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Jordi Corominas · Joan Martínez-Bofill · Albert Soler

A textural classification of argillaceous rocks and their durability

Abstract Argillaceous rocks can display a wide range of durability behavior after excavation and in cut slopes. In this paper, we propose a classification of argillaceous rocks based on their textural characteristics. Three main components of the classification scheme are the clastic framework, the fine-grained matrix, and the cementing agent. Unlike other schemes, the unlithified argillaceous sediments are included as well. The names proposed for the rocks broadly follow the existing nomenclature used in petrographic classifications. The durability of some argillaceous rock types has been assessed by taking into account a set of degradation features of the excavated slopes. It has been observed that the ratios of these textural components exert a strong control on the long-term durability of slopes.

Keywords Argillaceous rock · Durability · Slope deterioration · Classification

Introduction

Argillaceous rocks are frequent in the nature. They form around two-thirds of the stratigraphic column (Blatt 1982) and about one-third of all rocks exposed at the earth surface (Franklin 1983). Although strictly speaking an argillaceous rock is a rock made of clay, in its practical usage, it has a broader meaning and it is equivalent to terms such as lutite or mudrock. It encompasses rocks such as argillite, claystone, siltstone, mudstone, shale, clay shale, or marl (Potter et al. 2005). They are all mostly siliciclastic rocks whose predominant constituent particles are silt and/or clay-size. Though argillaceous rocks are mainly composed of detritus from preexisting rocks, they may contain significant amounts of chemically precipitated cement (such as calcium carbonate, silica, iron oxide, among others).

The mineralogy of the argillaceous rocks is controlled by the source of the sediment and the conditions of the depositional environment. Typical clastic components are quartz, feldspar, and phyllosilicates such as mica, chlorite, illite, and other clay minerals. During diagenesis, compaction and cementation transform sediment into a rock. This is an ongoing process involving the progressive reduction of void space and the crystallization of authigenic minerals that results in an increase in strength and decrease in compressibility and permeability. This process is summarized by Czerewko and Cripps (2006).

It is difficult to assess when argillaceous sediment becomes rock because the conversion of sediment into rock is a continuous process. Soils are defined as natural aggregates of mineral grains that can be separated by gentle mechanical means such as agitation in water while rocks are natural aggregates of minerals connected by strong and permanent cohesive forces (Terzaghi and Peck 1967). The soil–rock boundary is usually established based on their strength. British Standards (BS5930:1999) define a lower limit for the undrained shear strength of very stiff soils of 150 kPa and an upper unconfined compression strength for weak rocks of 12.5 MPa. Other limits have been proposed by other researchers (i.e., Hawkins 2000). The boundary between hard soil and soft rock is commonly recognized around 1 MPa (Marinos 1997; Czerewko and Cripps 2006) although there is no complete agreement on this limit since these materials are part of a continuum (Johnston and Novello 1993).

Argillaceous rocks display a contrasting behavior in construction works. Blasting is often required to excavate these rocks. However, the newly excavated slope surfaces may experience physical weathering and disintegrate in a very short span of time, over a period of months to years. The shallow, progressive, physical, and chemical alteration of rock material and its subsequent detachment and removal or redistribution by transport agents is defined as deterioration (Nicholson 2004).

Weathering predisposes the instability of the excavated slopes (Calcaterra and Parise 2010). Although surface deterioration of cuts is perceived as having low risk, it affects the safety of the users and involves costly maintenance works (Martinez-Bofill et al. 2004). Listric joints may develop parallel to the slope face being a main source of instability (Fig. 1). This type of discontinuities is seldom identified in boreholes or in field surveys as they develop mostly after the rock has been exposed. The exposed rock surface may experience swelling and breakdown facilitating the erosion and compromising the appropriate performance of the remedial and/or stabilization measures (Fig. 2). When interbedded layers of limestone, sandstone, or conglomerate are present, disaggregation of the argillaceous rock results in overhangs, which may produce topples and failures, especially if vertical joints parallel to the slope face exist (Fig. 3).

The described behavior cannot be generalized, and some road cuts in argillaceous rocks may remain virtually unweathered without signs of degradation for years (Fig. 4).

This contrasting behavior has attracted the interest of engineers involved in the design, construction, and maintenance of embankments, road cuts, and tunnels. In fact, most the maintenance cost is due to the inability to accurately identify and classify these rocks and anticipate their behavior.

Characterization of the argillaceous rocks for engineering purposes

Many attempts have been made to classify and characterize the argillaceous rocks in order to predict their behavior. Classical soil analyses such as particle size and Atterberg limits are not appropriate for characterizing the argillaceous rocks because they cannot be easily disaggregated. Porosity, degree of saturation, and fissuring are parameters that govern the strength and deformability of the argillaceous rocks. Similarly to other rocks, the Uniaxial Compressive Strength (UCS) tends to increase with the increase of packing density. Recent reviews on the wide range of properties and on the engineering performance of stiff sedimentary clay were prepared by Chandler (2010), Simpson (2010) and Pineda et al. (2014). Weathering of the argillaceous rocks reduces UCS and shear strength (Taylor 1988; Bhattarai et al. 2006). Czerewko and Scripps (2006) summarized the

Fig. 1 Slope surface deterioration with the development of listric (curvilinear) failures on mudstones in the C-17 road at Tona, Barcelona province, NE Spain

variation of the mudrock properties with the different stages of the diagenetic maturity. Despite all this work, several researchers have reported that standard rock tests are unsuitable to properly characterize the long-term behavior for most of argillaceous rocks and its durability (Czerewko and Cripps 2006; Nickmann et al. 2006, 2010). The reason is that routine geomechanical tests are oriented to determine rock strength or the capability to withstand loads but they are not primarily focused to assess the susceptibility of the rock to weaken upon exposure and disintegrate along time. In other words, they are not designed to assess the durability.

The durability of a rock expresses its ability to resist abrasion, wear, and breakdown with time (Santi 1998). There exist several converging points of views on the factors that govern durability of the argillaceous rocks and mechanisms leading to slaking and dispersion of soil particles. Among them stand the swelling produced by stress release and water absorption (Mitchell 1993). After excavation, stress release results in the development of fissures. These microstructures, rock pores, and fissures induce the infiltration and evaporation of water (cycles of wetting and drying) with the subsequent volume changes that produces the slaking of the rock.

Fig. 2 Cut slope surface deterioration in the N-1 road at Ormaiztegi in the Gipuzkoa province, N Spain. The argillaceous rock decomposes around the bolt thus preventing its proper operation

Fig. 3 Differential weathering along the C-16 road at Navàs, Barcelona province, N Spain. Spalling and disaggregation of the mudstone have generated overhangs in the sandstone layers which eventually fall

Compaction and cementation are critical post-depositional processes that control the properties and long-term behavior of the argillaceous rocks (Morgenstern 1974; Dick and Shakoor 1997). In the first stages of diagenesis, materials are poorly indurated and have a strong tendency to disaggregate upon immersion in water. The prominent role of bonding on durability was highlighted by Mead (1936) and Underwood (1967) who classified shales into two broad groups. The first includes the compacted shales (mudrocks) which have been consolidated by the weight of the overlying sediments without intergranular cement. Meteoric agents may return the consolidated argillaceous rock to an assemblage of minerals and rock fragments. The second group includes cemented shales (mudrocks) that have a cementing agent (calcareous, siliceous, or ferruginous) or bonding material formed by recrystallization of clay minerals which reduce porosity and enhance durability by preventing the entrance of water and air. The removal of cement as well as the poor binding efficacy may become a cause for rock degradation.

The role of the stress history of the argillaceous rocks in controlling both the fabric and bonding of the rock and explaining its

Fig. 4 Slightly deteriorated cut slope. Well-preserved blast holes are observable several years after the excavation of the slope in the C-17 road at Torello, Barcelona province, NE Spain

mechanical behavior has been summarized by Alonso and Pineda (2006) and Gens (2013). Bjerrum (1967) attributed the swelling of unloaded shales to release of the locked in strain energy of the diagenetic bonds. The less indurated clays will more readily release the strain energy stored during compaction

The fundamental influence of the mineralogy has been also discussed by several authors (Gökçeoglu et al. 2000; Sadisun et al. 2005). Russell (1981) observed that the low durability of shales was partly due to the inefficient cementing by calcite. Instead, the presence of hard bands and shaly limestone increased significantly the durability. The strength of fine-grained argillaceous rocks is found inversely related to the total percentage of clay minerals (Gökçeoglu et al. 2000; Ward et al. 2005) while the presence of expandable minerals such as smectites (Czerewko and Cripps 2006), or sulfides (Quigley and Vogan 1970; Grattan-Bellew and Eden 1975; Sadisun et al. 2005) enhances the response to changes in moisture content or changes in pore water chemistry. High carbonate content is associated to the high durability of the rocks (Gökçeoglu et al. 2000). In most of these studies, the influence of the mineralogical content on the durability of the rocks has been established by means of statistical relations. However, neither a precise nor the quantitative proportions of the mineralogical constituents governing the durability have been proposed so far.

