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An approach for characterizing the weathering behaviour of Flysch slopes applied to the carbonatic Flysch of Alicante (Spain)

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Abstract

Various studies indicate that most of the slope instabilities affecting Flysch heterogeneous rock masses are related to differential weathering of the lithologies which make up the slope. Therefore, the weathering characteristics of the intact rock are of great importance for the study of these types of slopes and their associated instability processes. The main aim of this study is to characterize the weathering properties of the different lithologies outcropping in the carbonatic Flysch of Alicante (Spain), in order to understand the effects of environmental weathering on them, following slope excavation. To this end, 151 strata samples obtained from 11 different slopes, 5 to 40 years old, were studied. The lithologies were identified and their mechanical characteristics obtained using field and laboratory tests. Additionally, the slaking properties of intact rocks was determined, and a classification system proposed based on the first and fifth slake-cycles (Id1 and Id5 respectively) and an Index of Weathering (IW5), defined in the study. Information obtained from the laboratory and the field was used to characterize the weathering behaviour of the rocks. Furthermore, the slaking properties determined from laboratory tests were related to the in situ weathering properties of rocks (i.e. the weathering profile, patterns and length and weathering rate). The proposed relationship between laboratory test results, field data and in situ observations provides a useful tool for predicting the response of slopes to weathering after excavation during the preliminary stages of design.

Keywords: Carbonatic Flysch lithologies · Slake Durability Test · index of weathering · weathering profile · weathering rate.

Résumé

Certains études indiquent que la plupart des instabilités de pente qui affectent les masses rocheuses hétérogènes telles que des formations de Flysch sont liés au l'effritement différentielle des lithologies qui composent la pente. Par conséquent, la caractérisation du comportement devant de l'effritement de la matrice rocheuse c'est un aspect clé pour l'étude de ces types de pentes et de leurs processus d'instabilité associés. Le principal objectif de ce travail est la caractérisation des propriétés de résistance aux intempéries des différentes lithologies qui affleurent dans la zone d'étude afin de connaître leur comportement devant l'effritement après l'excavation des pentes. A cet effet, ont été étudiés 151 échantillons obtenus à partir de strates de 11 pentes différentes, âgés de 5 à 40 ans. Ces lithologies ont été identifiées et caractérisées mécaniquement en utilisant des critères de terrain et en laboratoire. En plus, le comportement devant le *slaking* de la matrice rocheuse a été déterminé, en proposant une classification basée sur le premier et le cinquième cycle de l'assai cyclique de durabilité (Id_1 et Id_5 respectivement) et un index défini dans le présent travail, appelé Index of Weathering (IW_5).Toute l'information compilée à partir de laboratoire et de terrain a été utilisé pour caractériser les différents comportements devant l'effritement des roches étudiées. En outre, les propriétés du *slaking* basées sur des tests de laboratoire ont été liées avec la résistance aux intempéries des roches in situ (c'est-à-dire, le profil d'effritement, modèles et longueur et taux d'effritement). La relation indiquée entre le laboratoire, les données de terrain et les observations *in situ* fournit un outil très utile pour évaluer l'évolution devant l'effritement espéré des pentes depuis leur excavation aux étapes préliminaires d'avant-projets.

Mots clés : Lithologies carbonatées du Flysch · essai cyclique de durabilité · index d'effritement · profil d'effritement · taux d'effritement

1. Introduction

The lithologies that outcrop in the study area consist of Palaeogene sediments from the *Surco Flysch El Campello-Villajoyosa* formation (Leret-Verdú et al. 1976 and Colodrón and Ruiz 1980). This zone which extends along the littoral and pre-littoral area of Alicante province, bordered by Aguas de Busot to the West, the Mediterranean Sea to the East, Alicante to the South and Benidorm to the North (Figure 1), is densely populated and crossed by three main transport arteries (the AP-7 and N-332 highways and the FGV railway). The cut slopes of these routes and the buildings placed over the coastal cliffs in this area are affected by numerous instabilities that are often related to the differing durability of the outcropping lithologies (Cano and Tomás 2013a).

The durability of weak rocks is an engineering property commonly used for measuring their resistance to weakening and disintegration (Franklin and Chandra 1972). Slaking resistance depends on different parameters, commonly cited in literature as permeability, porosity, adsorption, etc. (Crosta 1998). Due to the complexity of the phenomenon, many authors have worked on this topic (Franklin and Chandra 1972; Richardson and Long 1987; Gamble 1971; Taylor 1988; Dick et al. 1994; Dick and Shakoor 1995).

The main scope of this paper is to study the weathering properties of Flysch slopes in Alicante throughout their lifetime. This study aims to provide expected weathering rate values and patterns of newly excavated slopes from geological and geomechanical descriptions, and the slaking properties of the lithologies of the slope. Note that the determination of the weathering rate is highly useful because most of the instabilities observed in the 194 previously studied slopes in the study area are closely linked with the degradation of the marly lithologies (Cano and Tomás 2013a).

The study area is characterized by the absence of frosts and high temperature gradients (AEMET 2005) and as a consequence the weathering of the different lithologies is mainly caused by drying-wetting cycles due to rainfall and atmospheric moisture (Table 1). Furthermore, no evidence of rock weathering caused by salt precipitations was observed in the slopes which were studied.

Table 1. Normal climatic values of Alicante from 1971 to 2000), AEMT (2005).

Month	T (°C)	TM (°C)	Tm (°C)	R (mm)	H (%)	DR	DN	DT	DF	DH	DD	I
January	11.5	16.8	6.2	22	67	4	0	0	0	1	8	177
February	12.4	17.8	7.0	26	64	3	0	0	0	0	6	180
March	13.7	19.2	8.2	26	64	4	0	1	1	0	7	230
April	15.5	20.9	10.1	30	62	4	0	2	0	0	6	246
May	18.4	23.6	13.3	33	65	4	0	2	0	0	5	278
June	22.2	27.2	17.1	17	64	2	0	2	0	0	10	300
Juliet	24.9	30.1	19.7	6	64	1	0	1	0	0	16	333
August	25.5	30.6	20.4	8	67	1	0	1	0	0	13	304
September	23.1	28.4	17.8	47	68	3	0	2	0	0	8	255
October	19.1	24.4	13.7	52	69	4	0	2	0	0	6	220
November	15.2	20.4	10.0	42	68	4	0	1	0	0	6	179
December	12.5	17.6	7.3	26	68	4	0	0	0	0	7	163
Year	17.8	23.1	12.6	336	66	37	0	14	2	1	97	2864

T= monthly/annual average temperature, TM= monthly/annual average of daily maximum temperature, Tm= monthly/annual average of daily minimum temperature, R= monthly/annual average rainfall, H= average relative moisture, DR= monthly/annual average days with rainfall higher to 1 mm, DN= monthly/annual average of snowy days, DT= monthly/annual average of stormy days, DF= monthly/annual average of foggy days, DH= monthly/annual average of frosty days, DD= monthly/annual average of cloudless days, I= monthly/annual average of sunny days

Consequently, due to area’s climate, the weathering potential of the lithologies in the study area was expected to be related to their slaking properties. Thus, durability was studied using the Slake Durability Test, originally developed by Franklin and Chandra (1972) and commonly used worldwide (as well as being recommended by the International Society for Rock Mechanics (ISRM 1977)). This test allows two different durability indices to be obtained, based on one-cycle (Id_1) and two-cycle (Id_2) tests. Subsequently this method was standardized by the American Society for Testing and Materials (ASTM 2004) taking the two-cycle Slake Durability Test as the only weathering quantification index.

In this study the different lithologies present in the study area are classified attending to their slaking durability properties and a new slaking index is defined. Furthermore, weathering penetration into the slope was measured in the field for the different lithologies. Weathering patterns were also studied and lithologies were characterized based on field descriptions and mineralogical analysis. Finally, rock strength was evaluated in the field according to ISRM (1981) recommendations and in the laboratory using Point Load Tests (ISRM 1985).

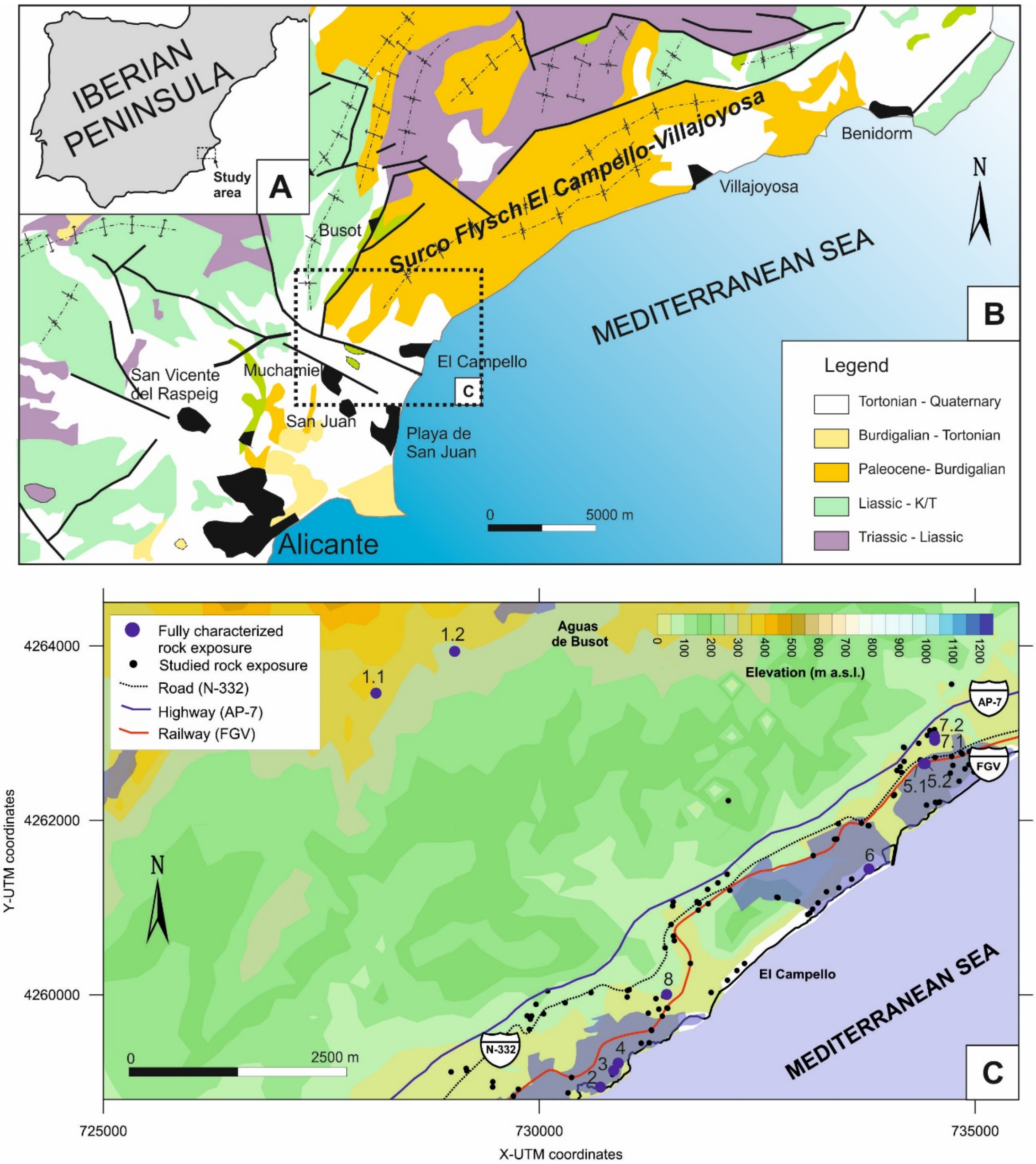


Figure 1. Location and geological maps of the study area (based on Vera (2004) in Guerrera et al. (2006)) and the rock exposures studied in this paper.

