples with weathering degrees W4 and W5 have another significant peak at 1 µm. Furthermore, the samples with weathering degrees W3, W4 and W5 have further small peaks between 6 and 100 µm. Chemical weathering increases the porosity from weathering degree W0 to W1. No significant increase in pore size can be observed. With weathering degree W2, where physical weathering begins, the existing pores are enlarged and additional new pores are created. This is particularly pronounced in weathering degree W2 and W3, where the peaks become larger. From weathering degree W4 onwards, new pores are no longer created but the existing pores are enlarged, which is shown by the increase in pore size. One of the samples with weathering grade W5 shows a typical structural fracture of a rock (crack in Fig. 12f).

Figure 13 shows the pore proportions determined by MIP as a function of the degree of weathering. Between the rocks with weathering degrees W0 and W1 there is hardly any difference between the pore proportions. Probably the dissolution of anhydrite in the first stage of weathering preferentially creates nonporous. In addition, nonporous may be formed by the anhydrite-gypsum transformation. Figure 12 shows that there are still pores at the end of the pore spectrum that cannot be measured with the MIP. However, by determining the pore content with grain density and dry density, it could be shown that the pore content in weathering degree W2 has increased compared to weathering degree W1 (Fig. 11). In the case of rocks with weathering grade W2, the intraaggregate pore content has increased sharply due to sulfate leaching shown in Fig. 6 and the associated aggregate loosening. The proportion of interaggregate pores, on the other hand, increases only slightly. From weathering degree W2 onwards, both the inter- and the intraaggregate pore content increase (Fig. 13a).

According to Busch and Luckner (1973) pores > 3 to 8 µm are hydraulically effective. In the rocks examined here, the proportion of pores > 8 µm increases slightly up to the degree of weathering W2 and then increases sharply (Fig. 13b).

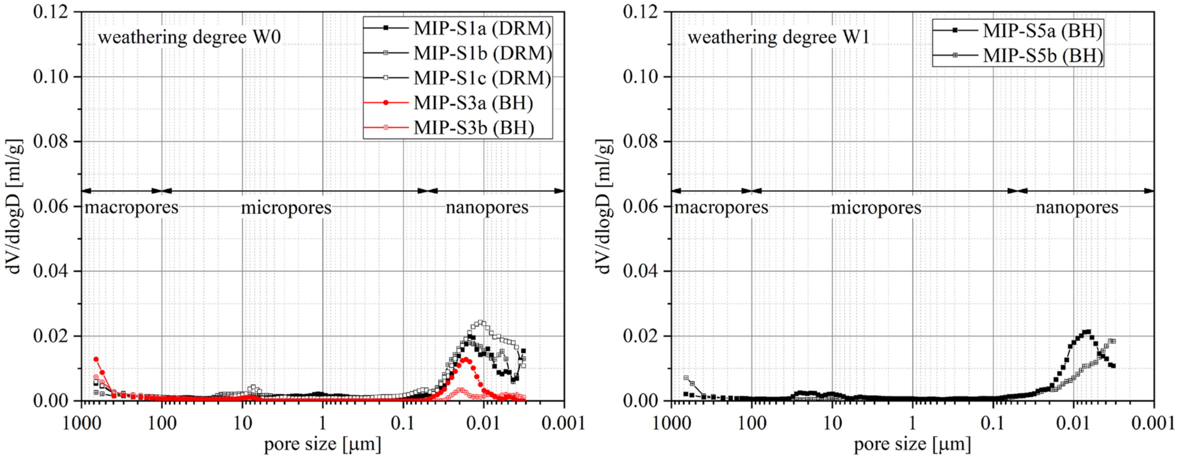
The entry pore sizes initially increase slightly with increasing weathering. As of weathering degree W3, the entry pore size increases strongly (Fig. 14).

Figure 15 summarizes which pore sizes change significantly during the weathering of the rocks of the Grabfeld-Formation. Chemical weathering processes predominate from weathering grade W0 to W2. From weathering grade W3, the rocks weather due to physical processes.