Most widely used tests to assess rock durability are the slake durability test (SDT) (Franklin and Chandra 1972) or the jar test (Wood and Deo 1975) which aim at determining the effects of alternate drying and wetting on the durability of soil and rock. Although these tests may be useful for assessing the short-term performance of certain argillaceous rocks, the extensive experience on their performance indicates that their results are far from yielding fully satisfactory results in the characterization of the long-term durability of argillaceous rocks (Nickmann et al. 2006). This is attributed to the fact that durability is not dependent on a single property but on combination of parameters such as the porosity, compressive strength (expression of the bond strength of the matrix), grain size distribution, texture (grain or matrix supported), mineralogical constituent, degree of cementation, and stress history (Santi 1998; Czerewko and Cripps 2006; Nickmann et al. 2006; Martinez-Bofill 2011).

A classification scheme for argillaceous rocks

The successful construction and performance of engineering works in argillaceous rocks depends on correctly anticipating the long-term behavior of these particular materials. As discussed above, conventional laboratory tests often prove to be unable to fully characterize durability while the search for predictors of the long-term behavior of the weak rocks after their exposure is still a challenge.

The mineralogy (Grainger, 1984), particularly expansive clays (Dick and Shakoor 1992; Dick and Shakoor 1997) and the cementation (Shakoor and Brock 1987), are widely accepted as important factors controlling the deterioration of the rock cuts. Consequently, it might be possible to establish a relationship between the mineralogical constituent, the cement content, and the durability of the argillaceous rocks. The names of sediments and sedimentary rocks have been traditionally proposed based on a wide range of criteria such as the mineral content, texture, and other physical attributes as well as the depositional environment, genetic relationship, and economic importance (Hallsworth and Knox 1999). However, as stated by Gens (2013), a shortcoming of classifications based only on grain size is that they give no information on the intensity of bonding or lithification, which is an important aspect in the context of durability. In order to overcome these drawbacks, we present a new classification scheme for the argillaceous rocks.

A classification should meet the needs of providing a concise and systematic method for designating various types of rocks, and, if engineering properties are important, the classification should also enable to derive soil properties. The proposed classification scheme is based on the rock texture which specifically accounts for the bonding constituent. This classification does not attempt to replace the existing and widely accepted terms. It also does not intend to change the established proportions of the constituents of the argillaceous rocks and soils. Only when several options exist, we have selected the most appropriate one.

The previously proposed classifications involving argillaceous rocks are first reviewed, retaining their original terms. Traditionally, sediments and sedimentary rocks have been classified independently and do not take into account of schemes for other sediments and rocks with which they overlap. Thus, limestone, sandstone, and ironstone are classified separately although in nature they share strong compositional and genetic links. Furthermore, the criteria used to classify each sedimentary group are usually different. As a result, terms of sediment and sedimentary rocks tend to be inconsistent and lacking in basic or general guidelines (Hallsworth and Knox 1999). Many classification schemes of detrital sediments and rocks have been proposed. Hallsworth and Knox (1999) and USGS (2004) presented complete reviews of the existing classification schemes which will be taken as starting point.

Krynine (1948) used rock texture, including mineralogical content as criteria for classification. Grain size was the primary criterion for grouping conglomerates, sandstones, and fine clastics. Williams et al. (1982) presented a ternary plot naming conglomerates and sandstones, those clastic rocks having respectively more than 50 % of coarse fraction (pebbles and cobles) and sand. Folk (1954, 1980) based his classification on the particle size (Fig. 5). In his ternary plot, the vertices are gravel, sand, and mud. He proposed the term conglomerate when gravel content exceeds 80 % and several combinations of the terms gravel, sand, and mud (silt and clay). This scheme has been widely accepted.

Pettijohn et al. (1972) adapted Krynine's (1948) classification and introduced the term fine matrix to distinguish between arenites and mudstones. Rock with more than 75 % of fine-grained content (<0.03 mm) is named mudstone. Rocks with contents between 15 and 75 % of fine particles are named wackestone (Fig. 6). Sand size aggregates with fine-grained content less than 15 % (this boundary is 10 % in the proposal of the US Geological Survey and USGS 2004) correspond to sandstones.

On the other hand, carbonatic sediments and rocks (limestone, dolomite) are defined as having more than 50 % of carbonate content. This percentage must not include the carbonatic cement although this requirement is not necessary in the classification of the USGS (2004).

Several researchers suggest that the classification of the argillaceous rocks based on particle size and mineralogical composition may not be appropriate due to the difficulty of separating the individual grains from each other (Czerewko and Cripps 2006).

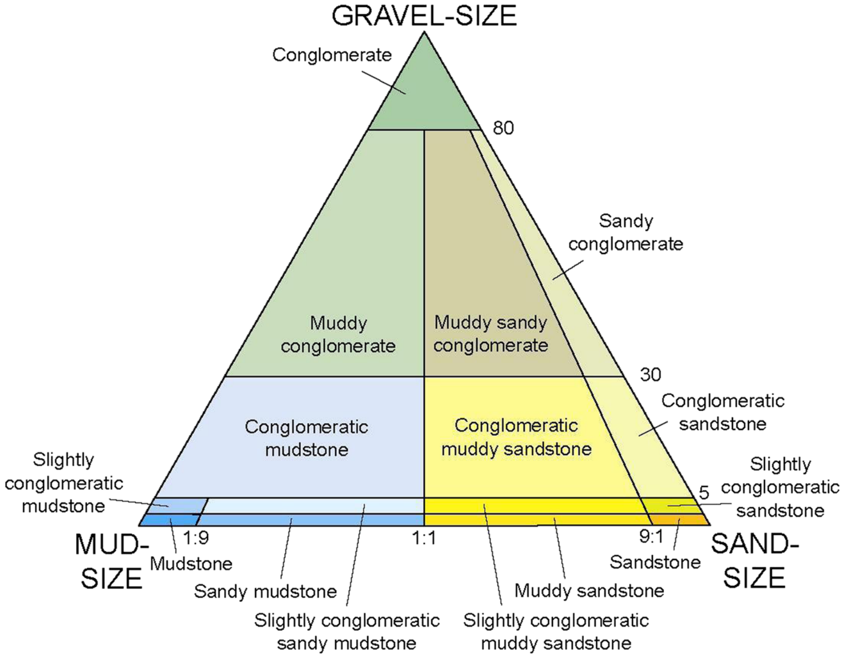

Fig. 5 Classification of sedimentary detritic rocks (from Folk 1954)

We propose a new classification, based on textural attributes of the argillaceous rocks. The nomenclature consists of root names which combine information on grain size (grain framework, matrix) and the amount of cementing agent. To classify a sample, one needs to determine the content of clastic framework (sand size), matrix, and cement.

The proposed scheme (Fig. 7) is based on a ternary plot in which the vertices are sand-size content (between 0.032 and 2 mm), mud-size content (<0.032 mm), and cement (calcium carbonate). The boundary of 0.032 mm is the one proposed by Dott (1964), Hallsworth and Knox (1999), and USGS (2004). It is also found as a practical boundary for visually identifying individual grains using a petrographical microscope. Smaller-sized grains often appear overlapped in thin sections and may be subjected to misinterpretations.

The scheme includes the boundary proposed by Dott (1964) between arenites, mudstones, and wackes. The latter are however considered arenaceous rocks. Despite this apparent inconsistency, we have included wackes in the classification of the argillaceous sediments because most of wackes are classified as shales or mudstones in the field and because in the classification of terrigenous sediments, Folk (1954), adopted by USGS (2004) the

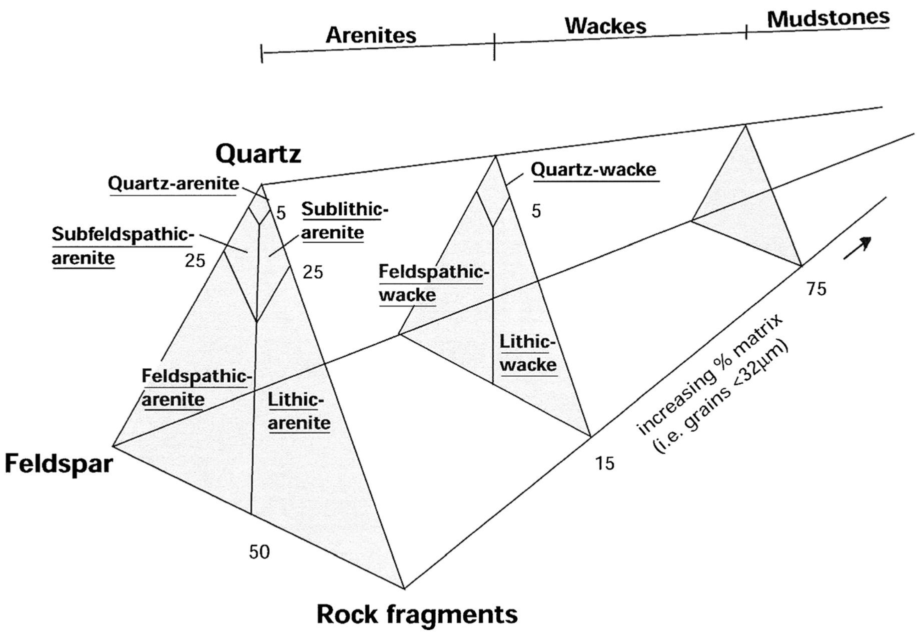

Fig. 6 Classification of the arenaceous rocks from Pettijohn et al. 1972 in USGS (2004)

