TXT-tool 3.034-1.1
A Textural Classification of Argillaceous Rocks and Their Durability

Jordi Corominas, Joan Martinez-Bofill and Albert Soler

Abstract

Argillaceous rocks can display a wide range of durability behavior after excavation and in cut slopes. This Text-Tool describes a new classification of argillaceous rocks based on their textural characteristics, highlighting the importance of properly classifying this type of rocks in order to predict the cut slope deterioration rates. 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.

J. Corominas (✉) · J. Martinez-Bofill
Department of Civil and Environmental Engineering,
Universitat Politècnica de Catalunya BarcelonaTech,
Jordi Girona 1-3, 08034 Barcelona, Spain
e-mail: jordi.corominas@upc.edu

J. Martinez-Bofill
e-mail: joan.martinez-bofill@upc.edu;
martinezbofill@geomar.cat

J. Martinez-Bofill
GEOMAR Enginyeria del Terreny, SLP. Valencia 1
subsòl Local 12, 08015 Barcelona, Spain

A. Soler
Grup de Mineralogia Aplicada i Geoquímica de
Fluids, Departament de Mineralogia, Petrologia i
Geologia Aplicada, Facultat de Geologia,
Universitat de Barcelona (UB), Martí Franquès, s/n,
Barcelona, Spain
e-mail: albertsolergil@ub.edu

K. Sassa et al. (eds.), *Landslide Dynamics: ISDR-ICL Landslide Interactive Teaching Tools*, https://doi.org/10.1007/978-3-319-57777-7_24

Keywords
Argillaceous rock · Durability · Slope deterioration · Classification

Contents

1 Introduction

Argillaceous rocks are frequent in the nature, and 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, and encompasses many fine-grained sedimentary detrital rocks such as argillite, claystone, siltstone, mudstone, shale, clay shale, or marl (Potter et al. 2005), whose predominant constituent are silt and/or clay-sized particles, coming from preexisting rocks. Thus, 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, and they may contain significant amounts of chemically precipitated cement such as calcium carbonate, silica, iron oxide, among others. 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).

Argillaceous rocks display a contrasting behavior in construction works. Blasting is often required to excavate these rocks, but the newly excavated slope surfaces may experience physical weathering and disintegrate in a short span of time. 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). Listric joints may develop parallel to the slope face being a main source of instability. 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. 1a). 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. 1b). However, the described behavior cannot be generalized, and some road cuts in argillaceous rocks may remain virtually unweathered without signs of degradation for years. Although surface deterioration of cuts is perceived as minor slope instability process, it affects the safety of the users (highways, high-speed railways …) and generates costly maintenance works (Martinez-Bofill et al. 2004).

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.

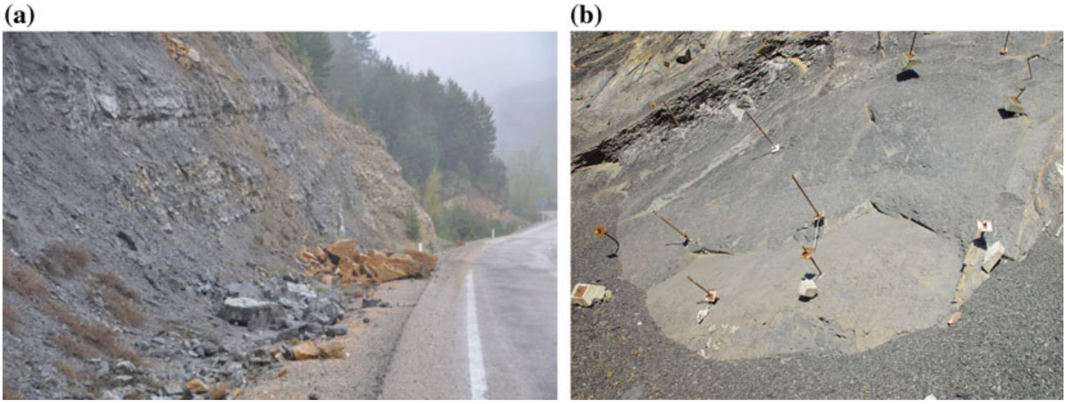

Fig. 1 *Left* **a** Differential weathering along a road at Cantavieja, Teruel Spain. Spalling and disaggregation of the mudstones have generated overhangs in the sandstone layers which eventually fail. *Right* **b** Cut slope surface deterioration at Ormaiztegi, Spain. The argillaceous rock decomposes around the bolt thus preventing its proper operation

2 Characterization of the Durability of 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. Many attempts have been made to classify and characterize the argillaceous rocks in order to predict their behavior. Despite all this work, standard rock tests have found to be 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.