This data allowed the different lithologies to be classified from a mineralogical, mechanical and visual perspective and their slaking properties related with these characteristics. Furthermore, the different slaking properties were related to the weathering patterns and profiles observed in the field.

Some authors have proposed indices for quantifying the degree of alteration of rocks (e.g. Taylor 1988, Kiliç 1999). However, these indices are very difficult to be applied to the soft altered rocks from the study area. For example, the Unified Alteration Index (Kiliç 1999) requires parameters such as the uniaxial compressive strength and the ultrasonic velocity which are impossible to obtain for the most altered samples which are degraded almost to soil.

The paper is structured as follows. In the second section the geological setting of the study area is briefly defined. Section three describes the study methodology. Section 4 is focused on the description of the lithological and geomechanical properties of the rock masses which were studied. The proposed method for the weathering characterization of carbonatic Flysch lithologies is presented in section 5. The results are presented, analysed and discussed in section 6. The main conclusions are summarized in section 7.

2. Lithological setting of the study area

The Flysch sequence of Alicante (Figure 1) is composed of pelagic sediments, predominated by sequences of grey marls and thin white marly limestones (hemipelagites) that constitute the rythmite predominated by marls. This sequence may overlap calcarenitic turbiditic episodes. However, the sedimentological complexity of the Flysch formation is even greater because there are some superposed composite gravitational processes such as mélanges and debrites (Cano and Tomás 2013a).

In this study, 11 slopes were described and fully characterized (Figure 1 and Table A1). 151 intact rock samples were taken from these slopes and tested. These samples were extracted from the different lithologies present in the selected slopes and were described in detail at field and geologically classified as: a) Thick bedding calcarenites (Grainstone of turbiditic facies of channel (Ta-b)); b) Thick bedding calcarenites (grainstone of turbiditic facies of channel (Ta-b) or sheet flood facies (Tb, Tb-c)); c) Thin bedding calcarenites (Turbiditic thinbeds of fan fringe facies (Tb-c-d)); d) Poorly cemented thick bedding calcarenites (Grainstone of turbiditic facies of channel (Ta-b)); e) Poorly cemented thin bedding calcarenites (Turbiditic thin beds of fan fringe facies (Tb-c-d)); f) Slightly marly limestones; g) Marly limestones; h) Silty calcareous marls; i) Silty marls; j) Calcareous marls-marls; k) Sheet silty marls; l) Soft marls; m) Sheet marls; n) Soft calcareous mélanges; and o) Calcareous debrites.

3. Methodology

3.1. General overview

The main aim of this study is to characterize the weathering properties of the different lithologies outcropping in the study area for use in predicting their expected weathering behaviour after slope excavation. For this purpose, the different lithologies were identified and their mineralogical and mechanical characteristics obtained. 5-cycle slake durability tests were performed on intact rock samples. Additionally, the weathering patterns of the lithologies studied were described based on field observations and weathering profiles, and weathering rates were measured (Figure 2). The following paragraphs give details of the testing which was performed.

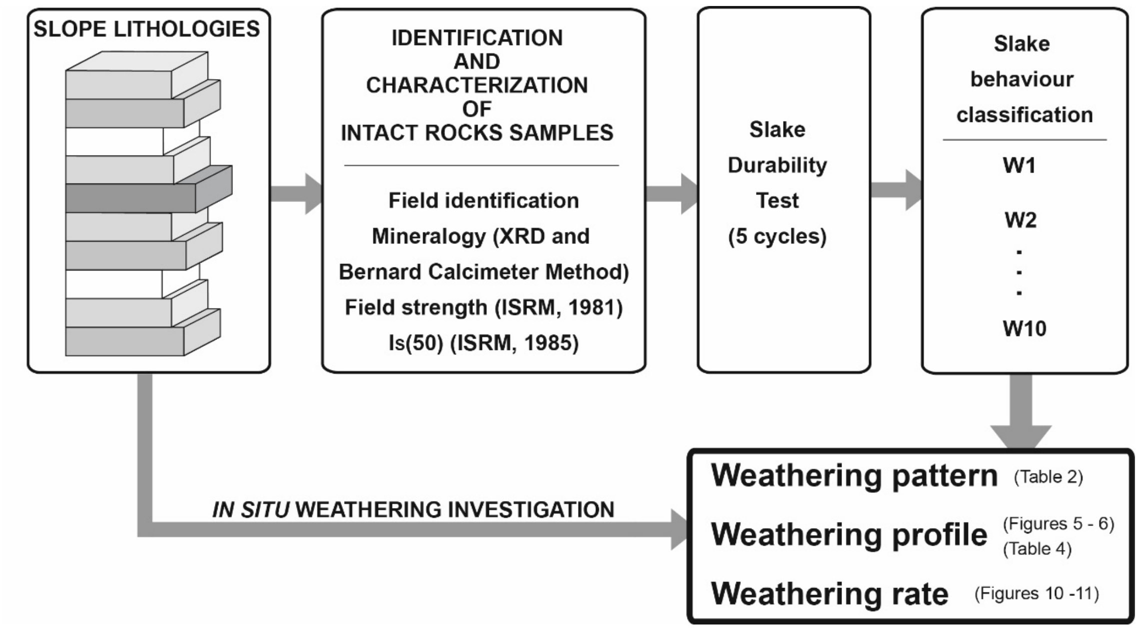


Figure 2. Conceptual sketch of the weathering profile characterization of the Flysch lithologies.

3.2. Intact rock mineralogy

In order to characterize intact rock from a geomechanical point of view it is necessary to define its physical properties and mechanical properties (mainly mechanical strength and durability) (Goel and Singh 2011). In this study, the different lithologies are described in the field using a simplified geological classification of rocks based on its genetic category, structure, composition and grain size (Geological Society of London 1977). Furthermore, a mineralogical characterization of the samples by X-ray diffraction was performed. Because some of the samples were of marly composition, they were characterized in two different stages. Firstly, X-ray diffractograms of all the samples were obtained. Secondly, X-ray diffractograms of the oriented aggregate of samples with high phyllosilicate content were obtained in order to identify them according to Robert and Tessier's (1974) methodology. Finally, for some representative samples the carbonatic contents obtained from the interpretation of the X-ray diffractograms were compared with those obtained using the Bernard calcimeter method (ASTM 2007), in order to validate these results.

Data were collected and interpreted using the XPowder software package, (Martin 2004) whose qualitative search-matching procedure was based on the ICDD-PDF2 database.

3.3. Intact rock mechanical strength: Point Load Test

Mechanical strength can be evaluated by means of uniaxial compressive strength, tensile strength and point load test results (ISRM 1981). Mechanical strength may also be estimated through simple field indices (ISRM 1981). In this study, Point Load Tests were performed in order to classify the different lithologies according to their point load strength index ($I_s(50)$). Anisotropy (which was pronounced in the turbiditic rock samples) was considered using the ISRM procedure (ISRM 1985), by obtaining the point load strength in two orthogonal directions. This data allowed the anisotropy factor to be calculated (i.e. the ratio between the maximum and the minimum point load strength values calculated for a sample in two orthogonal directions). When the samples exhibited anisotropy (i.e. an anisotropy factor higher than 1.6 similar to the value proposed by Ramamurthy (1993)) the lower $I_s(50)$ value was adopted as representative instead of the mean value.

3.4. Intact rock slaking properties: Slake Durability Test

The Slake Durability Test was also used in this study. It is one of the simplest tests in rock mechanics and is a very useful and widely used tool for characterizing the environmental weathering resistance of rock. The main reason why this test was selected was due to its potential as a tool for classifying the carbonatic flysch lithologies in order to predict the deterioration of Flysch rock slopes based on wetting and drying cycles.

Although originally the Slake Durability Test was developed for testing the weathering potential of shales, mudstones, siltstones, and other clay-bearing rocks (Franklin and Chandra 1972), the slake durability index is typically used for testing weak rocks such as mudrocks, marls, ignimbrites, conglomerates, and poorly cemented sandstones (Sabatakakis et al. 1993, Santi 1998, Czerewko and Crips 2001, Erguler and Ulusay 2009, Miščcević and Vlastelica 2011). As such, although in the Flysch formation there are some very competent, hard turbiditic rocks that show very high durability indices, in order to classify the Flysch lithologies using a uniform weathering potential criteria the Slake Durability Test was used for testing all of the samples. Usually, the durability of weak rocks is assessed using the second-cycle slake durability index. Nevertheless, some researchers (Gamble 1971, Taylor 1988, Moon and Beattie 1995, Ulusay et al. 1995, Bell et al. 1997, Crosta 1998, Gökçeoğlu et al. 2000, Miščcević and Vlastelica 2011) suggested that index values taken after three or more cycles of slaking and drying may be useful when evaluating rocks of higher durability, such as those in this study. For example, Ulusay et al. (1995) performed a five-cycle Slake Durability Test on a marly spoil pile material and on samples of the original rock from the benches of a coal strip mine, because weak laminated and clay-bearing rocks with slake durability index (Id_2) equal to or greater than 90% (medium high and high durability according to Gamble 1971) degrade to a spoil material. On the other hand, Miščcević and Vlastelica (2011), following a similar argument, performed a four-cycle slake durability test on forty samples from a Flysch formation in Dalmatia (Croatia), observing the influence of the number of slaking cycles on the slake durability index, and grouping the samples into families according to their properties. The need to evaluate the long-term weathering properties of the rock also involves performing several cycles. Another reason for using a low number of cycles is because the higher the number of cycles, the longer the duration of the test (note that each cycle can last more than 24 h due to the need to oven dry the samples).

In the study area it was noted that some calcareous marls whose intact rock samples provided high Id_1 and Id_2 values ("Very high" or "Extremely high" durability according to Franklin and Chandra's (1972) classification and "Medium-high" durability according to Gamble's (1971) classification, based on Id_1 and Id_2 respectively) exhibited different durability properties in the field. The observed weathering of the rocks was much higher than that predicted by the SDT indices (Figure 3).