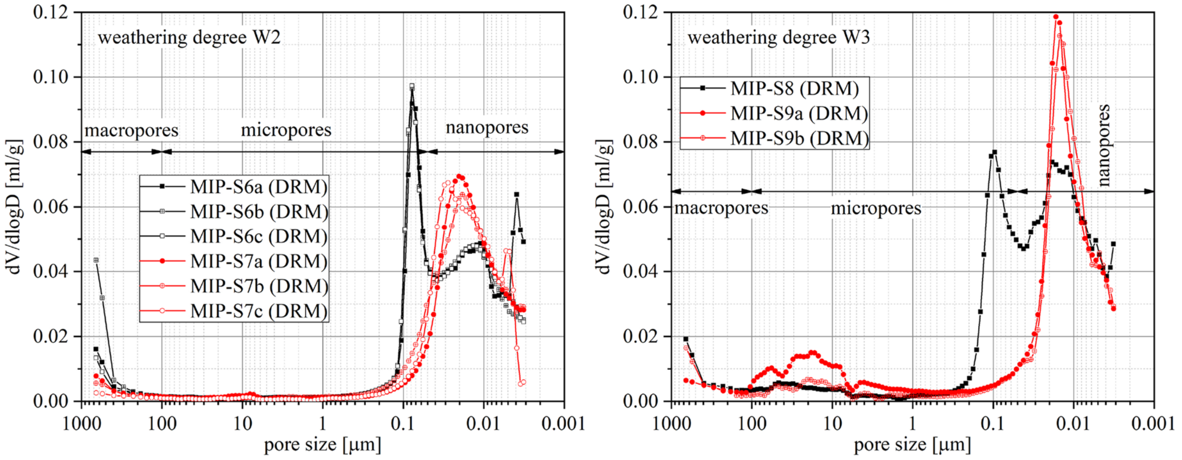
3.3 Influence of Pore Size Distrubution on the Mechanical Behaviour

Figure 16 shows the uniaxial compressive strength as a function of the inter- and intraaggregate pore content. A distinction is made between the unleached (with sulfate, W0-W2) and the leached (without sulfate, W2 - W5) samples.

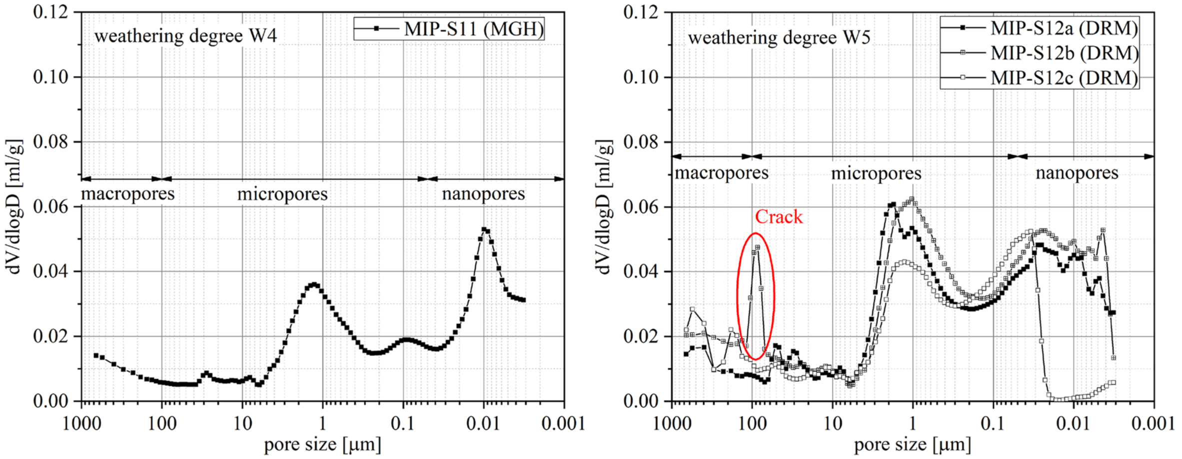
It can be seen that a slight increase in the interaggregate pore content leads to an exponential decrease in compressive strength (Fig. 16a). The drop is particularly strong in the area of small pore contents and high compressive strength. The larger the pore content, the less a further increase in the pore content causes a degradation in compressive strength. Figure 16b shows that during leaching, the intraaggregate pore content rises sharply, but the compressive strength is almost unaffected. The compressive strength of the rock is therefore mainly influenced by the interaggregate pore content. Interaggregate pores are large pores between aggregates, while intraaggregate pores are fine pores within aggregates. An increase in large interaggregate pores between aggregates results in a greater loss of stability than an