Different tests have been proposed to assess rock durability. The most widely used are the slake durability test (SDT) (Franklin and Chandra 1972) and 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).

The mineralogy (Grainger 1984), particularly expansive clays (Dick and Shakoor 1992, 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.

3 A Classification Scheme for Argillaceous Rocks

Mineralogical content and cementation have been identified as key factors that control the long-term behavior of the weak rocks after their exposure.

We present here a new classification scheme of the argillaceous rocks, which is based on the rock texture and accounts specifically for the bonding constituent (Corominas et al. 2015). 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. 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. 2) 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

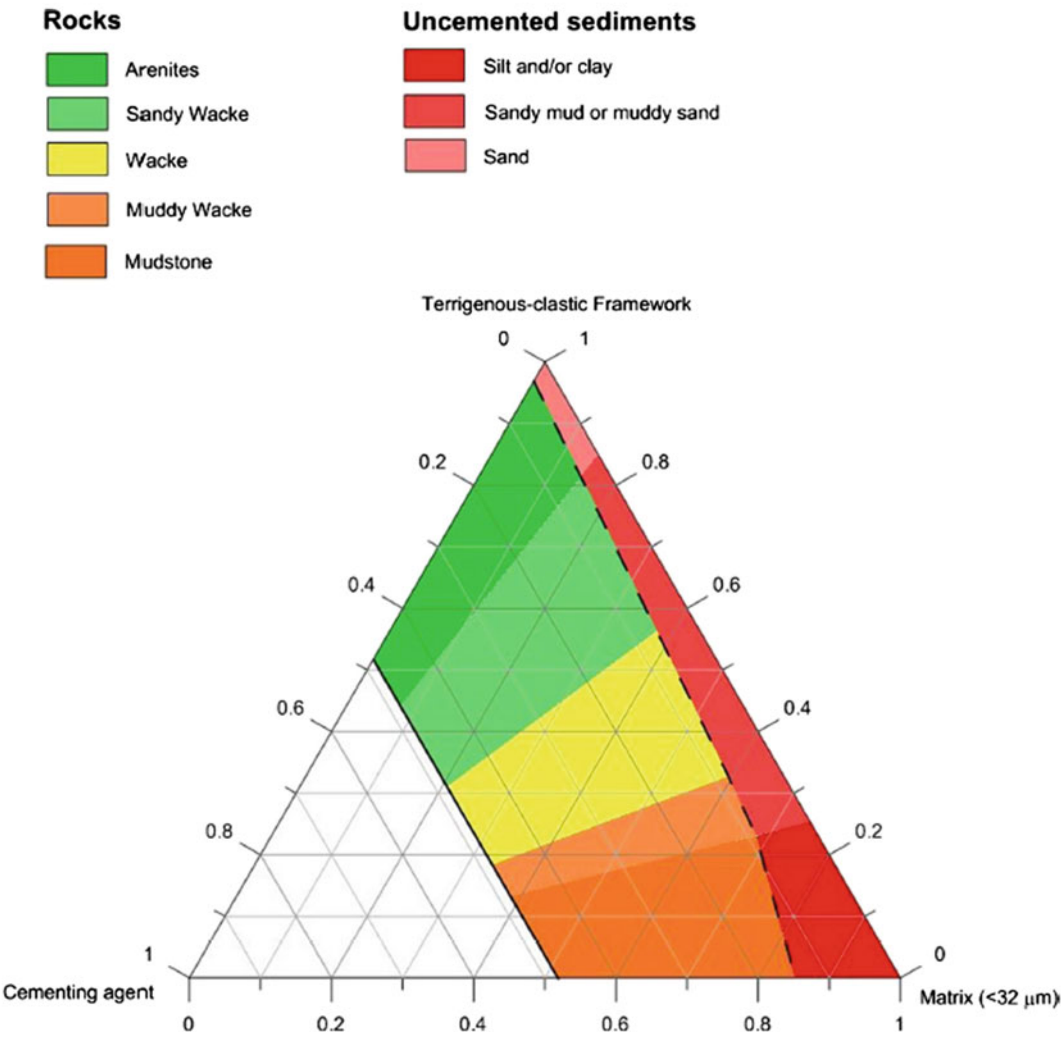

Fig. 2 Proposed textural classification of the argillaceous rocks (Corominas et al. 2015)