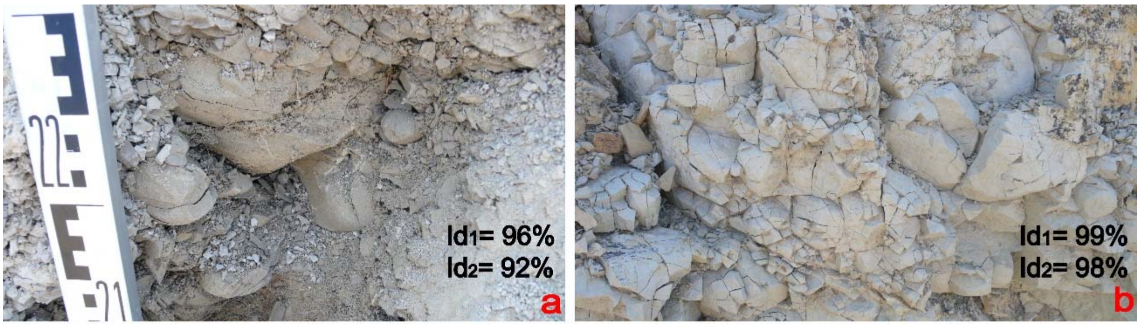


Fig. 3. Example of heavily degraded calcareous marls with high Id_1 and Id_2 indices. Note that the one-cycle (Id_1) and two-cycle (Id_2) SDT results classify both lithologies as "Extremely high" (samples a and b), "Very high" (sample a) and "Extremely high" durability (sample b), respectively. See the text for more details.

When the whole slope (Figure 4) from which the samples shown in Figure 3 were obtained is analysed, a general degraded state may be observed. However, surprisingly 20 layers from the 22 recognized strata showed an Id_1 index higher than 95% ("Extremely high" durability). The rest of the strata showed an Id_1 index of between 90 and 95, and as a consequence may be classified as of "Very high" durability. According to Id_2 indices, the durability of the different layers of the slope can be classified as "Medium-high" (Id_2 from 85 to 95%), "High" (Id_2 from 95 to 98%) and "Very high" (Id_2 higher than 99%) for four, twelve and six layers, respectively (Figure 4). As a consequence, it is obvious that Id_1 and Id_2 indices do not adequately reproduce the real degradation properties of the Flysch lithologies studied, providing optimistic values.

It should be noted that the superficial rock specimens found on the slopes usually present signs of weathering or even intense degradation. As a consequence, the Flysch rock samples tested correspond to intact rocks that were obtained from the interior of the slope.

Taking into account the aforementioned issues, intact rock samples were subjected to more cycles than the number of cycles specified by the ASTM (2004) procedure for Slake Durability Test, in order to better characterize the durability of Flysch lithologies over longer time periods.

Furthermore, detailed analysis of SDT results for the different lithologies (Figure 8) highlighted an attenuation of the mass lost between the fourth and fifth cycle. As a consequence, the five-cycle slake durability test index (Id_5) is adopted as a reference value for characterizing the resistance of Flysch rocks to degradation.

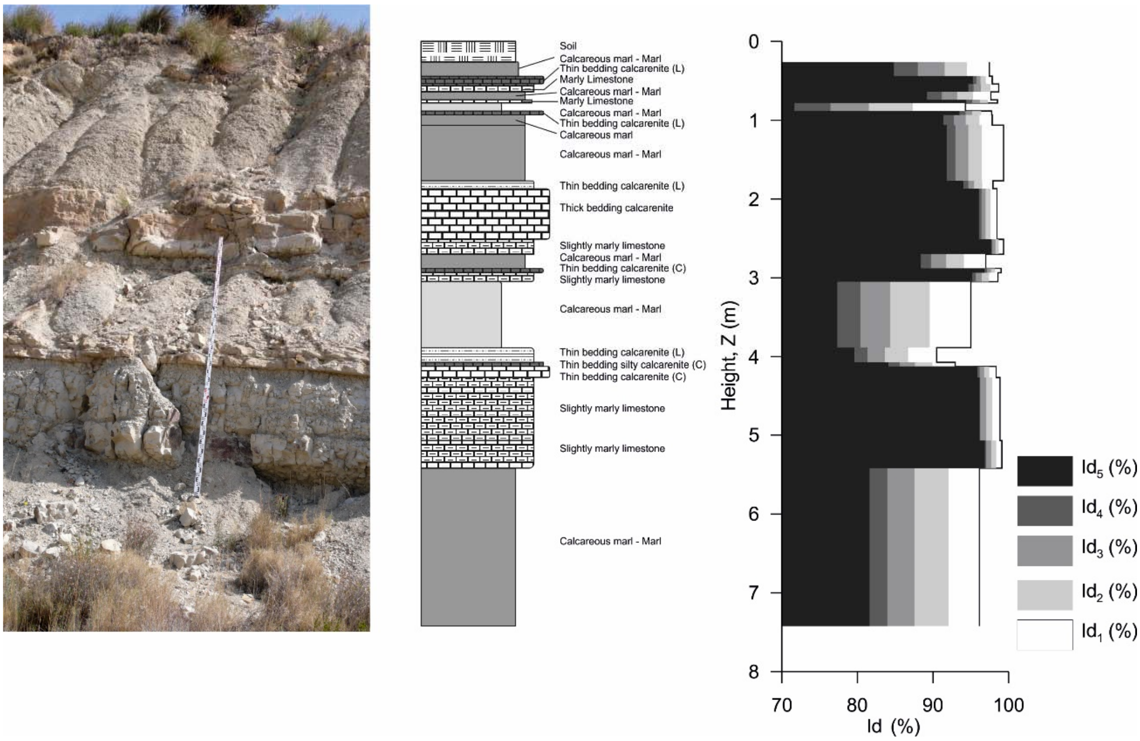


Fig. 4. General view of a slope included in this study (left) and the Id_1 to Id_5 values of the 22 carbonatic lithological layers of which it is composed (right).

Thus to summarise, in this study the Slake Durability Test was employed following the procedure suggested by ASTM (2004), adopting five cycles as the adequate number of cycles to be considered because of: a) the need to compare hard and soft lithologies using the same parameter; b) the existence of some hard rocks which are unaffected by a low number of cycles; c) the need to study the long-term behaviour of the rock weathering properties; and d) the need to avoid an excessively long test period.

The samples were obtained from the unaltered rock, removing the superficial disintegrated layer. Subsequently the intact rock samples were transported to the laboratory in plastic bags, and maintained at a constant temperature. The time between storage and testing was always less than one week.

While the tests were performed the laboratory temperature was also kept constant (24 ºC) in order to conserve the humidity and temperature conditions.

The tests were performed according to the ASTM (2004) procedure that recommends the use of distilled water with similar aggressiveness to the rainwater that is the responsible for the humidity changes in the rock slopes being studied.

151 specimens obtained from 11 different slopes located between El Campello and Villajoyosa (9 slopes) and Aigües de Busot (2 slopes) were tested (Figure 1). Four of these slopes were only partially characterized using at least 2 samples which were taken from representative areas of the slopes in which clear differential weathering was observed (Table A1).

3.5. Weathering patterns

In order to relate slake durability to field weathering behaviour, different weathering patterns of the lithologies in the study area were defined, studying the strata from which the intact rock samples were extracted for their characterization and testing in the laboratory. Furthermore, 87 strata were excavated from the slope surface to bedrock, in order to measure the length of the strata affected by the different weathering patterns, and subsequently establish their weathering profiles.

Note that the outcrops which were studied are composed of alternating layers of different weathering potential. As a consequence, when the marly layers weather, this generates highly impermeable residual soils which act as a protection layer that considerably reduces water infiltration and protects the underlying layers against weathering.

Although the depth of weathering is usually measured vertically from surface level, (Chigira et al. 2002, Jeong et al. 2005), in this study it was measured from the slope face in order to characterize the weathering profile of the different lithologies which compose the strata of the slope. The weathering profile was studied only for the slopes whose excavation age was known and which had not been re-excavated or scaled since their original excavation. The weathering profile characterization was performed using a reference line (in this case a long metal ruler) which was aligned with the harder strata of the slope that were not degraded or only slightly degraded and had not suffered rockfalls resulting from sapping (Figure 5). The slope dip was measured on the reference line and was compared with the original slope design in order to ensure that the slope's geometry had not changed. Once the original geometry of the slope was known, the next step consisted of the measurement of the length of removed material (L_r) and the weathered lithology (L_w) of a layer affected by different weathering patterns, until the bedrock was reached (Figure 5). The sum of the removed (L_r) and the number (*n)* of altered lengths (L_{wi}) of a stratum from a slope is defined as weathering profile length (WPL; Figure 5):

$$WPL = L_r + L_w = L_r + \sum_{i=1}^{n} L_{wi} \qquad (1)$$

And, consequently, the weathering rate (WR) may be calculated as:

$$WR = \frac{WPL}{t} = \frac{L_r + L_w}{t} = \frac{L_r + \sum_{i=1}^{n} L_{wi}}{t} \qquad (2)$$

Where *t* is the age (in years) of the slope (time from its excavation to the present).

Figure 5. Methodology used for the measurement of the field weathering profile of a stratum. WPL: weathering profile length, L_r: length of removed material; L_{wi}: length of weathering corresponding to each weathering pattern.

Figure 6 shows an example of the material excavated in a marly stratum in order to determine the weathering profile.

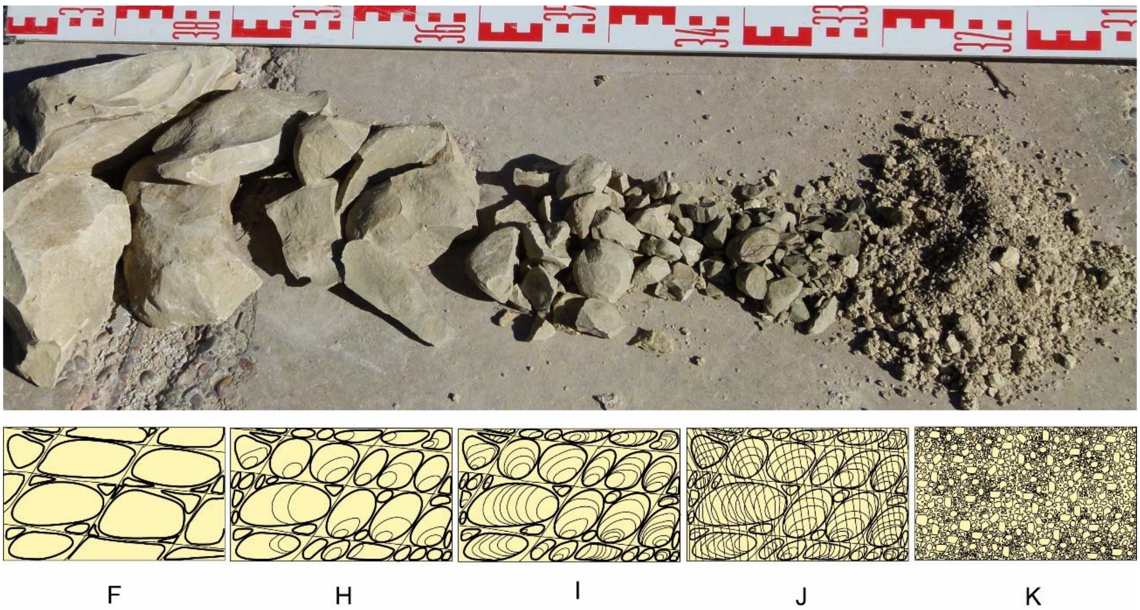


Figure 6. Above: Weathering profile from a marly stratum. Below: Schematic weathering profile with the definition of the different weathering patterns (see Table 2 for a detailed description of the weathering patterns).