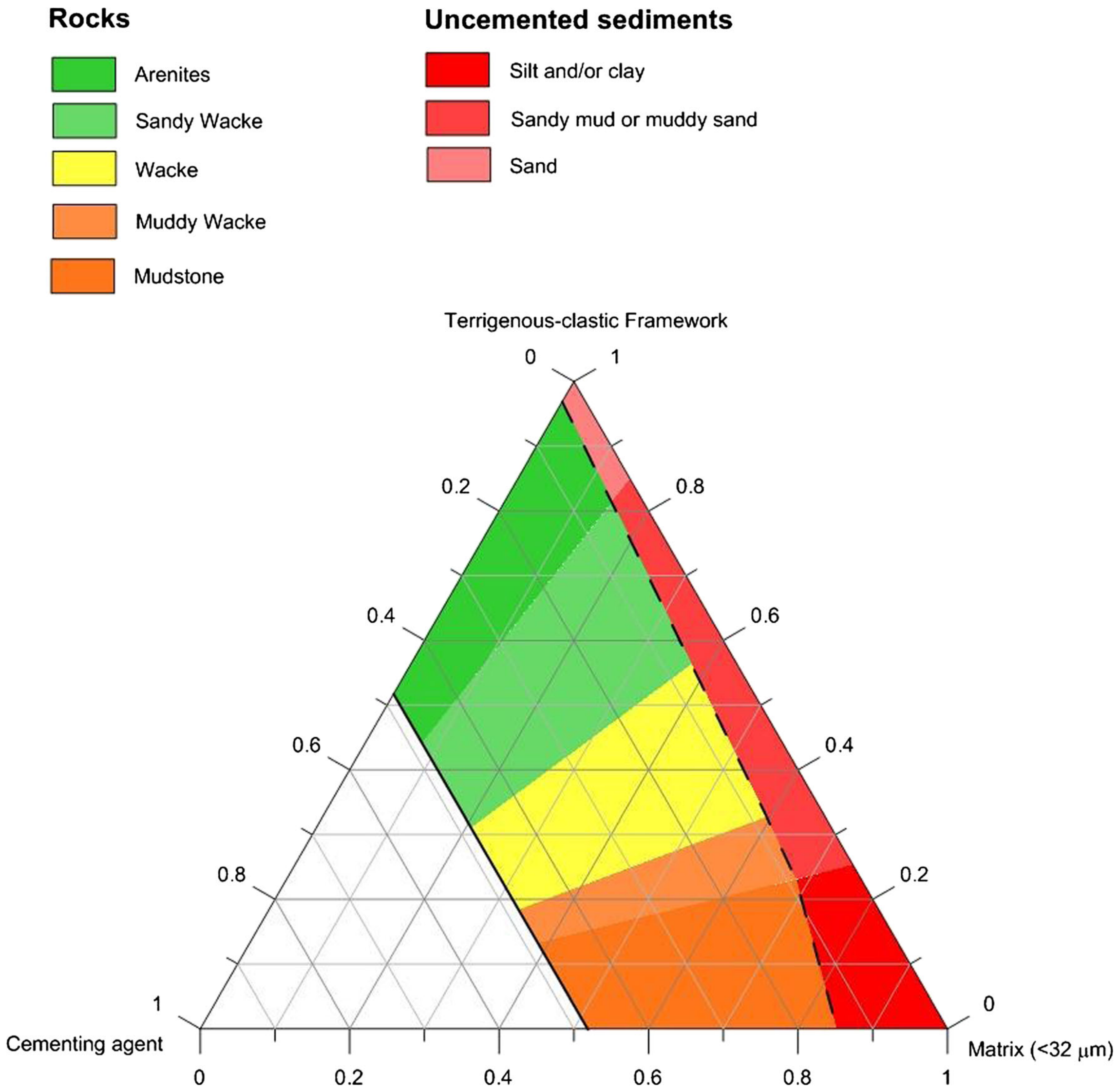

Fig. 7 Proposed textural classification of the argillaceous rocks

boundary between of mudrocks and sandy rocks corresponds to a relative proportion of 50 % of mud-size constituents.

We have adopted the same criterion as USGS (2004) for the compositional attribution of the grain-size framework. No distinction has been made on whether the grain framework is mostly siliciclastic, carbonate, or other.

The argillaceous rocks may contain authigenic minerals formed during the diagenesis at temperatures and pressures less than that required for the formation of the metamorphic rocks. In this classification of the argillaceous rocks, the authigenic minerals may correspond to the anchimetamorphism that is the final stage of the deep diagenesis or the first effects of metamorphism (Kornprobst 2003).

The term mud and mudstone is given to sediments and rocks containing at least 75 % of fine-grained constituent. Mixtures of mud with sand with the former ranging between 75 and 15 % are named wackes. The predominance of fine components (up to 65 %) or sandy components (up to 60 %) qualifies wackes as muddy wacke or sandy wacke, respectively.

Cement is the textural constituent of the proposed classification not considered in other classification schemes. Cement is a fundamental rock constituent that determines the strength and makes the difference between soils and rocks. Cement is usually calcium carbonate (calcite) or calcium magnesium carbonate (dolomite). However, cementing agents of a different composition (i.e., silica, iron oxide) may also be present.

The proposed classification (Fig. 7) establishes the boundary between sediments and rocks ranging between 4 % and 15 % of cement content. This boundary is defined based on the recommended percentages of cement used in soil stabilization (ACI-American Concrete 1997; USACE 1994). At the other extreme of the plot, a 48 % of cementing agent content has been taken to define the boundary between detritical rocks and chemical sedimentary rocks. This value of 48 % is the porosity of a simple cubic packing of identically-sized spheres (Conway and Sloane 1993) in which cement may grow. In chemical sedimentary rocks, the cementing agent can be found not only as a post-sedimentary phase, but also having been formed during the sedimentation.

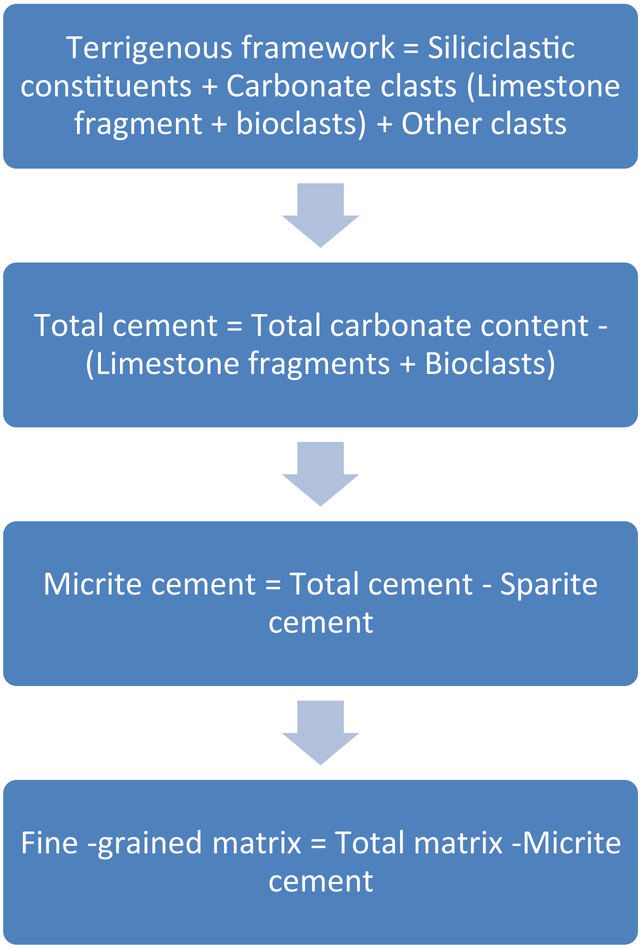

Fig. 8 Procedure for determining the textural components of the argillaceous rocks (see explanations in the text)

The mineral composition of terrigenous clastic constituents can be determined reliably with the petrographic microscope and by X-ray diffraction. Fine matrix has a size smaller than 32 μm and may be identified in the microscope as well. However, the distinction between matrix and cement can be only achieved if the cement crystals are bigger than 32 μm (i.e., sparite in carbonate cemented rocks). Smaller crystals (microsparite and micrite) are unresolvable for quantitative analysis with the petrographic microscope, and the cement cannot be distinguished from the matrix. In this case, the amount of cement may be determined with a procedure such as the one described below.