thin sections and may be subjected to misinterpretations. A detailed explanation about how boundaries and names were selected can be found at Corominas et al. (2015).

The scheme includes the boundary proposed by Dott (1964) between arenites, mudstones, and wackes. Usually, most of wackes are classified as shales or mudstones in the field. No distinction has been made on whether the grain framework is mostly siliciclastic, carbonate, or other.

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. 2) establishes the boundary between sediments and rocks ranging between 4 and 15% of cement content. 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. 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.

4 Quantifying the Constituents of the Argillaceous

Determining the components of the proposed classification scheme is not straightforward, because they cannot be mechanically separated. The 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 order to overcome this uncertainty and determine the composition of the argillaceous rocks, the following procedure (Fig. 3 *left*) developed for rocks containing carbonate cement is proposed (Martinez-Bofill 2011). This procedure may be adapted for the quantification of the components of the argillaceous rocks indurated with other cementing agents (i.e. silica, iron oxides):

- 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. Mineral constituents are obtained by counting each mineral occurrence along a series of traverse line across the thin section (Fig. 3 *right*). 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). We recommend to carry out between 1000 and 2000 counts per each analyzed thin section. The petrographical microscope allows to identify textures (homogeneous and heterogeneous) as well as grain size, grain distribution and any textural features that can't be observed with XRD and other mineralogical techniques.
- The total amount of carbonate content of the sample is determined with the Bernard calcimeter method (ASTM D4373). The total carbonate content includes both carbonate clasts and carbonate cement. By subtracting the amount of carbonate clasts from the total