(a) weathering degree W0 **(b)** weathering degree W1

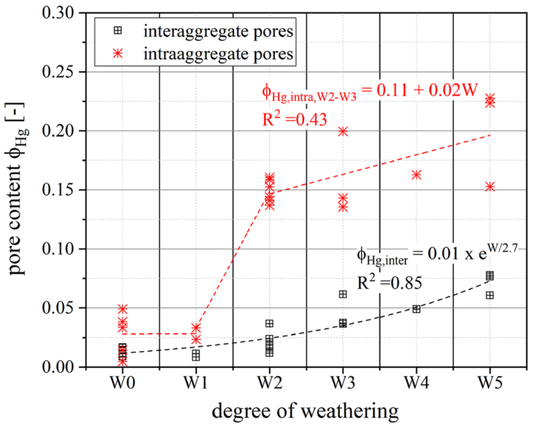


(c) weathering degree W2 **(d)** weathering degree W3

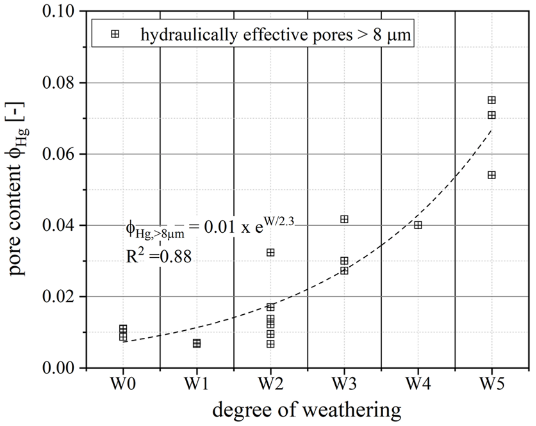


(e) weathering degree W4 **(f)** weathering degree W5

◂**Fig. 12** Density function of the pore diameter. *DRM* Dunkelroter Mergel, *BH* Bochinger Horizont, *MIP* mercury intrusion porosimeter, *P* sample number



(a) content of inter- and intraaggregate pores



(b) content of hydraulically effective pores

Fig. 13 Results of the mercury intrusion porosimetry. Inter- and intraaggregate pore components as well as the components of hydraulically effective pores as a function of the degree of weathering

increase in fine pores within aggregates due to the pore sizes and decrease in bonds between aggregates.

3.4 Influence of Pore Size Distrubution on the Distintegration

Figure 17 shows the reaction as a function of the inter- and intraaggregate pore content during a water storage test of different samples. Up to an intraaggregate pore content of about 15% and an interaggregate pore content of about 4% (samples with weathering degree W0 to W2), no or only slight reactions of the samples with the water are detectable. Since chemical weathering dominates in the weathering degree W0 to W2, the microstructure of the rocks has not yet been significantly disturbed. This result is confirmed by the uniaxial strength of these samples (Fig. 16). With the onset of physical weathering (>W2), the studied samples react much more strongly with the water. This is clearly visible from an interaggregate pore content of about 4%.

4 Conclusions

Soft rocks are susceptible to weathering and disintegrate during dehydration and rewetting. In construction practice, these rocks are of great interest as they are often found in the shallow subsurface rocks. It is important to recognize how severely weathered a rock is. The aim of this study is to further investigate the causes of rock weathering with focus on determining the influence of the degree of weathering on the pore space. The changing pore size distribution during weathering of sulfate-bearing soft rock was investigated. The results are related to changes in mineralogy and mechanical behaviour during weathering.