Quantifying the constituents of the argillaceous rocks

Determining the components of the proposed classification scheme is not straightforward, because they cannot be mechanically separated. Furthermore, the grain sizes of both cementing agent and fine matrix are often unresolvable using a petrographic microscope. The fine-grained cement cannot be distinguished from the matrix thereby requiring an alternative procedure to separate the two constituents.

X-ray fluorescence (XRF) and X-ray powder diffraction (XRD) are the techniques most frequently used to determine the constituents of the argillaceous rock. XRF yields the chemical composition of the rock as oxides of the different elements (Potts 1992). This composition relates to the mineralogy but it does not provide the real mineralogical species of the rock. For example, the CaO content may correspond to calcite, dolomite, or Ca silicates (plagioclase), which may be either part of the detrital constituents of the rock (calcite fragments and/or carbonated fossils) or cementing agent or both.

The XRD is a rapid analytical technique used for mineral identification of a crystalline material (Bish and Post 1989). The mineralogical content of the rock can be determined by the semi-quantitative Rietveld analysis of X-ray powder diffraction, determining the amount of each mineral (Young 1993). The Rietveld XRD permits the accurate determination and quantification of the mineral species present in the rock although no information is provided on whether these minerals are part of the terrigenous framework or of the fine-grained matrix.

In order to overcome this uncertainty, we performed the following procedure (Fig. 8) developed for rocks containing carbonate cement (Martinez-Bofill 2011). The procedure may be adapted for the quantification of the components of the argillaceous rocks indurated with other cementing agents:

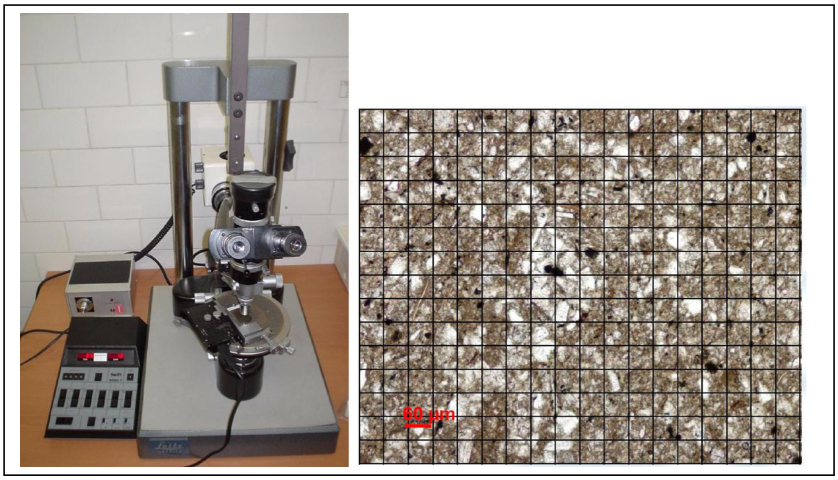

Fig. 9 Determination of the clastic framework, matrix, and cement bigger than 32 μm in the petrographic microscope (see explanation in the text)

Table 1 Total carbonate content of samples collected in different cut slopes in Spain (see next section) measured with the Bernard calcimeter and the amount of calcite and dolomite obtained with X-ray difractometry. Differences are usually less than 5 %

Sample	% CO_2 calcimetry	% CO_2 calcite XRD Rietveld	% CO_2 dolomite XRD Rietveld	Difference calcimetry-XRD
A-2.1 m1	28.84	31.19	0.65	−3
A-2.1 m2	5.1	3.97	1.94	−0.81
A-2a.2	6.73	0	8.3	−1.57
A-2.3	19.57	16.93	2.76	−0.12
A-2.5	19.57	16.24	2.65	0.68
A-2.6	30.44	29.59	2.16	−1.31
A-2.7	21.59	9.13	11.59	0.87
A-2.8	27.79	0	34.8	−7.01
C-16.1 m1	15.57	13.23	1.65	0.69
C-16.2	14.77	13.89	1.81	−0.93
C-16.3	13.94	12.77	0	1.17
C-16.4 m1	18.56	16.41	0.68	1.47
C-16.4 m2	8.49	8.11	1.63	−1.25
C-16.4 m3	23.83	21.43	0.37	2.03
C-16.6	17.9	15.32	0.6	1.98
C-16.7	9.81	7.2	2.77	−0.16
C-17.1	16.75	15.87	3.85	−2.97
C-17.2	16.91	16.59	2.87	−2.55
C-17.3	15.21	13.63	2.19	−0.61
C-17.4	8.66	7.77	4.91	−4.02
C-17.5	17.21	13.64	3.2	0.37
C-25.1	23.83	21.02	1.62	1.19
C-25.2	13.81	12.79	2.94	−1.92
C-25.3	18.81	15.34	2.81	0.66
C-25.4 m1	16.44	13.6	1.59	1.25
C-25.4 m2	17.32	17.25	1.39	−1.32
C-25.5 m1	8.18	8.28	0.77	−0.87
C-25.5 m2	8.09	7.8	2.59	−2.3
C-25.7 m1	17.32	19.47	0.91	−3.06
C-25.7 m2	22.73	16.97	1.39	4.37
C-25.9	13.06	12.49	3.02	−2.45
C-25.10	18.64	11.3	8.7	−1.36
C-25.11	15.84	9.53	0.81	5.5
C-25.12 m1	10.04	10.32	2.3	−2.58
C-25.12 m2	11.62	9.36	0.89	1.37
C-25.13	18.82	12.4	3.33	3.09
C-25.14 m1	34.93	21.5	1.35	12.08
C-25.15 m1	36.62	29.91	1.24	5.47
C-25.16	16.66	12.32	2	2.34
C-25.17	2.2	0	0	2.2
C-55.1 m1	23.82	23.63	0.68	−0.49

Table 1 (continued)

Sample	% CO_2 calcimetry	% CO_2 calcite XRD Rietveld	% CO_2 dolomite XRD Rietveld	Difference calcimetry-XRD
C-55.1 m2	15.77	13.31	1.63	0.83
C-55.1 m3	16.21	12.18	1.3	2.73
C-154.1 m1	25.41	28.37	1.62	−4.58
L-301.1 m1	10.95	5.82	4.31	0.82
L-301.2 m1	20.57	13.45	1.25	5.87
L-301.2 m2	17.94	14.94	1.14	1.86

First, the terrigenous clastic framework, the matrix content, and sparite cement (>32 μm) are determined in the optical microscope on thin sections of rock samples, provided with a point counter. Between 1000 and 2000 counts per section are recommended to be performed. Mineral constituents are obtained by counting each mineral occurrence along a series of traverse line across the thin section (Fig. 9).

All clasts are identified and counted using the polarizing microscope. The terrigenous framework is mostly composed of siliciclastic constituents although it may contain clasts of calcium carbonate composition (i.e., limestone fragments, bioclasts). The terrigenous framework is then divided between carbonate clasts (limestone fragments, bioclasts) and the rests (mostly quartz, feldspars, and lithic fragments).

Cutslope	Comment
	Stage 1 More than 20 years old cutslope composed of sandstones in the C-17 road at Borgonyà, Spain. Drill holes are still observable in the excavated rock surface
	Stage 2 More than 20 years old cutslope in the C-17 road at Borgonyà, Spain. Rock chips (few cm length) fall from the slope surface and scattered failures of rock blocks. Chips accumulate at the bottom of the slope without further slaking. Failures governed by pre-existing tectonic joint are not considered deterioration features

Fig. 10 Deterioration features observed in selected excavated slopes. The period of time during which these deterioration features are generated reduces from stages 1 to 5

	Stage 3 10 years old cutslope in the C-17 road at Malla, Spain Mid-term deterioration of the excavated slope composed of mudstones. Tendency of slope recession and frequent block failures (listric failures). Rock chips tend to break apart decomposing up to sand-size.
	Stage 4 6 years old cutslope composed of mudstones in the C-25 road at Gurb, Spain Tendency to form regolith at the excavated surface
	Stage 5 2 years old cutslope in the C-25 road at Fontfreda, Spain Slope composed by poorly indurated silts and clays

Fig. 10 (continued)

The total amount of carbonate content of the sample is determined with the Bernard calcimeter method (UNE-103-200:93, ASTM D4373). The total carbonate content includes both carbonate clasts and carbonate cement. By subtracting the amount of carbonate clasts from the total carbonate, the total amount of cement is obtained. The latter is composed of sparite carbonate crystals (>32 μm) and microsparite and micrite (<32 μm) which are included within the matrix. The micrite content which is unresolvable with the petrographic microscope is obtained by subtracting the sparite content from the total cement.

The fine-grained matrix contains all constituents smaller than 32 μm including the micritic cementing agent. The amount of silt and clay (mud) constituents is obtained by subtracting the microsparite and micrite content from the total amount of matrix.