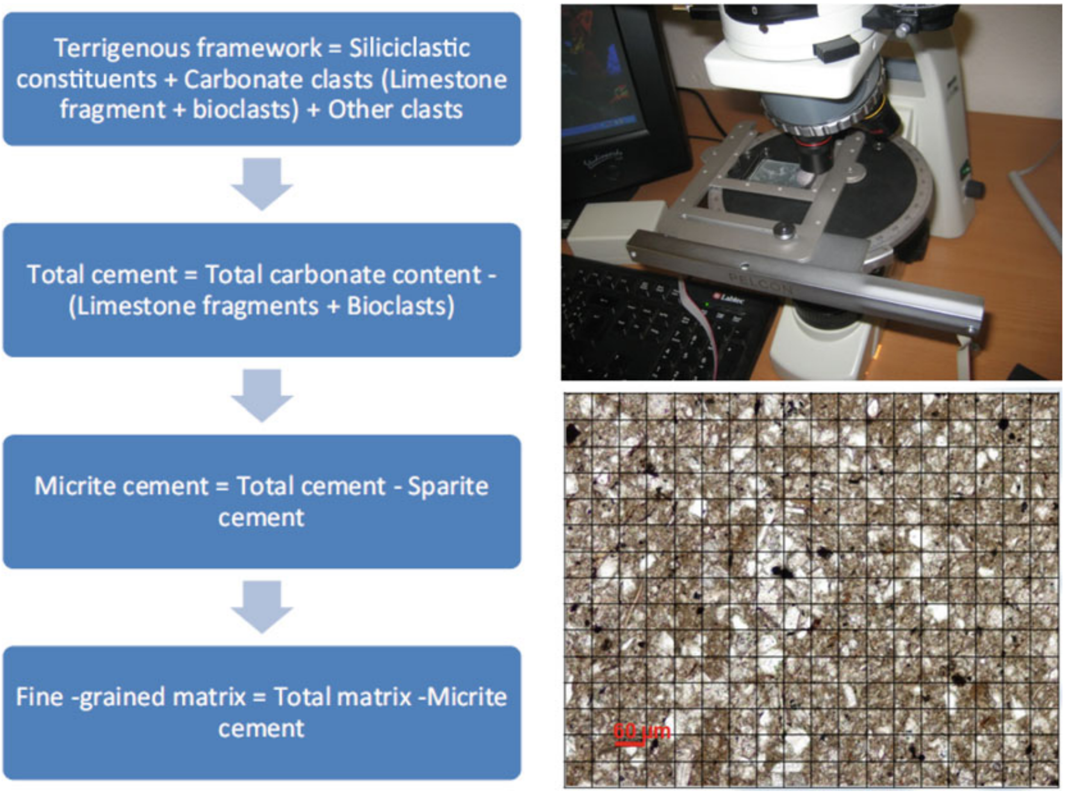

Fig. 3 *Left* procedure for determining the textural components of the argillaceous rocks. *Right* determination of the clastic framework, matrix and cement bigger than 32 µm in the petrographic microscope

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.

We have checked the results obtained with the X-ray powder diffraction (XRD) technique, which is a common and rapid analytical technique used for mineral identification. It yields the mineralogical composition of the whole rock. This is especially useful for determining the fine grained minerals that compose the matrix and cannot be identified by using the microscope. The amount of minerals can be determined by the semiquantitative Rietveld analysis of X-ray powder diffraction, (Young 1993). The Rietveld XRD accurately determines and quantificafies 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.

5 Performance of the Classification Scheme of the Argillaceous Rocks

The aim of this classification is to provide a concise and systematic method for designating various types of rocks, and also enable to derive durability properties.

The potential of this classification in predicting the durability of the argillaceous rocks was 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 consisted of confronting the qualitative description of the deterioration features of the cuts (accounting for the time elapsed since its excavation) with both the slake durability index (SDI) and the textural composition of intact rock samples collected in the cuts. The samples cover a wide range of argillaceous rock compositions, and were obtained taking 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 absence of expandable clays to avoid the inclusion of factors that may generate additional scattering in the assessment of the durability of the materials.

5.1 Field Characterization of the Cut Slopes

The cut slopes were first grouped based on their deterioration stage, which are defined using the following descriptors (Martinez-Bofill et al. 2004) (Fig. 4):

5.2 Petrographic and Mineralogical Characterization

The petrographic and mineralogical characterization was performed following the procedure described at Sect. 4. As mentioned above, the procedure to quantify the textural components has some uncertainty due to the assumptions made for the quantification of the cementing agent. It is noticeable that despite most of the samples have been classified in the field as mudstones and shales, only a few of them fulfil 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. 5a). Conversely, heterogeneous textures show a pattern of different types of textures and grain size distribution (Fig. 5b).

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.

5.3 Characterization of the Durability

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, ASTM D4644) up to five cycles.

Samples extracted from cut slopes classified as deterioration stages 1 and 2 have homogeneous coarse and sandy wacke texture and yield slake durability indexes (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, results 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

	**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 More than 20 years after its excavation..
	**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.

Fig. 4 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 4:** Heavily weathered slope surface. Six years after its excavation, intense slaking of the rock surface is observed and tendency to form regolith. Continuous slaking and falling of chunks prevent the slope from rock falls. Weathered rock surface (regolith) may reach depths up to several decimeters. Original rock structure cannot be recognized at the slope face. Blast holes have virtually disappeared. Erosion and gullying often appear at 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. Steep slopes are unstable with frequent rotational failures. Gullying develops even with low slope angles.

Fig. 4 (continued)

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. High values (>90%) of the SDI may also be found in cuts with deterioration stages 1–4, 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. The 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).

5.4 Analysis of the Influence of Textural Composition in Durability

The cut slope degradation stages have been contrasted against the textural composition of the exposed argillaceous rocks. The results have been split considering homogeneous and heterogeneous rock textures (Fig. 6a, b).