4. Lithological and geomechanical characterization

In this section the different lithologies in the study area are described and characterized in mineralogical and geomechanical terms.

Firstly, the lithologies in the study area were identified and described in the field using a simplified geological classification (Geological Society of London 1977). Secondly, the mineralogy of the different lithologies was described using X-ray diffraction (XRD). The 132 samples analysed contained (Table 4) calcite, dolomite (sometimes ferric dolomite), quartz (Qtz) and phyllosilicates (Phy). The phyllosilicate fraction was also analysed through oriented aggregate diffractograms, showing important contents of caolinite, illite and mica and trace evidence of smectite in some samples.

The carbonate percentages derived from the X-ray diffractograms were also compared with those obtained using the Bernard calcimeter method (ASTM 2007) for 34 rock samples selected at random. A good agreement between the results was observed (mean difference of 5%).

The geomechanical properties of the intact rock samples from the lithologies studied were obtained through mechanical tests, and their weathering properties observed and described in the field. As explained previously, mechanical strength was evaluated using the $I_s(50)$ index and the PLT (ISRM 1985). The results were grouped by lithologies and durability categories (Table 4). Note that the different lithologies were also classified according to field criteria (ISRM 1981), allowing both the field and mechanical properties of the different lithologies to be related (Table 4).

It may be noted in Table 4 that some mineral content dispersion exists for the different lithologies. The differing mineral content conditions both the slake properties and the mechanical properties. Furthermore, anisotropy, which highly conditions the mechanical properties of the rock, was recognized from PLT tests for some specific lithologies. It is related with the sedimentary origin of the turbiditic lithologies which show a typical Bouma sequence and even lateral facies changes. A correlation between the total carbonate content, Cb (i.e. the sum of calcite and dolomite content) and the mechanical index $I_s(50)$ was observed (Figure 7 a). A correlation between the phyllosilicate content (Phy) and $I_s(50)$ (Figure 7 b) was also observed. Note that, although the calculated coefficients of determination (r^2) for both correlations are 0.50 and 0.46, the p-values are lower than 0.01, which indicates that the correlations are statistically significant.

The relationship shown in Figure 7, i.e. that rock strength increases directly proportional to the carbonatic content and inversely proportional to the phyllosilicate content, has been also recognized by other authors for similar carbonatic marls (e.g. Lamas et al. 2011).

However, there was no clear relationship between the mineralogical composition of different lithologies and durability class to which they belonged. This fact was previously noted by Crosta (1998), who found a low correlation between durability index values and calcium carbonate content. This is probably due to the fact that rock parameters other than mineralogy, such as microscopic texture (Martínez-Bofill et al. 2004) or microfabric (Kaufhold et al. 2013), play a key role in this relationship.

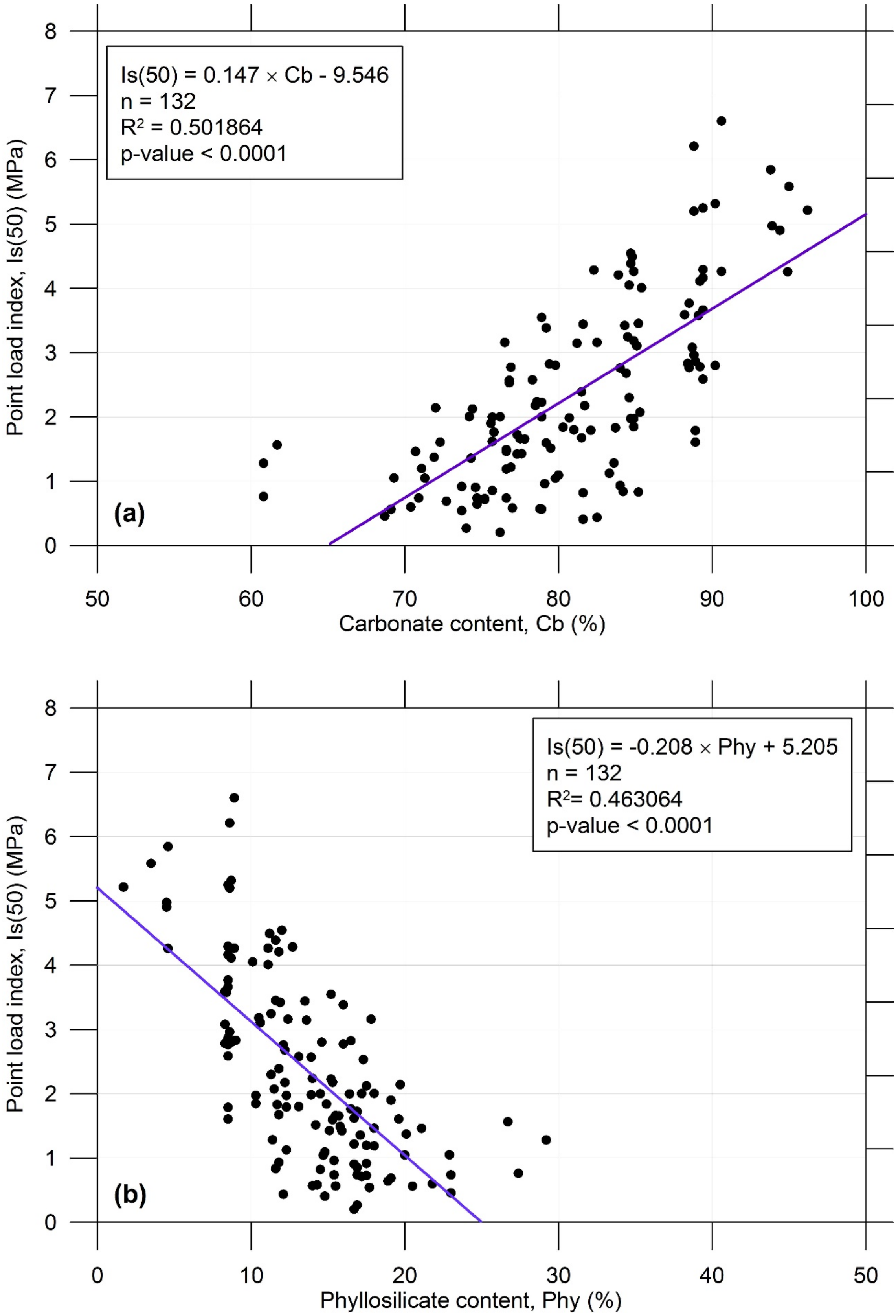
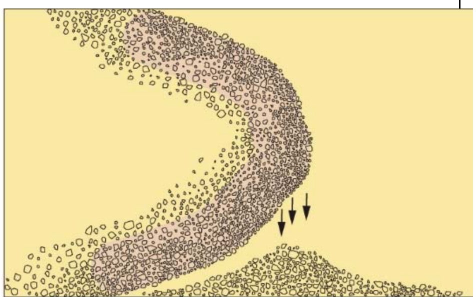
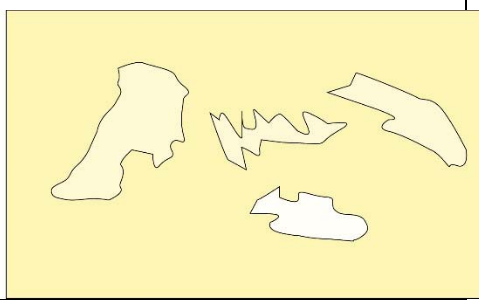


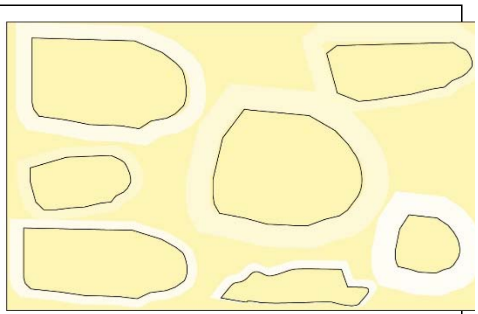
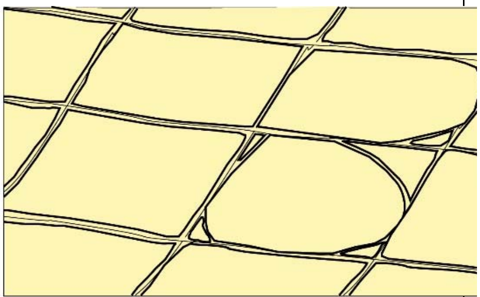
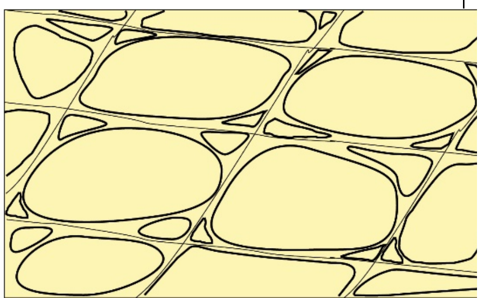
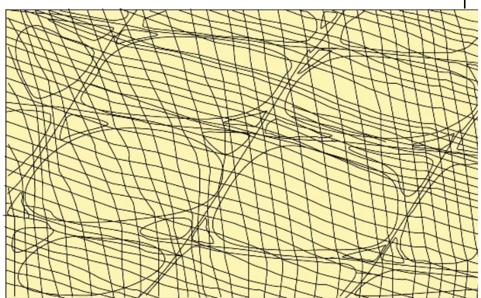
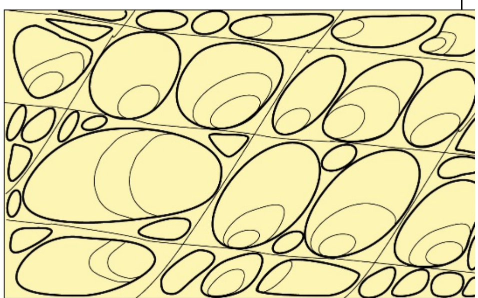
Figure 7. Relationship between carbonate (Cb) a) and phyllosilicate (Phy) b) contents and $I_s(50)$. *n* is the number of samples tested.