This procedure has been complemented when necessary by the Rietveld XRD. The latter is particularly useful for double-checking the total calcium carbonate content measured with the Bernard calcimeter (Table 1) and for obtaining the composition of rock samples mostly composed of fine matrix, in which the mineralogical constituents are unresolvable using a petrographic microscope.

Performance of the classification

The performance of this classification has been assessed by analyzing the mid/long-term behavior (between 2 and 30 years) of cut slopes excavated in different argillaceous rock formations of Catalonia and Basque Country in Spain.

The analysis consists of confronting the qualitative description of the deterioration features of the cuts (taking into account the time of exposure) with both the slake durability index (SDI) and the textural composition of intact rock samples collected in the cuts. The cut slopes were first grouped based on their deterioration stage. Contrary to other schemes aiming at assessing the susceptibility to deterioration (i.e., Nicholson 2004), grouping of the cut slopes is only descriptive and based on the present state of the slope face. The deterioration stages are defined using the following descriptors (Martinez-Bofill et al. 2004) (Fig. 10):

- Stage 1: intact cut slope. Blast holes are fully visible. Intact or virtually intact excavated slope surface. The slope is stable and only sporadic rockfalls occur.
- Stage 2: slightly weathered slope surface. Fissures and spheroidal exfoliation cracks may appear after some years. It is an overall stable slope. Local (small size) rockfalls occur associated to scattered listric joints. Blast holes are observable for most of the length. The original profile of the excavated slope is kept in average. Unweathered rock chips of a few centimeters in length may accumulate at the bottom of the slope
- Stage 3: weathered slope surface. The excavated surface loses the rocky appearance with time. Spalling and disintegration of the rock surface takes place in less than 10 years. Blast holes are poorly preserved. Frequent small size slides and falls occur through listric joints (curved) generated after the excavation. Debris starts accumulating at the slope foot. The accumulated material decomposed up to sand size and rarely to smaller sizes. Generally stable but receding slope.
- Stage 4: heavily weathered slope surface. Intense slaking of the rock surface and tendency to form regolith. Continuous slaking and falling of chunks prevent the slope from rock falls. Weathered rock surface (regolith) may reach depths of some decimeters (Fig. 11). Original rock structure cannot be recognized. Blast holes have virtually disappeared. Erosion and gullying of the slope surface. Fallen debris easily decomposes to silt-clay size fragments. Receding slope profile. Steep slopes tend to be unstable.
- Stage 5: slope composed of poorly indurated silt and clay. The original rock color has vanished. Weathering and cracking of the rock reach depths of more than 25 cm. Steep slopes are unstable with frequent rotational failures. Gullying develops even with low slope angles.

In this description, the slope failures generated along preexisting joints in the rock mass were not considered as rock deterioration features.

Seventy-two rock samples were collected from 43 excavated slopes. The samples were extracted with a portable drilling machine. Cores of 30 mm diameter and 30 cm length were obtained and sent to the laboratory for mineralogical and textural characterization. For the selection of the slopes and the rock samples, we took into account the following factors: (i) presence of either marine or continental formations; (ii) lithological variety such as mudstones, marls, and shales, in order to assess the influence of the mineralogical and textural components; (iii) absence or a low degree of structural deformation of the layers and, whenever possible, the presence of expandable clays to avoid the inclusion of factors that may generate additional scattering in the assessment of the durability of the materials.

Fig. 11 Gully of more than 20 cm depth in the regolith developed on the surface of a 6-years old excavated slope of the C-25 road at Gurb, Spain (stage 4)

The samples cover a wide range of argillaceous rock compositions, and the results are presented in Fig. 12. As mentioned above, the procedure to quantify the textural components has some uncertainty due to of the assumptions made for the quantification of the cementing agent. Therefore, the mineralogical content has been replicated by performing a semi-quantitative Rietveld analysis by X-ray powder diffraction (Martinez-Bofill 2011). It is noticeable that despite most of the samples having been classified in the field as mudstones and shales, only a few of them fulfill the requirement of having more than 75 % of fine-grained constituents.

The main textural feature that can be identified at first sight during the microscope observation or even at nude eyesight in the counterlight is the homogeneity. Samples may be homogeneous or heterogeneous (Martinez-Bofill et al. 2008): homogeneous textures are characterized by a regular and uniform grain-size and matrix distribution, without remarkable disturbing signs (Fig. 13). Conversely, heterogeneous textures show a pattern of different types of textures and grain size distribution (Fig. 14).

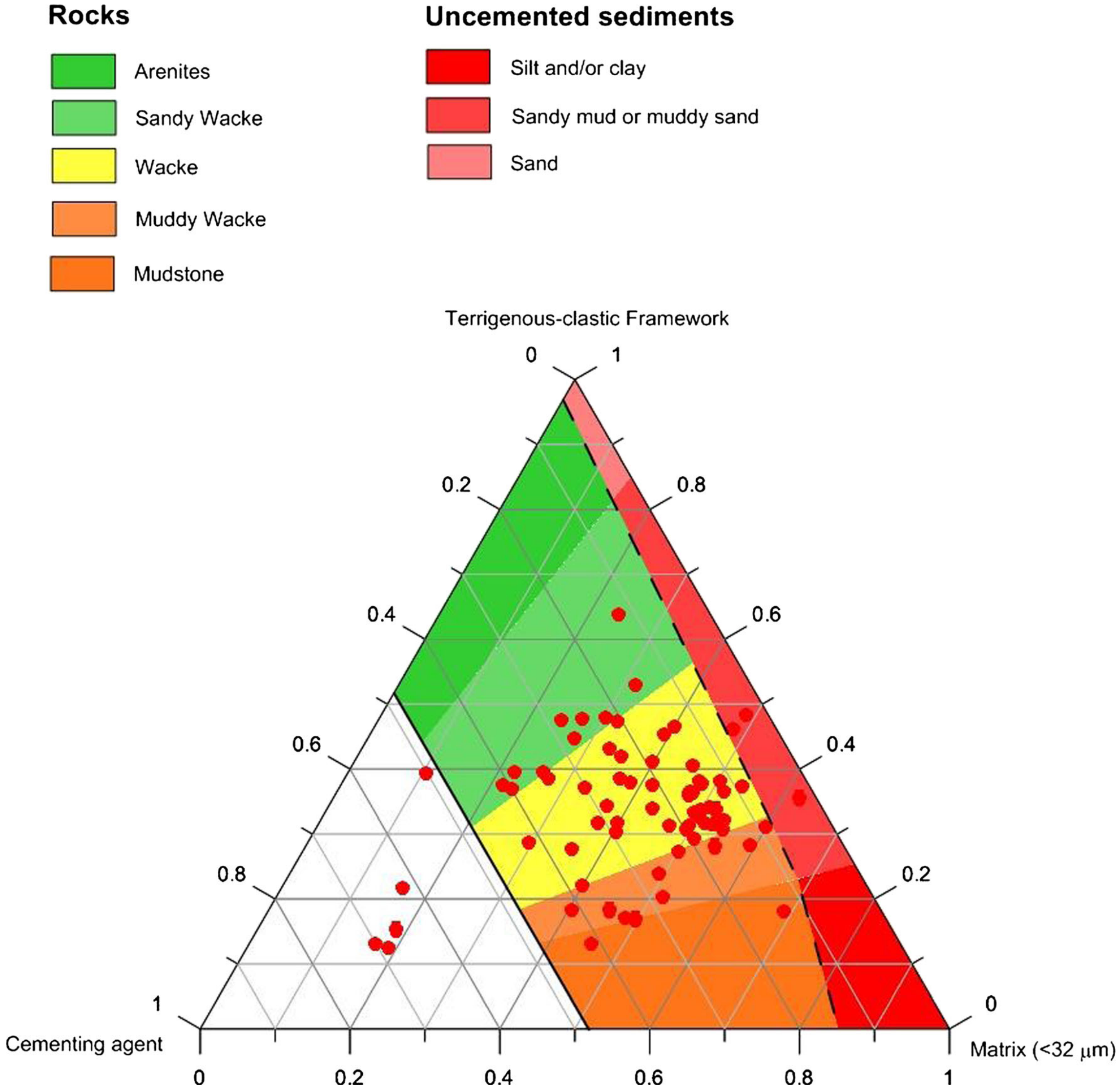

Fig. 12 Textural content of the collected samples using the classification scheme proposed in this paper

The most distinctive features that classify homogeneous textures are grain size distribution that can be coarse (sandy) or fine (muddy), or presence of fine matrix between coarse clasts (wacky). Fine-grained matrix can be bonded either by micrite or sparite crystals or both. Matrix may also be indurated but not cemented, composed by silt and clay without carbonate cement. The heterogeneous textures are characterized by the presence of clusters of either coarse grains or fine-grained matrix.