A mercury intrusion porosimeter (MIP) was used to investigate the pore size distribution of the differently weathered Keuper marls. For correlation, the influence of changes of the pore space during weathering on the mechanical behaviour and the disintegration behaviour uniaxial compression tests and water storage tests were carried out.

The results show that with increasing weathering the sulfate content decreases (Fig. 6). The investigations of the pore space show that with increasing weathering the total pore content increases (Fig. 11). During chemical weathering (W0 to W2) the increase in pore content is non-linear. There is a strong increase during leaching out between weathering degree W1 and W2. During the physical weathering process (W2 to W5) the increase in pore content is linear. The investigation of the pore space using a mercury intrusion porosimeter further revealed that the proportion of pores is almost constant between weathering degrees W0 and W1. However, with the calculation from grain density and dry density, an increase in porosity could be determined. However, these pores are too small to be detected with the MIP. The intraaggregate pore fraction specifically increases

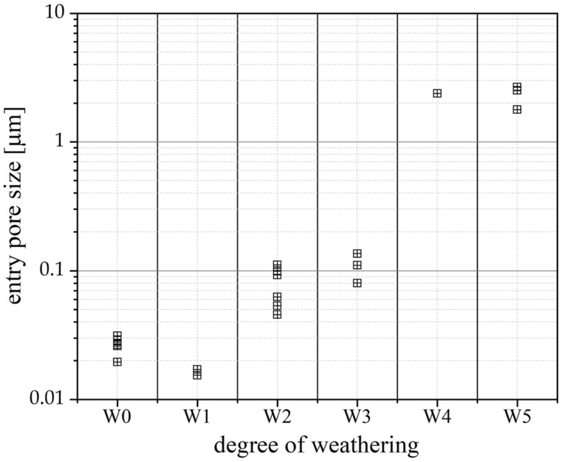


Fig. 14 Entrancy pore size as a function of the degree of weathering

between W1 and W2 (Fig. 13a). Accordingly, sulfate leaching particularly reduces the fine pore space within the aggregates. This means that the aggregates loosen due to the loss of cementative bonds. The interaggregate pore fraction increases especially in the areas of physical weathering (W2 - W5).

The uniaxial compressive strength of the rock (Fig. 16) and the fraction in water storage tests are mainly influenced by the interaggregate pore content (Fig. 17). However, the interaggregate pore fraction only increases significantly after leaching of the rocks. Therefore, the chemical weathering process at the beginning of weathering is the basis of the degradation of the strength and increase of tendency to decay.

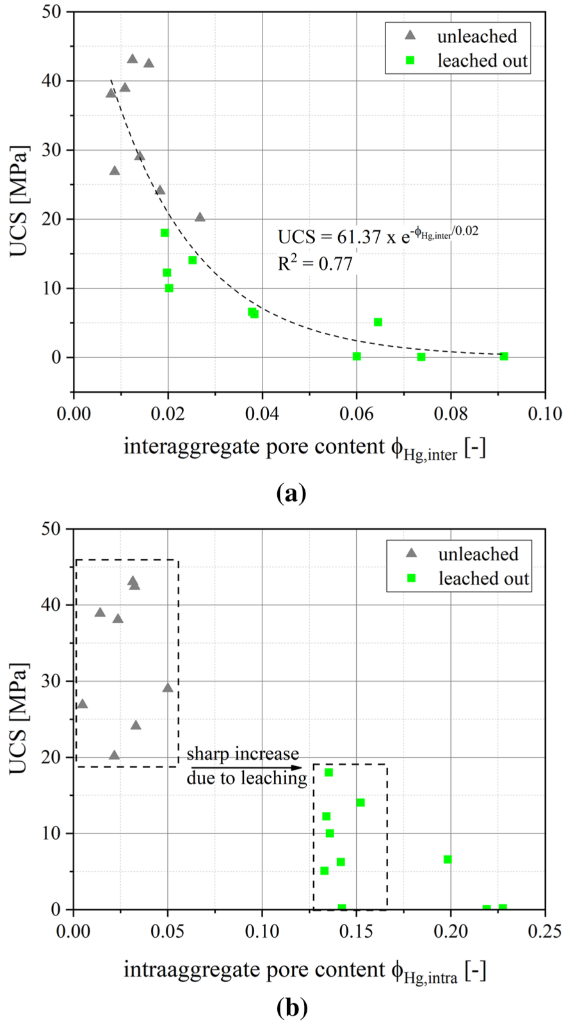


Fig. 16 Influence of the pore size distribution on the uniaxial compression strength (UCS) (Knopp and Moormann 2021)