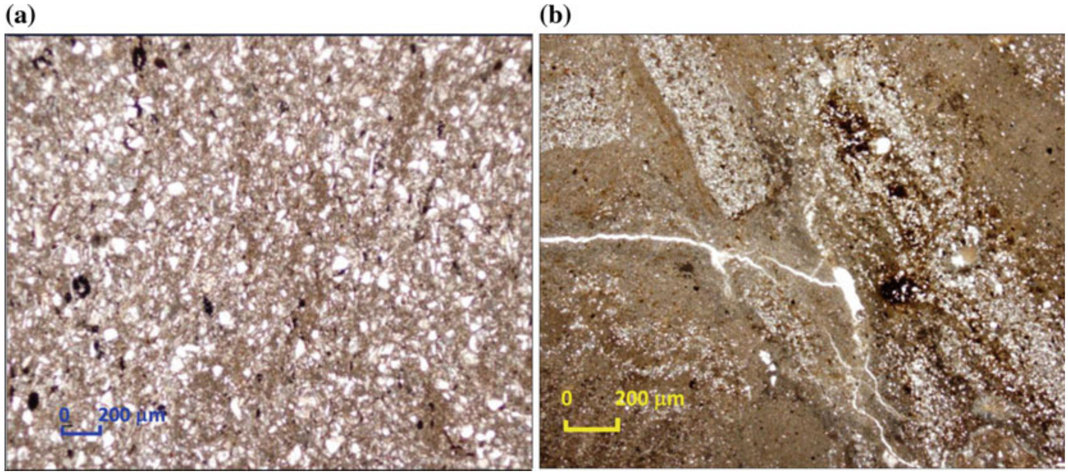

Fig. 5 *Left* **a** homogeneous texture in thin section: wacky texture, composed of sand sized quartz grains with fine-grained cemented matrix. *Right* **b** heterogeneous texture in thin section: heterogeneous muddy predominant

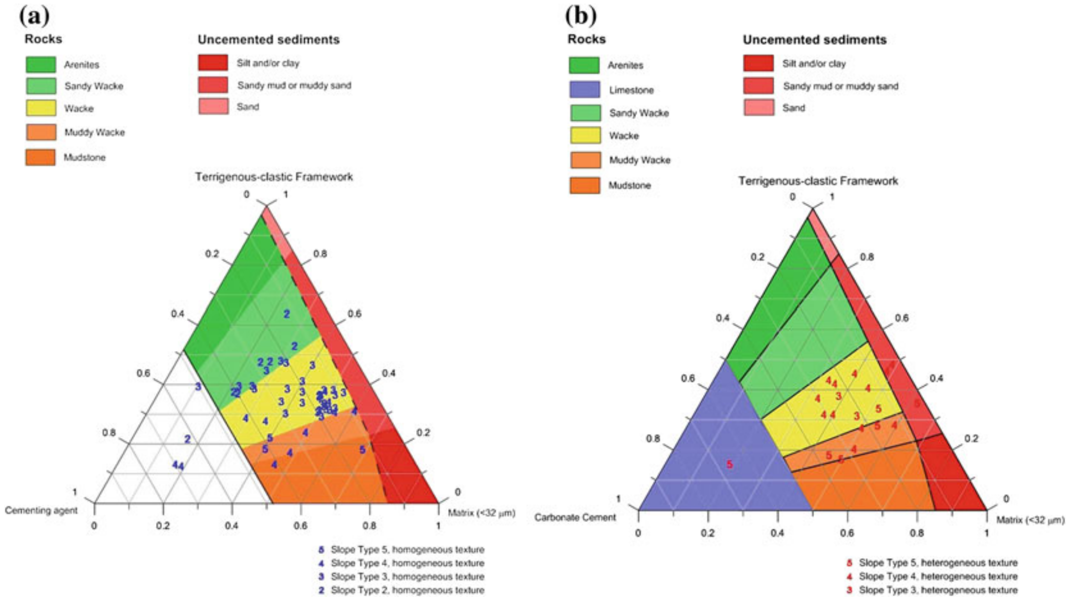

Fig. 6 Distribution of the samples showing homogeneous textures (*left*, **a**) compared to samples with heterogeneous texture (*right*, **b**) from the analyzed cut slopes and their relation to the slope deterioration stages plotted on the classification scheme proposed in this paper

5.4.1 Slopes in Homogeneous Argillaceous Rocks

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 show instability features. In that respect, the response of the texturally homogeneous argillaceous rocks (Fig. 6a) shows a contrasting response and has a reasonable correspondence with the deterioration stage of the excavated slopes.