All the samples were tested using a standard slaking test to characterize their durability. The procedure followed was the slake durability test (Franklin and Chandra 1972) up to five cycles (Figs. 15 and 16 and Table 2).

Samples extracted from cut slopes classified as deterioration stages 1 and 2 have homogeneous coarse and sandy wacke texture and display a slake durability index (SDI) higher than 90 % for the two-cycle test. These samples correspond to wackestones, with a high content of sandy grains and, commonly, a grain-supported texture and carbonate bonding. Conversely, samples displaying two-cycle SDI smaller than 60 % were obtained from cut slopes with deterioration stages 4 or 5. These samples correspond to rocks with both homogeneous and heterogeneous muddy textures (Martinez-Bofill et al. 2008).

However, Figs. 15 and 16 show that no unique SDI range of values can be assigned to a specific deterioration stage. Despite the fact that several classification schemes consider those rocks displaying two-cycle SDI over 80 % as durable rocks (Franklin and Dusseault 1989; Sadisun et al. 2005; Santi 2006), in our study area high SDI values do not guarantee the presence of intact slopes on the mid/long term. In fact, two-thirds of the tested samples yielded two-cycle SDI over 80 %. Figure 15 shows that samples extracted from cuts with deterioration stages 3 and 4 have yielded two-cycle SDI values ranging from

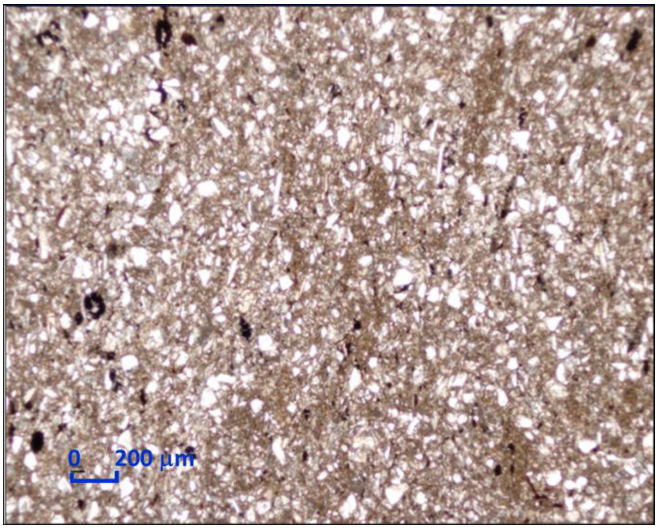

Fig. 13 Homogeneous texture in thin section: wacky texture, composed of sand-sized quartz grains with fine-grained cemented matrix

98.9 to 91.2 % and 97.6 to 77.1 %, respectively. High values (>90 %) of the SDI may also be found in cuts with deterioration stages 1 to 4, indicating that in the study area, the SDI is unable to adequately predict whether any particular slope will evolve towards deterioration stages 3 and 4 or it will remain unweathered. Such a lack of sensitivity of the two-cycle SDT to the rock durability (here, to the cut slope behavior) has been observed by several researchers (Taylor 1988; Moon and Beattie 1995; Gökçeoglu et al. 2000; Erguler and Shakoor 2009).

Finally, the cut slope degradation stages have been contrasted against the textural composition of their exposed argillaceous rocks. The results have been split considering homogeneous and heterogeneous rock textures (Figs. 17 and 18).

Slopes excavated in sandy wackes consistently show few deterioration features while the slopes excavated in mudstones and muddy wackes deteriorate easily and are highly erodible and unstable. In that respect, the texturally homogeneous argillaceous rocks (Fig. 17) show a contrasting response and a reasonable correspondence with the deterioration stage of the excavated slopes. Texturally heterogeneous slopes (Fig. 18) display a higher degradability for similar textures. It is suggestive that heterogeneity, and particularly the uneven distribution of the grain, favors on one hand the existence of preferential flow paths (highly connected porosity or permeability) of the weathering agents and on the other hand the inability of the cementing agents for accessing the fine-grained clusters.

In Fig. 17, two samples composed of about 80 % of total calcium carbonate were studied further to find a more in-depth explanation. As mentioned in the previous section, the main assumption in the procedure followed is that all the carbonate content of the fine-grained matrix is a cementing agent. Figure 19 is an image obtained with a scanning electron microscope with energy dispersive X-ray spectroscopy. It shows well-developed dolomite crystals mostly ranging between 2 and

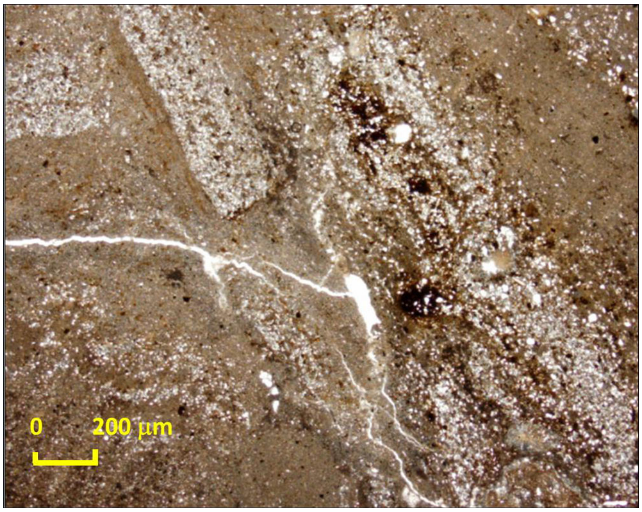

Fig. 14 Heterogeneous texture in thin section: heterogeneous muddy-predominant texture

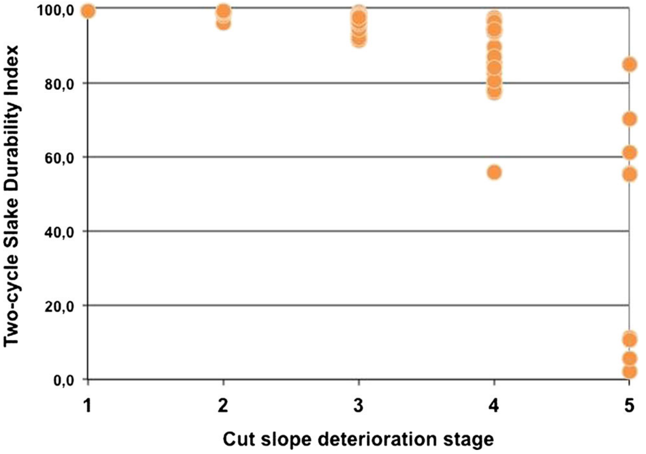

Fig. 15 Two-cycle slake durability index (SDI) of rock samples taken from cut slopes showing different deterioration stages (Fig. 10)

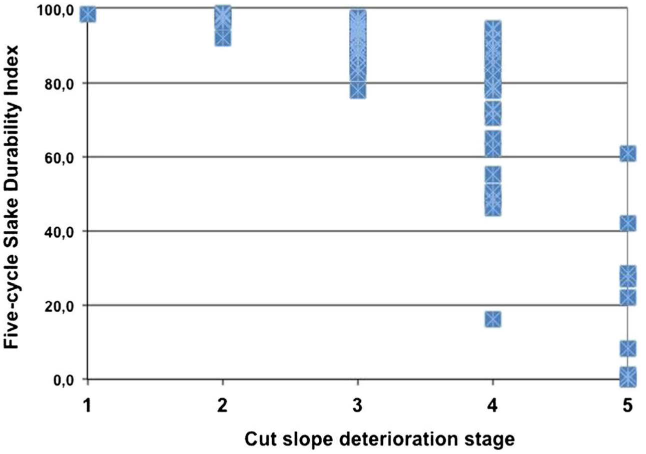

Fig. 16 Five-cycle slake durability index (SDI) of rock samples taken from cut slopes showing different deterioration stages (Fig. 10)

Table 2 Two-cycle and five-cycle slake durability indexes (SDI) of samples collected in the studied cut slopes and their deterioration stages