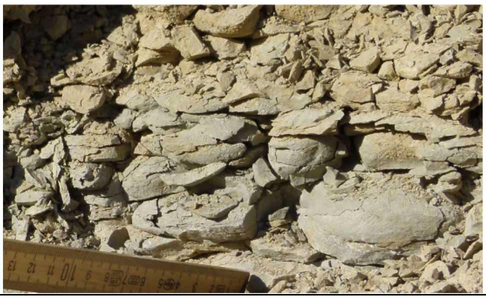
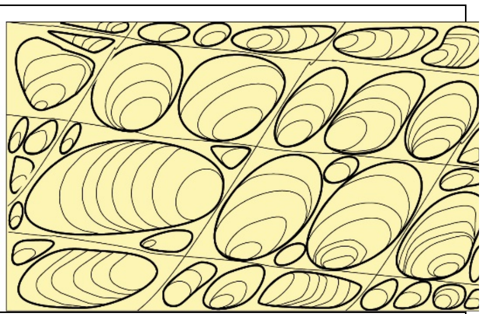
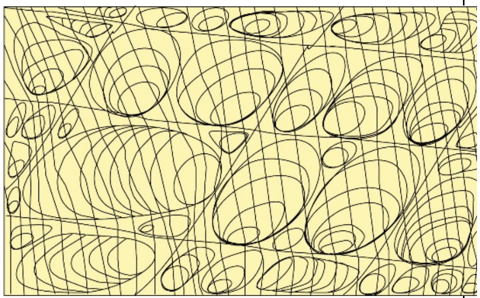
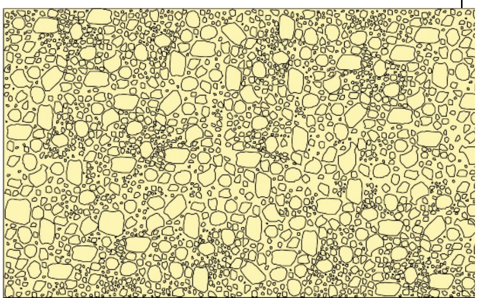
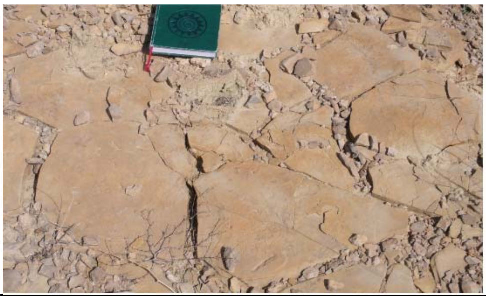
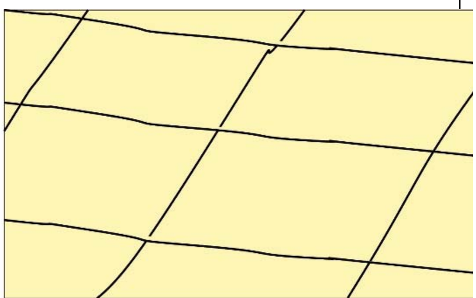
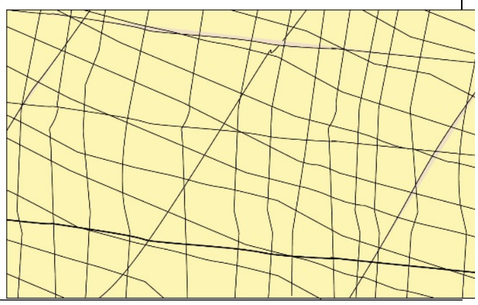
The way in which the different lithologies weathered was studied in the field. To this end, the weathering horizon of each lithology stratum from slope surface to bedrock was studied by excavation. The weathering lengths were determined by measuring the length of removed material and the thicknesses of the different weathering patterns (Figure 5) from a reference line corresponding to the original slope surface. A total of 87 strata were studied in order to define their weathering patterns and profiles. The remaining strata (note that a total of 151 were tested in the laboratory) were used to validate the expected weathering patterns of the different lithologies in the field, checking only the most superficial layers.

The weathering patterns are defined as follows (Table 2): Not weathered (NW); slight discoloration (A); reduction by arenization (B); flat weathering front peeling off (C); conchoidal peeling off (D); incipient rounding of blocks formed by tectonic joints (E); ellipsoidal morphology blocks formation (F); cubic centimetre fracturing of ellipsoidal block (G); incipient conchoidal fracture of ellipsoidal blocks and formation of ellipsoidal blocks of minor size (H); total conchoidal exfoliation of ellipsoidal blocks (I); massive fracturing in centimetric pseudocubic blocks (J); residual soil (K); centimetric rhomboidal fracturing in centimetric thickness strata (L); and massive fracturing of centimetric thickness strata (M). Table 2 summarizes, illustrates and describes in detail the different weathering patterns (from modes B to M) observed in the field.

Table 2. Detailed description of the weathering patterns obtained from the excavation of 87 strata from the slope surface to the bedrock.

Weathering pattern	Picture and schematic plot
B. Reduction by arenization. Decomposition to sand through a process which causes the loss of permanent cohesive forces between the rock particles.	 
C. Flat weathering front of millimetre to centimetre length. Peeling off and spalling.	 

D. Centimetric conchoidal peeling off. A one centimeter thick halo around the rock blocks is generated. The gradual peeling off penetrates inwards the not weathered rock mass.		
E. Incipient rounding of blocks mostly formed by tectonic planar joints and bedding. Occasional blocks of minor size.		
F. Ellipsoidal blocks with many intercalated minor size rounded blocks which partially mask the original joint sets.		
G. Cubic centimetre fracturing of ellipsoidal block. The original joint planes cannot be easily recognized.		
H. Incipient conchoidal fracture of ellipsoidal blocks and formation of ellipsoidal blocks of minor size. The original joint planes cannot be easily recognized.		

I. Total concentric conchoidal exfoliation of ellipsoidal blocks. The original joint planes cannot be easily recognized.		
J. Massive fracturing in centimetric pseudocubic blocks of conchoidal blocks. The ellipsoidal geometry of the isolated blocks is preserved.		
K. Highly graduated residual soil. The original structure of the rock mass has been completely destroyed.		
L. Centimetric spacing rhomboidal fracturing in centimetric thickness strata with incipient fracturing of lower spacing.		
M. Massive rhomboidal fracturation of centimetric thickness strata which generate foliation of small sheets.		

As previously described, the addition of the removed (L_r) and altered lengths (L_{wi}) of a stratum from a slope is defined as the weathering profile length (WPL) (Figure 2). This weathering profile is comprised of the sum of different weathering patterns (see Figure 5 and Table 2). In the field it was observed that weathering profiles depended on the lithological nature of the strata, although some lithologies exhibited similar weathering profiles (e.g. NW-A, AB, AC, AD, EFG, FHIJK, LM;

Table 4). The weathering lengths (expressed in centimetres) and rates (expressed in centimetres per year) were calculated from the slopes whose age (i.e. the time from their excavation to the present) was known and which had not suffered evident re-excavation, resloping and/or rockfall activity. Where any of these had occurred the length could not be measured, as the slope would have been altered by factors other than weathering over time.

5. Determination of durability categories from slaking properties

The first standardised durability classifications were based on one or two cycle slake indices (Franklin and Chandra 1972 and Gamble 1971). However, other researchers such as Nickmann et al. (2006), Sri-in and Fuenkajorn (2007), Fuenkajorn (2011) and Miščcević and Vlastelica (2011) considered slaking properties by using several slake cycles in order to distinguish between the different rock classes. In this study, similarly to Nickmann et al. (2006), Sri-in and Fuenkajorn (2007) and Fuenkajorn (2011), a classification system is proposed based on sample properties during several slake-cycles and a proposed Index of Weathering (IW_5), which, together with the Id_1 and Id_5 indices allows the classification of rocks into ten different categories. IW_5 is calculated from the Id_i values obtained from five different cycles through the expression:

$$IW_5 = \frac{1}{5}\sum_{i=1}^{i=5} Id_i \quad (3)$$

Notice that IW_5 represents the average Id_i index for the five slake-cycles and thus is related to the mean properties throughout the five slaking cycles. This parameter, in conjunction with Id_1 and Id_5, is used to determine the durability category of the rock samples. Note that for the definition of these durability categories we have also considered the whole durability curve along five cycles because the morphology of the slaking curves shown in Figure 8 allows to better differentiate the distinct slaking behaviours. The parameters IW_5, Id_1 and Id_5 (derived from the five-cycle tests performed on 151 samples, see Figure 8) allow different rock weathering properties to be distinguished, which can be split into ten different classes (Table 3) according to the Id_i curve morphology (general trend, attenuation of mass lost, slope of the different segments, etc.).

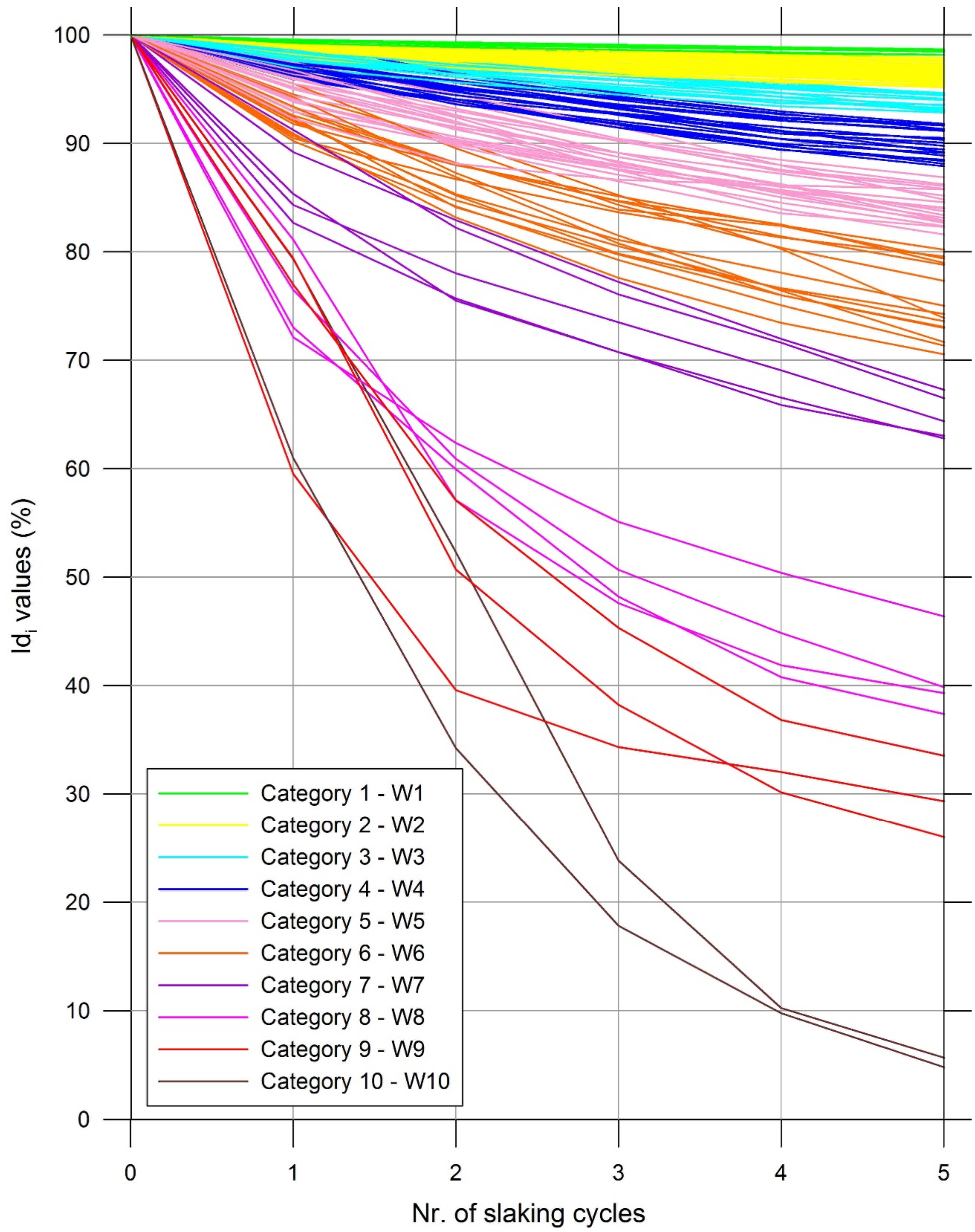


Figure 8. Change in the slake durability index (Id_i) of the 151 tested samples throughout five cycles. Each group of categories (W1 to W10) corresponds to a different Id_i curve morphology and this is plotted in a different colour.