5.4.2 Slopes in Heterogeneous Argillaceous Rocks

The texturally heterogeneous slopes (Fig. 6b) are more degradable than the homogeneous ones. 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) which allows the penetration of the weathering agents into the rock and on the other hand the cementing agents are unable for accessing the fine-grained clusters.

The results obtained so far, show that the proposed classification scheme is capable to explain the mid-long term road cut evolution: However, there exist additional factors that can influence the actual performance. Therefore, for the use of this classification scheme and for the interpretation of the results, the following factors should be taken into account:

- The proposed classification is based on the behaviour of rocks with absence or a low degree of tectonic deformation and with a low content of expansive clays. These factors may generate additional scattering in the assessment of the durability of the materials.
- Furthermore, other well-known factors affecting rock durability such as the connected porosity or the presence of soluble minerals have not been considered in the scheme either.
- The excavation process disturbs the rock mass by releasing confinement and causing expansive recovery and cracks (Gerber and Scheidegger 1969; Nichols 1980). This makes the rock more susceptible to the environmental conditions particularly to moisture and temperature changes.
- The relationship between cement content and durability is complex. The results show that the increase in content of the calcium carbonate cement in the different types of wackestones does not result in a significant reduction of the deterioration of the excavated slope face. Instead, the analysis of the textural diagrams suggests that the clastic framework and the fine-grained matrix ratio is what control the efficiency of the bonding and consequently, the durability of the argillaceous rocks.

In summary, further work is still needed on the role of factors not considered in the classification scheme and on how to integrate them. Despite of this, texturally homogeneous argillaceous rocks have shown a satisfactory correspondence with the long-term performance of the excavated slopes.

6 Conclusion

This Text-Tool describes a new classification of argillaceous rocks based on their textures. This highlights the importance of properly classifying this type of rocks in order to explain the mid-long term deterioration behaviour of the cut slopes. Although the texture and the mineralogical composition of the argillaceous rocks are well-known factors controlling their durability (i.e., Gökçeoglu et al. 2000; Sadisun et al. 2005), the textural-based classification scheme presented here provides a quantitative measure of the texture and unlike other classification schemes, the cementing agent has been included. Three components form the basis for the classification: the clastic framework, the fine-grained matrix, and the cement content.

To implement this classification, quantitative petrographical and mineralogical analysis is required to determine the textural components, by using an optical microscope and supported with semi-quantitative Rietveld mineralogical analysis based on X-ray powder diffraction. 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 minor deterioration features while the slopes excavated in muddy wackes and mudstones deteriorate more rapidly, 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. Results suggest 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 first order estimate of the mid-long term behavior of argillaceous rock cuts but there are still shortcomings that need to be overcome with future research. There are a variety of factors that are not considered 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 addressed in future investigations.

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).

References

Blatt H (1982) Sedimentary petrology. WH Freeman and Company, San Francisco

Corominas J, Martinez-Bofill J, Soler A (2015) A textural classification of argillaceous rocks and their durability. Landslides 12(4):669–687

Czerewko MA, Cripps JC (2006) The implication of diagenetic history and weathering on the engineering behaviour of mudrocks. In: 10th IAEG international congress: engineering geology for tomorrow's cities. Paper number 118. http://www.iaeg.info/iaeg2006/start.htm

Dick JC, Shakoor A (1992) Lithological controls of mudrock durability. Quat J Eng Geol 25:31–46

Dick JC, Shakoor A (1997) Predicting the durability of mudrocks from geological characteristics of mudrocks: In: Santi P, Shakoor A (eds) Association of environmental and engineering geologists. Special Publication No. 9, pp 89–105

Dott RH (1964) Wackstone, graywacke and matrix—what approach to inmature sandstone classification? Num 34:625–632

Erguler ZA, Shakoor A (2009) Quantification of fragment size distribution of clay-bearing rocks after slake durability testing. Environ Eng Geosci 15:81–89

Franklin JA (1983) Report RR29 research and development branch research. Toronto, Ministry of Transportation and, Evaluation of shales for construction projects: an Ontario shale rating system