Sample	Two-cycle SDI	Five-cycle SDI	Cut slope stage	Sample	Two-cycle SDI	Five-cycle SDI	Cut slope stage
A-2.1 m1	2.1	0.0	5	C-25.5 m2	95.9	91.9	3
A-2.1 m2	5.7	0.0	5	C-25.7 m1	61.2	28.6	5
A-2.3	94.4	89.5	4	C-25.7 m2	85.0	60.9	5
A-2.5	84.8	72.6	4	C-25.9	93.4	78.6	4
A-2.6	97.6	94.5	4	C-55.1 m1	99.0	98.2	2
A-2.7	89.5	77.7	4	C-55.1 m2	94.9	89.5	3
A-2.8	93.4	79.1	4	C-55.1 m3	80.4	48.9	4
A-2a.2	82.6	65.0	4	L-301.1 m1	70.3	42.1	5
C-154.1 m1	98.6	96.7	3	L-301.2 m1	91.2	84.0	3
C-16.1 m1	96.2	91.6	4	L-301.2 m2	96.6	93.0	3
C-16.2	96.9	94.3	4	C-16.1 m2	99.1	98.5	1
C-16.3	94.3	88.1	4	C-16.8	88.2	74.2	4
C-16.4 m1	55.4	22.1	5	C-25.6	93.6	81.9	4
C-16.4 m2	77.1	48.3	4	C-25.8	84.0	46.1	4
C-16.4 m3	96.1	91.8	2	IM-2	97.3	94.1	3
C-16.6	55.1	27.2	5	IM-3	97.5	94.1	3
C-16.7	85.5	70.6	4	IM-5	95.8	90.6	3
C-17.1	98.6	96.8	3	IM-6	96.9	93.5	3
C-17.2	97.7	95.0	3	IM-8	96.2	91.9	4
C-17.3	98.9	97.4	3	IM-9	92.9	86.7	3
C-17.4	95.9	87.7	3	IM-11	92.0	88.1	3
C-17.5	97.7	94.2	3	IM-12	95.5	91.7	3
C-25.1	94.7	86.5	4	IM-13	92.7	77.8	3
C-25.10	78.0	62.0	4	IM-15	98.0	96.7	3
C-25.11	11.1	8.4	5	IM-16	97.4	95.3	3
C-25.12 m1	86.8	72.9	4	IM-17	98.9	98.2	2
C-25.12 m2	94.2	89.0	4	IM-18	94.3	84.8	4
C-25.13	98.3	96.9	3	OM-2	91.4	82.6	3
C-25.14 m1	99.2	98.5	2	OM-5	91.8	84.0	3
C-25.15 m1	98.2	96.2	2	OM-6	97.9	95.7	3
C-25.16	79.8	50.5	4	OM-8	97.2	93.8	3
C-25.17	10.5	1.2	5	OM-9	97.5	93.9	3
C-25.2	96.2	88.8	3	OM-10	94.4	88.7	3
C-25.3	98.5	96.8	2	OM-12	97.8	95.7	3
C-25.4 m1	55.9	16.3	4	OM-13	95.9	92.0	3
C-25.4 m2	97.1	94.7	3	OM-15	96.3	91.7	3
C-25.5 m1	77.9	55.3	4	OM-18	99.3	98.6	2
				OM-19	97.6	93.3	3

12 μm in size. These crystals have replaced previously existing calcite crystals, reaction that produces a reduction of the volume with the subsequent loss of the effectiveness of the bonding action.

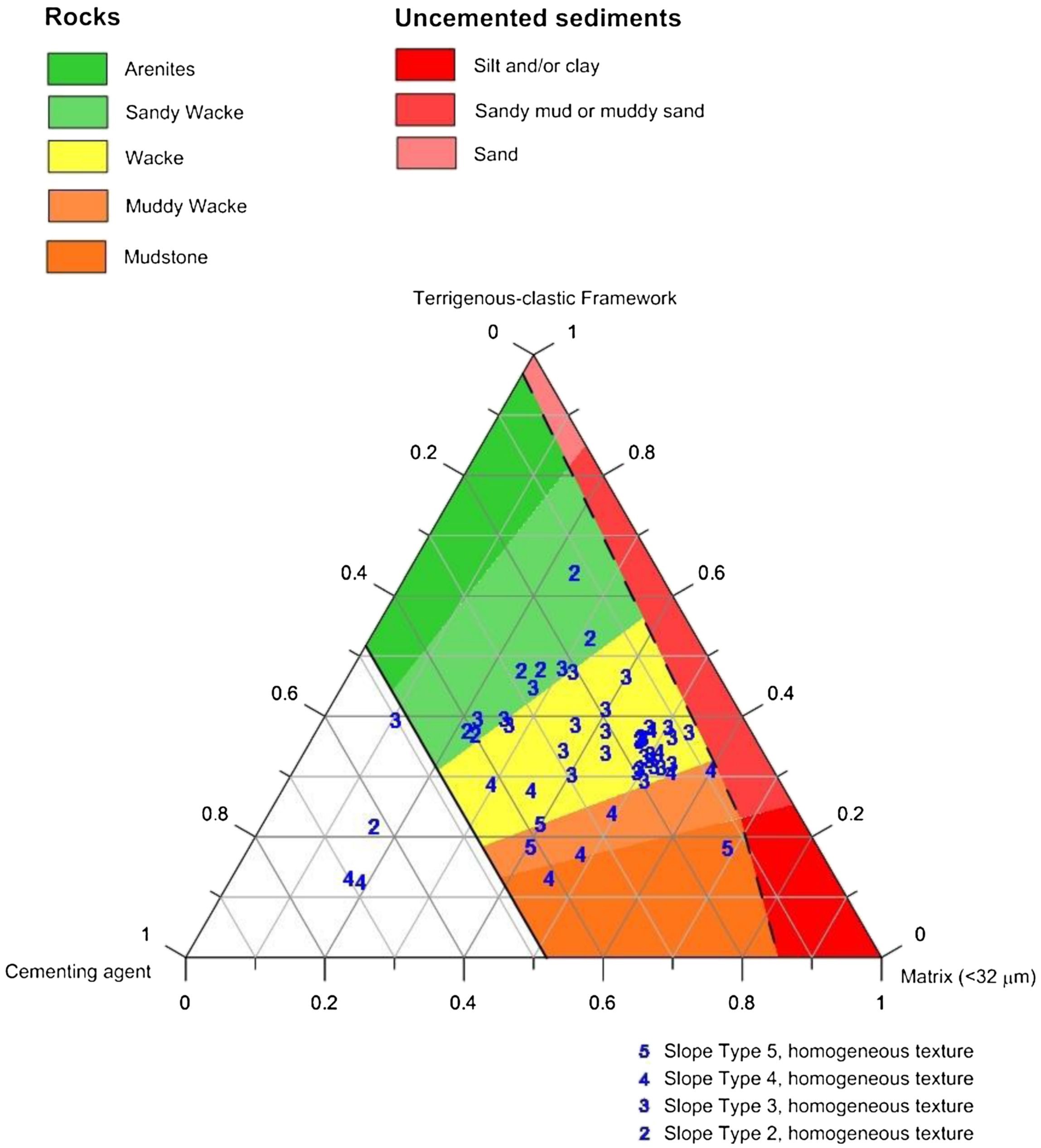

Fig. 17 Distribution of samples showing homogeneous texture from the analyzed cut slopes and their association to the slope deterioration stages (Fig. 10) plotted on the classification scheme proposed in this paper

This case shows that while the proposed classification scheme provides a good indicator of likely road cut performance, there are additional factors that can influence the actual performance.

One must take into account that the excavation process disturbs the rock mass by releasing confinement and causing expansive recovery (Gerber and Scheidegger 1969; Nichols 1980) and exposes it to the environmental conditions particularly to moisture and temperature changes. Other well-known factors such as the connected porosity, presence of the expansive or soluble minerals, which have been identified as influencing durability, have not been considered in the classification. Therefore, it will require further analysis and development. Despite of this, texturally-homogeneous argillaceous rocks have shown a satisfactory correspondence with the long-term performance of the excavated slopes.

The analysis of the Figs. 17 and 18 also highlights that the relationship between cement content and durability is complex. Surprisingly, changes in the cement content of the rocks per se are not reflected in the nature and quantity of deterioration features observed in the excavated slopes. Figure 17 shows that the increase in content of the calcium carbonate cement within the different types of wackestones does not result in an increase of the durability of the corresponding excavated slope. On the other hand, Fig. 17 suggests that it is the ratio between the clastic framework