Figure 9 shows the plot of Id_1 versus Id_5 values and the ten different categories (W1 to W10). Note that the 151 Flysch samples lie between the functions:

$$Id_5 = 1.73Id_1 - 72.73 \quad (4)$$

$$Id_5 = 12.24Id_1 - 1124 \quad (5)$$

It follows that the area of the plot located over the main diagonal (Id_1=Id_5) represents the zone with no possible Id_1-Id_5 combination values, because a point located in this area would have an Id_5 value higher than or equal to Id_1.

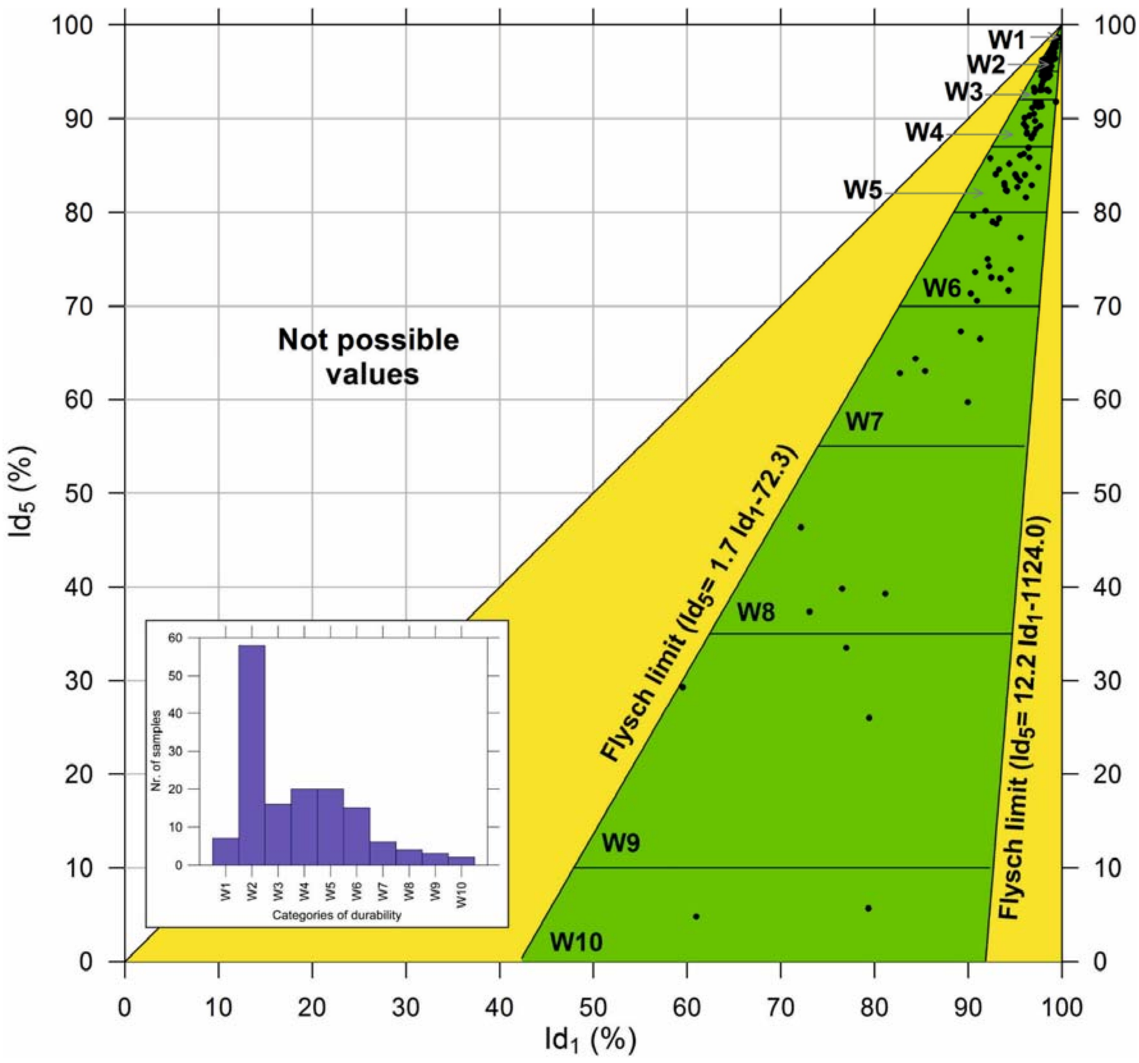


Figure 9. Id_1-Id_5 plot of the 151 samples. W1 to W10 refers to the durability category of the rocks, as explained in Table 3. The number of samples in each durability category (W1 to W10) is shown in the plotted histogram. The slake properties observed for the different categories are shown in Figure 8.

The different categories show very small range of IW_5 values. High IW_5 values correspond to extremely durable rocks. However, this range increases, mainly for the W4 category. The same trend can be observed for Id_1 and Id_2 defined intervals. The categories exhibit different weathering properties depending on the manner of degradation throughout the different cycles, and as a consequence, under natural conditions, also depending on time. A detailed description of the different categories based on the Index of Weathering (IW_5), the Id_1 and Id_5 values, the different properties throughout the slake cycles and the associated Flysch lithologies is shown in Table 3. Note that for the lithologies in each category the field-based strength value according to ISRM (1981) is included in the classification.

Table 3. Classification of Flysch carbonate rocks into ten different classes based on the rock behaviour along five cycles of Slake Durability Test (Id_i curve morphology, Figure 8) and the five-cycles Index of Weathering (IW_5). The number of samples of each lithology is in square brackets. R0 to R6 represent rock strength according to ISRM (1981).

Categories of durability	Index of Weathering (IW_5)	Id_1	Id_5	Behaviour	Lithologies
W1 Extremely good	>99	>99	>98	From an initial average loss of mass near 0.6% for the first slake-cycle the next indexes (Idi) vary approximately linearly with a drop between cycles near 0.3%.	– Thick bedding calcarenites. Grainstone of turbiditic facies of channel (Ta-b). Very strong rocks, grade **R5**. [7]
W2 Very good	97-99	95-99	95-98	From an initial average loss of mass near 1.5% for the first slake-cycle the next indexes (Idi) vary approximately bi-linearly with first-second and second-fifth cycle drops near 0.8% and 0.5% respectively.	– Slightly marly limestones (predominance). Strong rocks grade **R4**. [38] – Thin bedding calcarenites (Compact). Turbiditic thin beds of fan fringe facies (Tb-c-d). Strong rocks grade **R4**. [7] – Thin bedding calcarenites (Laminated). Turbiditic thin beds of fan fringe facies (Tb-c-d). Strong rocks grade **R4**. [2] – Thick bedding calcarenites. Grainstone of turbiditic facies of channel (Ta-b) or sheet flood facies (Tb, Tb-c). Very strong to strong rocks, grades **R5** to **R4**. [8] – Calcareous mélange. Strong rocks grade **R4**. [3]
W3 Good	95-97	95-99	92-95	From an initial average loss of mass near 2.0% for the first slake-cycle the next indexes (Idi) vary approximately bi-linearly with first-second and second-fifth cycle drops near 1.4% and 1.0% respectively.	– Marly Limestones. Medium strong rocks grade **R3**. [6] – Thin bedding calcarenites (Compact). Turbiditic thin beds of fan fringe facies (Tb-c-d). Strong rocks grade **R4**. [2] – Thin bedding calcarenites (Laminated). Turbiditic thin beds of fan fringe facies (Tb-c-d). Medium strong rocks grade **R3**. [2] – Silty marls. Medium strong rocks grade **R3**. [2] – Thick bedding calcarenites. Grainstone of turbiditic facies of sheet flood facies (Tb,Tb-c). Strong rocks grade **R4**. [1]

					– Calcareous debrites. Strong rocks grade **R4**. [1] – Calcareous mélange. Strong rocks grade **R4**. [1] – Silty calcareous marls. Medium strong rocks grade **R3**. [1]
W4 Medium	92-95	95-99	87-92	From an initial average loss of mass near 3.1% for the first slake-cycle the next indexes (Idi) vary approximately bilinearly with first-fourth and fourth-fifth cycle drops near 2.0% and 1.2% respectively.	– Calcareous marls - Marls. [9] – Marly limestones [6] – Thin bedding calcarenites (Compact). Turbiditic thin beds of fan fringe facies (Tb-c-d). [1] – Thin bedding calcarenites (Laminated). Turbiditic thin beds of fan fringe facies (Tb-c-d). [1] – Silty calcareous marls. [1] – Silty marls. [1] Medium strong rocks grade **R3**.
W5 Fair	85-92	90-97	80-87	From an initial average loss of mass near 5.0% for the first slake-cycle the next indexes (Idi) vary approximately bilinearly with first-fourth and fourth-fifth cycle drops near 3.0% and 2.0% respectively.	– Calcareous marls - Marls. [9] – Silty marls [3] – Silty calcareous marls. [2] – Thin bedding calcarenites (Compact). Turbiditic thin beds of fan fringe facies (Tb-c-d). [1] – Thin bedding calcarenites (Laminated). Turbiditic thin beds of fan fringe facies (Tb-c-d). [1] – Thin bedding silty calcarenites [1] – Marly limestones [1] – Soft calcareous mélange [1] – Poorly cemented thick bedding calcarenites. Grainstone of turbiditic facies of channel (Ta-b). [1] Medium strong to weak rocks, grades **R3** to **R2**.
W6 Fair-poor	80-85	90-95	70-80	From an initial average loss of mass near 7.5% for the first slake-cycle the next indexes (Idi) vary approximately bilinearly with first-third and third-fifth cycle drops near 5.2% and 3.4% respectively.	– Calcareous marls - Marls. [9] – Sheet silty marls. [2] – Thin bedding calcarenites (Laminated). Turbiditic thin beds of fan fringe facies (Tb-c-d). [2] – Thin bedding silty calcarenites [1]