Franklin JA, Chandra R (1972) The slake durability test. Int J Rock Mech Mining Sci Geomech Abstracts 9:325–328

Franklin JA, Dusseault MB (1989) Rock engineering. McGraw Hill Inc, New York, p 600

Gerber E, Scheidegger AE (1969) Stress-induce weathering of rock masses. Eclogae Gel Helv 62:401–416

Gökçeoglu C, Ulusay R, Sönmez H (2000) Factors affecting the durability of selected weak and clay-earing rocks from Turkey, with particular emphasis on the influence of the number of drying and wetting cycles. Eng Geol 57:215–237

Grainger P (1984) The influence of clay mineralogy and diagenesis of Upper Carboniferous shales on soil formation in parts of Devon. J Soil Sci 35:599–606

Hallsworth CR, Knox RWO'B (1999) BGS rock classification scheme, vol 3. Classification of sediments and sedimentary rocks. British Geological Survey. Research report number rr 99–03. Nottingham UK, 44 pp

Martinez-Bofill J (2011) Alterabilidad de limolitas, arcillitas y margas. Aplicación a la estabilidad de desmontes y excavaciones. PhD thesis. Universitat Politèccnica de Catalunya, 427 pp

Martinez-Bofill J, Corominas J, Soler A (2004) Behaviour of the weak rock cutslopes and their characterization using the results of the slake durability test. In: Lecture notes in earth sciences, 104. Engineering geology for infrastructure planing in Europe, pp 405–413

Martinez-Bofill J, Corominas J, Soler A (2008) Analysis of the relationship between durability and petrological characteristics of weak rocks. Euroengeo. In: Proceedings of the II European conference of international association for engineering geology, Madrid

Moon VG, Beattie AG (1995) Textural and microstructural influences on the durability of Waikato coal measures mudrocks. Q J Eng Geol 28:303–312

Nichols TC (1980) Rebound its nature and effect on engineering works. Q J Eng Geol 13:133–152

Nicholson DT (2004) Hazard assessment for progressive, weathering-related breakdown of excavated rock-slopes. Q J Eng Geol Hydrogeol 37:327–346

Nickmann M, Spaun G, Thuro K (2006) Engineering geological classification of weak rocks. In: 10th congress of the international association of engineering geology and the environment, paper number 492, Nottingham

Nickmann M, Sailer S, Ljubesic J, Thuro K (2010) Engineering geological investigations into the border between hard and weak rocks. In: Williams L et al (eds) Geologically active. Taylor & Francis Group, London, pp 2265–2272

Potter PE, Maynard JB, Depetris PJ (2005) Mud and mudstones. Springer, Berlin, p 308

Sadisun IA, Shimada H, Ichinose M, Matsui K (2005) Study on the physical disintegration characteristics of Subang claystone subjected to a modified slaking index test. Geotech Geol Eng 23:199–218

Santi P (1998) Improving jar slake, slake index, and slake durability tests for shales. Environ Eng Geosci 4:385–396

Santi P (2006) Field methods for characterizing weak rocks for engineering. Environ Eng Geosci 12:1–11

Shakoor A, Brock D (1987) Relationship between fissility, composition and engineering properties of selected shales from northeast Ohio. Bull Assoc Eng Geol 24:363–379

Taylor RK (1988) Coal measures mudrocks: composition, classification and weathering processes. Q J Eng Geol Hydrogeol 21:85–99

U.S. Geological Survey (USGS), North American Geologic-Map Data Model Science Language Technical Team (2004) Report on progress to develop a North American science-language standard for digital geologic-map databases; Appendix C1—sedimentary materials: science language for their classification, description, and interpretation in digital geologic-map databases; version 1.0 (12/18/2004). In: Soller DR (ed) Digital mapping techniques'04—workshop proceedings: U.S. Geological Survey open-file report 2004–1451, 595 p. Appendix C1 accessed at http://pubs.usgs.gov/of/2004/1451/sltt/appendixC/appendixC_pdf.zip

Wood LE, Deo P (1975) A suggested system for classifying shale materials form embankments. Bull Assoc Eng Geol 12:39–55

Young RA (1993) International union crystallography. The Rietveld method. Oxford University Press, New York