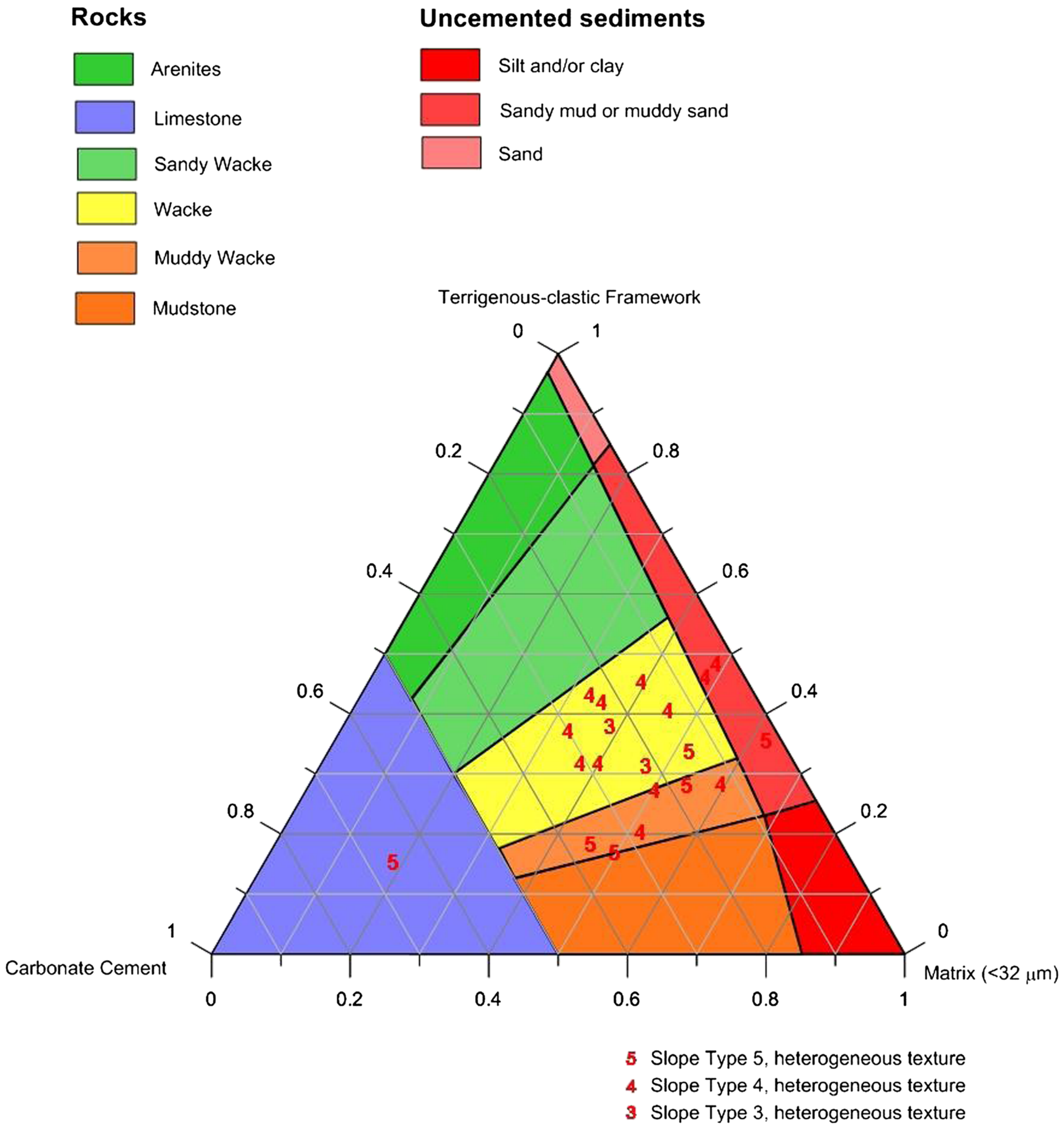

Fig. 18 Distribution of the samples showing heterogeneous texture from the analyzed cut slopes and their relation to the slope deterioration stages (Fig. 10) plotted on the classification scheme proposed in this paper

and the fine-grained matrix that actually controls the durability of the argillaceous rocks.

Based on this, we interpret that the effectiveness of the bonding between particles depends on the amount of matrix and, particularly on the content of phyllosilicate minerals (clay minerals, mica minerals, chlorite). The efficacy of the cementing agent in sandstones and sandy wackestones for creating strong bonds between the grains is high. This is because the bond is generated as grain-to-grain connection. In wackestones, muddy wackestones, and mudstones, the matrix content (i.e., phyllosilicates) is high. In this case, bonding takes place between grains of the clastic framework, phyllosilicate minerals, or between both. Degradation of the argillaceous rock may occur by splitting apart sheets of the phyllosilicate minerals through their exfoliation planes (Fig. 20) which are held to one another by weak residual forces, van der Waals, hydrogen bonds, and cations (Thorez 1975; Weaver 1989). In this case, rock deterioration can only be prevented by a cementing agent that is able to generate effective bonds between the grains of the clastic framework and/or around the phyllosilicate minerals.

Final remarks

Several researchers agree on that the texture and the mineralogical composition of the argillaceous rocks are critical parameters controlling their durability (i.e., Gökçeoglu et al. 2000; Sadisun et al. 2005). These two components condition the effectiveness of the

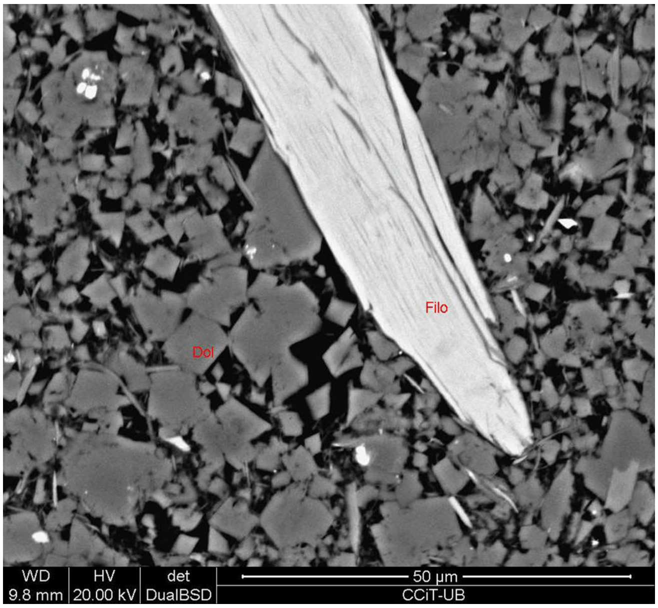

Fig. 19 Scanning electron microscope image of well-developed dolomite crystals (*Dol*) surrounding a crystal of phyllosilicate (*Filo*). This image is from one of the samples shown in the lower left edge (labeled with number 4) in Fig. 11

weathering processes in changing the intrinsic characteristics of the argillaceous rocks such as the mineralogy, porosity, particle cohesion, and the development of microfractures. Other parameters such as the geological history (degree of fracturing, stresses) and the stress release mechanisms must also exert a strong influence (Czerewko and Cripps 2006).

The textural-based classification scheme of the argillaceous rocks presented here aims at effectively accounting for the texture and unlike other classification schemes, the cementing agent has been considered. Three components form the basis for the classification: the clastic framework, the fine-grained matrix, and the cement content.

To implement this classification, either quantitative petrographical or mineralogical analysis is required to determine the textural components. In the samples analyzed in the study areas in Spain, petrographic analysis using an optical microscope and supported with semi-quantitative Rietveld mineralogical analysis based on X-ray powder diffraction has yielded consistent results. This procedure might appear time-consuming and expensive for the durability analyses of the rock. However, this drawback is not more restrictive than other mechanical analysis (i.e., UCS, triaxial tests) routinely performed in engineering projects.

The analysis of the behavior of the argillaceous rocks in different excavated slopes in Spain shows that road cuts in sandy wackes consistently show few deterioration features while the slopes excavated in muddy wackes and mudstones deteriorate easily, are highly erodible, and produce frequent falls. Texturally homogeneous sandy wackes, wackes, and muddy wackes are mostly associated with slope deterioration stages 2, 3, and 4–5, respectively.

The relationship between the cement content and the durability of the rock is complex. We have found that deterioration is mainly prevented by bonding of the grains of the clastic framework. The increase of matrix content and, particularly the presence of phyllosilicate minerals, makes bonding inefficient. Because of this, we conclude that the ratio between the clastic framework and the fine-grained matrix exerts a strong control on the durability of the argillaceous rock. The increase of cementing agent beyond a certain amount does not result in an improvement of the durability.

Argillaceous rocks showing heterogeneous textures are less durable. We interpret that heterogeneity favors the existence of preferential flow paths where the weathering agents can penetrate more easily and the presence of fine-grained clusters where the cementing agents are less effective.

The proposed classification scheme provides a good first-order estimate of the long-term behavior of argillaceous rock cuts but there are still shortcomings that need to be improved. There are a variety of factors that are not included as the presence of either expansive or soluble minerals, the stress history of the rock, the effect of textural heterogeneity, among others. The influence on durability of the different types of cementing agents (calcite, silica, iron oxide, etc.) also has to be considered in future investigations

Fig. 20 Interpretative sketch of the rock disaggregation. *Left*: sand-size calcite crystals (*yellow*) bonding both clasts (*white*) and phyllosilicates (*green*). *Right*: disaggregation of the rock is facilitated by the presence of weak phyllosilicate layers bonds

In the study area, the proposed classification scheme performs more satisfactorily than the two-cycle SDT in assessing the potential of the slopes to deterioration. Rock samples having two-cycle SDT values higher than 90 % are associated to cuts showing a wide range of deterioration stages (from stage 2 to 4).

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J. Corominas (✉) · J. Martínez-Bofill
Department of Geotechnical Engineering and Geosciences,
Technical University of Catalonia-BarcelonaTech,
Barcelona, Spain
e-mail: jordi.corominas@upc.edu

J. Martínez-Bofill
Geomar. Enginyeria del Terreny,
SLP,
Barcelona, Spain

A. Soler
Grup de Mineralogia Aplicada i Medi Ambient, Departament de Cristal•lografia,
Mineralogia i Dipòsits Minerals,
Universitat de Barcelona,
Barcelona, Spain