					Medium strong to weak rocks, grades **R3** to **R2**.
W7 Poor	70-80	80-90	55-70	From an initial average loss of mass near 12.9% for the first slake-cycle the next indexes (Idi) vary approximately stepwise with first-second and fourth-fifth cycle drops near 8.6% and 4.1% respectively.	– Sheet silty marls. [3] – Calcareous marls - Marls. [2] – Poorly cemented thin bedding calcarenites. [1] Medium strong to weak rocks, grades **R3** to **R2**.
W8 Very poor	50-70	70-80	35-55	From an initial average loss of mass near 24.3% for the first slake-cycle the next indexes (Idi) vary approximately stepwise presenting important cycle attenuations with first-second and fourth-fifth cycle drops near 15.6% and 3.7% respectively.	– Calcareous marls - Marls. [2] – Sheet silty marls. [1] – Poorly cemented thin bedding calcarenites. [1] Weak rocks to very weak rocks, grades **R2** to **R1**.
W9 Extremely poor	35-50	50-80	10-35	From an initial average loss of mass near 28% for the first slake-cycle the next indexes (Idi) vary approximately stepwise presenting important cycle attenuations with first-second and fourth-fifth cycle drops near 22.8% and 3.4% respectively.	– Soft Marls. Very weak rocks grade **R1**. [3]
W10 Exceptionally poor	<35	50-80	0-10	From an initial average loss of mass near 30.0% for the first slake-cycle the next indexes (Idi) vary approximately linearly until the third cycle. From the third cycle there is important cycle attenuation with third-fourth and fourth-fifth cycle drops near 11.0% and 5.0% respectively.	– Sheet Marls. Very weak rocks grade **R1**. [2]

It may be noted that the worst durability properties categories (i.e. W10, W9 and W8) were defined using a limited number of samples (see histogram in Figure 9). This is because in the study area, only a few samples of these rocks were present (Figures 8 and 9). However, the W2 category, which represents "Very good" quality samples, is well represented in the study area, with 58 samples (Figures 8 and 9). For a more complete and detailed description of the slopes and samples refer to the raw data contained in Table A1, included as complementary material.

6. Analysis and discussion

A classification system based on the first and fifth slake-cycles of intact rock samples, Id_1 and Id_5, respectively and a defined index of weathering (IW_5) is proposed, for use in characterizing the slaking properties of intact rocks. Ten different weathering classes (W1 to W10) that exhibit distinct degradation properties are defined. Moreover, the detailed field description of the different

Flysch lithologies, together with the mineralogical characterization of samples belonging to each stated class of weathering allowed the different durability categories to be related to the rock strength types (R1 to R6) suggested by the ISRM (1981) and point load strength ($I_s(50)$) according ISRM (1985). It was noted that the field weathering properties of the different lithologies are related to their slaking properties. However, these weathering profiles can be associated with different lithologies. As a consequence, a certain durability category can exhibit different weathering profiles. However, each lithology presents a single weathering profile, regardless of its durability category (Table 4). Furthermore, it was observed that the weathering rate corresponding to a certain age and durability category (Wi) depends on the weathering profile (mainly for the more resistant categories) (Figure 10). This effect seems to be attenuated for older slopes, probably due to a plausible passivation of the weathering process resulting from the accumulation of decomposed rock. However, this topic will be the aim of future research which will be confirmed with new data.

This is of great interest to field engineers and geologists because the weathering properties of the rocks can be easily predicted for preliminary planning purposes by recognizing the lithology and applying the criteria defined in Table 3.

Attending to the results of the detailed analysis of the properties of the lithologies in the study area along five slake-cycles (Table 3) and comparing them with the real properties, some interesting conclusions may be drawn. The thick bedding calcarenites provided very high Id_5 values of over 97%, usually exhibiting “Extremely good” (W1) real weathering properties and the weathering profile NW-A, or “Very good” (W2) and “Good” (W3) properties and the weathering profile AC. In all cases the weathering rate was lower than 1 mm/year for 5, 15, 20 and 40 year old slopes.

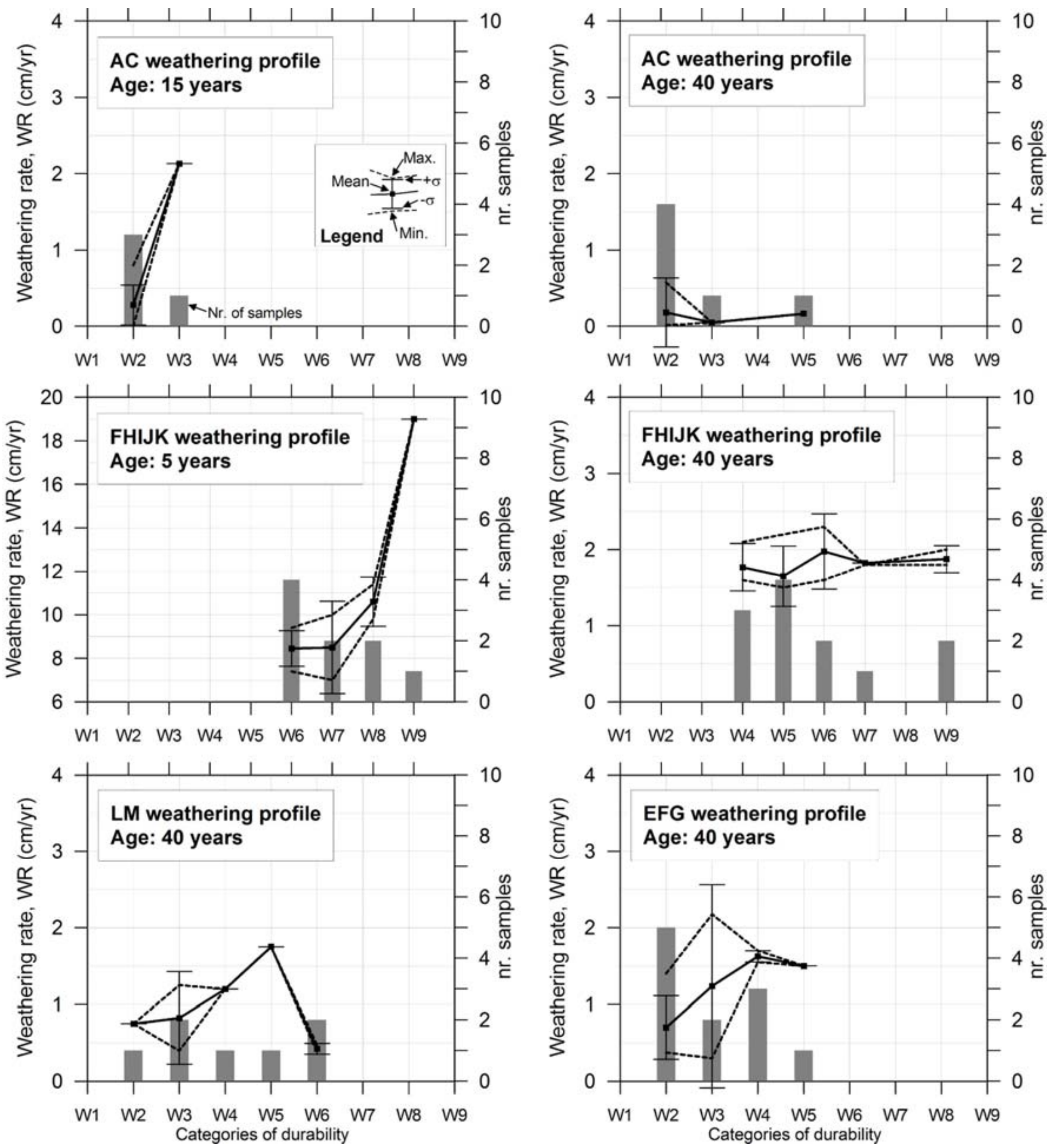


Figure 10. Variation of weathering rates as a function of the durability category for different weathering profiles and slope ages. σ: Standard deviation; Max.: Maximum value; Min. minimum value.

The slightly marly limestones belonged to the W2 ("Very good") category, exhibiting an EFG weathering profile and an average weathering rate of 3 cm/year for 15 year old slopes and 0,7 cm/year for 40 year old slopes. The calcareous mélange presented an AC weathering profile and an average weathering rate of up to 0.3 and 2.1 cm/year for the W2 and W3 categories, respectively. There were two types of thin bedding calcarenites present, according to their macroscopic texture. The first type of bedding calcarenites were compact and exhibited an AC weathering profile, with a weathering rate lower than 1 cm/year independent of the age of the slope and its category (W2 to W5). However, the bedding calcarenites which presented a laminated texture showed an LM weathering profile and a weathering rate lower than 2 cm/year for 40 year old slopes, regardless their category (W2 to W6). Calcareous debrites, which belonged to the W3 category, showed an AD weathering profile and an extremely low weathering rate (nearly nil). Marly limestones (categories W3 to W5) presented an EFG weathering profile. Their mean weathering rate was less than 2 cm/year for the older slopes (i.e. 40 year old slopes). Silty calcareous marls and silty marls belonged to the W3 to W5 durability categories. Although the former exhibited an FHIJK weathering profile and a weathering rate of up to 5 cm/year for 15 year old slopes. The latter presented an EFG weathering profile and an unknown weathering length and rate because the original slope surfaces where this lithology outcropped were unknown. Calcareous marls were dispersed into a wide range of durability categories. A trend was observed wherein the weathering rate increased with the durability category (9 cm/year for W6 and 10 cm/year for W8) for the 5 year old slopes. However, for this lithology, all durability categories showed similar weathering properties, with average weathering rates of near 2 cm/year in the long-term (i.e. 40 years). Soft calcareous mélange and thin bedding silty calcarenites exhibited a similar durability categories (W5 and W6) and the same weathering profile (LM). The weathering rates for the W5 durability category were 3.7 and 1.8 cm/year for 15 and 40 years respectively. For W6 the rate was 9.4 cm/year for 5 years. Sheet silty marls presented a FHIJK weathering profile and durability categories W6 to W8, which corresponds to an average weathering rate for 5 year old slopes of 8, 9 and 11 cm/year, respectively.

The poorly cemented thick bedding calcarenites and the poorly cemented thin bedding calcarenites also exhibited the same weathering profile (AB). However, the poorly cemented thick calcarenites belonged to the W5 category and had an average weathering rate of 0.6 cm/year for 20 year old slopes and the poorly cemented thin bedding calcarenites belonged to the W7 and W8 categories, with an average weathering rate of 6.4 cm/year for 5 year old slopes. The latter lithological groups identified in the field corresponded to soft marls and sheet marls which exhibited “Extremely poor” (W9) or “Exceptionally poor” (W10) properties, with Id_5 from 0% to 35%. These rocks, like those described above, can suffer very quick degradation processes that can be recognized even a few days after the excavation of slopes, with average weathering rates of 19 cm/year for 5 year old slopes (W9) and 12 cm/year for 15 year old slopes (W10). Both lithologies exhibited weathering profiles FHIJK.