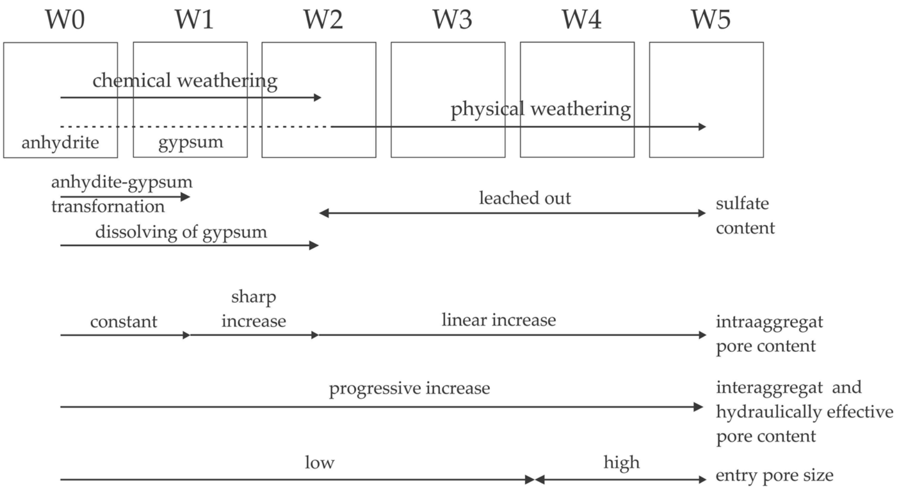


Fig. 15 Mineralogical and pore size changes during weathering. Partly based on Knopp (2020)

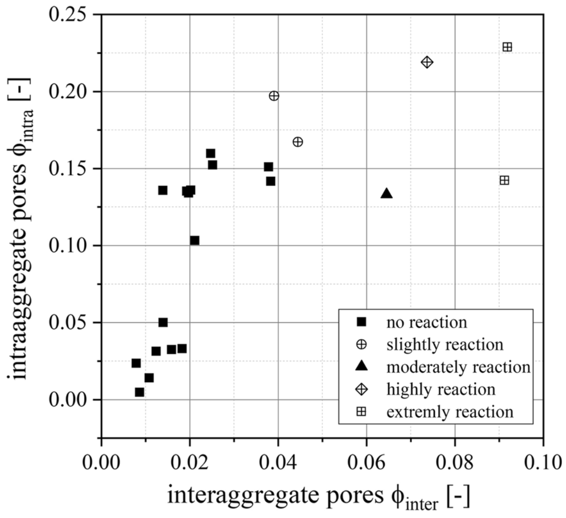


Fig. 17 Influence of the inter- and intraaggregate pore content on reaction in water storage test. Only from an interaggregate pore ratio of about 4% the tendency to disintegrate increases with simple water contact (Knopp and Moormann 2021)

It was found that the course of weathering—especially the subdivision into chemical and physical weathering—can be described most clearly with the pore fraction. For practical purposes, the prevention of leaching is of great relevance. Although physical processes are more relative for both a decrease in compressive strength and an increase in the tendency to decay, it has been found that these occur particularly after leaching.

The investigated Keuper rocks are sulfate-bearing in the unweathered initial state. Finally, please note that our results should not be transferred to other non-sulfate-bearing rock formations without further investigations.

Author Contributions The first draft of the manuscript was written by Dr.-Ing. Julia Knopp and all authors commented on previous versions of the manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL. The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availibility The datasets generated during and/or analysed during the current study are not publicly available, but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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