Note that the weathering rates presented in this study showed some dispersion, mainly due to the influence of different factors which can affect the weathering length and/or the acquisition of data in the field. For example, the geometric relationship between the slope and the bedding can favour the penetration of rainwater, the remobilization or accumulation of weathered materials and the occurrence of rockfalls which accelerate or slow the degradation processes, depending on the adopted values (Cano and Tomás 2013a). The steep or flat morphology of the slopes could be another reason for the material removal or accumulation on the slopes, respectively. The selection of the reference line (i.e. the line which defines the original slope geometry just after excavation) is also a key parameter in the determination of the weathering length. It is also important to highlight that the weathering rates change over time, probably due to the accumulation of degraded material on the slope's surface, which can have a passivating effect that reduces the rate of degradation. This fact can be clearly seen in calcareous marls with a W6 durability category which exhibited a very high weathering rate during the 5 first years after excavation (9 cm/year), falling to 1.2 cm/year from 5 to 20 years and finally being reduced to 0.8 cm/year between 20 and 40 years (Figure 11). This finding will be object of future research. Finally, note that the most resistant lithologies, both mechanically and against degradation, were less sensitive to IW5 than less resistant lithologies. This is because the parameter is derived from weathering lengths measured in the field. This fact is clearer for the older slopes (i.e. 40 years old). However, the most marly lithologies, which exhibited an FHIJK weathering profile and a higher short and medium-term weathering rate showed a clear correlation with the IW5 index which was attenuated in the long-term.

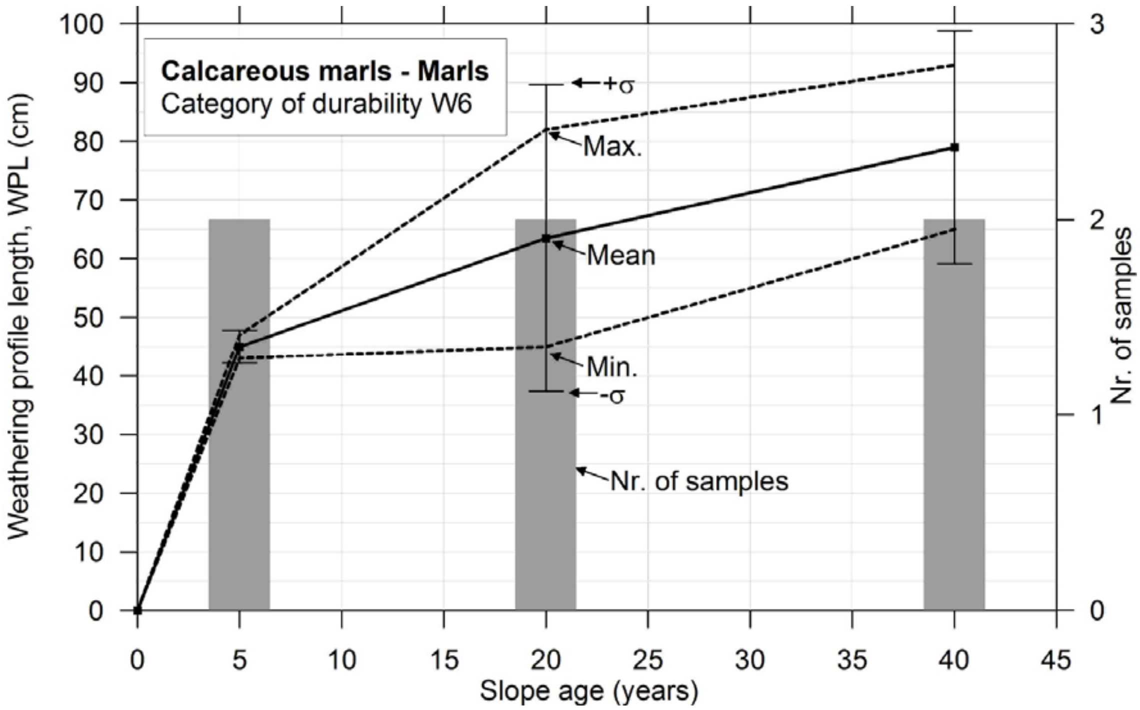


Figure 11. Variation of the weathering profile length (WPL) versus the slope age for a similar lithology and category of durability. σ: Standard deviation; Max.: Maximum value; Min. minimum value.

Table 4. Summarized weathering classification of the carbonatic Flysch lithologies of Alicante. Each lithology is associated with a particular weathering profile and different categories of durability. Additionally, mineralogy and rock strength are presented for each lithology. Moreover, each categories of durability is also associated with IW5, Id1 and Id5 indices and rock strength.

Table 4 Summarised weathering classification of the carbonatic Flysch lithologies of Alicante

Categories of durability →	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	Cb (%)	Qtz (%)	Phy (%)	IW_5	$I_s(50)$ (MPa)
Thick-bedded calcarenites	**NW-A**	**AC**	**AC**								91.6 ± 3.6	1.9 ± 1.4	6.4 ± 2.8	98 ± 1	4.9 ± 1.2
Slightly marly limestones		**EFG**									84.6 ± 3.8	3.9 ± 1.3	11.5 ± 2.6	98 ± 1	3.2 ± 0.9
Calcareous mélange		**AC**	**AC**								87.5 ± 2.4	3.2 ± 0.6	9.3 ± 1.9	97 ± 1	3.3 ± 0.4
Thin-bedded calcarenites (C)		**AC**	**AC**	**AC**	**AC**						81.5 ± 6.6	5.4 ± 3.1	13.1 ± 3.9	96 ± 2	2.8 ± 1.8
Thin-bedded calcarenites (L)		**LM**	**LM**	**LM**	**LM**	**LM**					76.7 ± 12.1	7.3 ± 4.5	16.1 ± 7.9	92 ± 5	1.7 ± 1.1
Calcareous debrites			**AD**								84.8 ± 0.0	4.0 ± 0.0	11.2 ± 0.0	96 ± 0	4.5 ± 0.0
Marly limestones			**EFG**	**EFG**	**EFG**						79.5 ± 3.1	5.5 ± 1.0	15.0 ± 2.6	94 ± 2	1.8 ± 0.4
Silty calcareous marls			**FHIJK**	**FHIJK**	**FHIJK**						82.4 ± 3.9	5.0 ± 1.9	12.7 ± 2.1	91 ± 4	1.1 ± 0.3
Silty marls			**EFG**	**EFG**	**EFG**						74.7 ± 3.1	7.6 ± 0.7	17.8 ± 2.6	93 ± 3	1.1 ± 0.6
Calcareous marls—Marls				**FHIJK**	**FHIJK**	**FHIJK**	**FHIKJ**	**FHIJK**			76.5 ± 4.1	6.8 ± 1.7	16.7 ± 2.8	86 ± 10	1.4 ± 0.6
Poorly cem., thick-bedded calc.					**AB**						83.3 ± 0.0	4.4 ± 0.0	12.3 ± 0.0	88 ± 0	1.1 ± 0.0
Soft calcareous mélange					**LM**						84.2 ± 0.00	4.2 ± 0.0	11.7 ± 9.7	89 ± 0	0.8 ± 0.0
Thin-bedded silty calc.					**LM**	**LM**					70.0 ± 11.7	10.1 ± 2.1	20.0 ± 9.7	85 ± 4	2.1 ± 0.7
Sheet silty marls						**FHIJK**	**FHIJK**	**FHIJK**			70.5 ± 6.7	8.4 ± 2.4	21.0 ± 5.9	72 ± 10	0.8 ± 0.4
Poorly cem., thin-bedded calc.							**AB**	**AB**			78.6 ± 5.5	5.9 ± 0.7	15.6 ± 4.8	64 ± 10	0.5 ± 0.1
Soft marls									**FHIJK**		75.4 ± 3.8	7.7 ± 0.9	16.9 ± 3.0	45 ± 6	0.6 ± 0.4
Sheet marls										**FHIJK**	72.7 ± 5.6	7.4 ± 1.3	20.0 ± 4.4	30 ± 6	0.6 ± 0.2
IW_5	>99	97–99	95–97	92–95	85–92	80–85	70–80	50–70	35–50	<35					
Id_1	>99	95–99	95–99	95–99	90–97	90–95	80–90	70–80	50–80	50–80					
Id_5	>98	95–98	92–95	87–92	80–87	70–80	55–70	35–55	10–35	0–10					
Field rock strength (ISRM 1981)	R5	R5–R4	R4–R3	R3	R3–R2	R3–R2	R3–R2	R2–R1	R1	R1					
Point load strength ($I_s(50)$) (MPa)	4.3–6.6	1.6–6.2	0.6–5.1	0.7–2.8	0.6–2.6	0.4–2.0	0.6–1.6	0.3–1.6	0.2–1.0	0.5–0.7					

Each lithology is associated with a particular weathering profile and different categories of durability. Additionally, mineralogy and rock strength are presented for each lithology. Moreover, each category of durability is also associated with IW5, Id1 and Id5 indices, and rock strength

Cb carbonates, dolomite plus calcite; *Qtz* Quartz; *Phy* phyllosilicates; IW_5 weathering index; $I_s(50)$ point load strength. A, B, C, D, E, F, G, H, I, J and K are the different field weathering patterns, *NW* non-weathered

7. Conclusions

The classification of rock durability based on Id_1 (Franklin 1972) or Id_2 (Gamble 1971) indices was proved to be inappropriate for predicting the natural degradation properties of carbonatic rocks from the Flysch of Alicante (Spain) or similar rocks. Additionally, in this study a new index (Index of weathering, IW_i) calculated as the average of *i* slake-cycles (Id_i) values is proposed jointly with Id_1 and Id_5 slake cycles for distinguishing different rock weathering properties.

For the study area a five-cycle index of weathering (IW_5) was proved to be adequate for distinguishing between the different weathering properties of Flysch lithologies observed in the field. As such, using the IW_5 index and the Id_1 and Id_5 values, ten different weathering categories were defined (W1 to W10). Furthermore, the detailed description of the samples from the lithologies outcropping in the study area allowed a direct relationship to be established between the different lithologies, their slaking properties (W1 to W10 according to the proposed methodology) and their weathering profile and rate.

The results shown in this study allow the prediction of the expected weathering pattern and rate of the different strata that outcrop in a slope from their geological and geomechanical characteristics. The identification of the lithology can be performed through a visual or, alternatively, mineralogical characterization and the mechanical properties derived from the field criteria stated by the ISRM (1981) or, alternatively, from $I_s(50)$. Finally the durability of the strata can be derived from the weathering index (IW_5) defined in this paper which is obtained from testing intact rock samples.

Because most of the instabilities affecting the cut-slopes and natural slopes in the areas which were studied are closely related to the degradation of marly lithologies (Cano and Tomás 2013b), this study allows the long-term weathering properties of carbonatic Flysch rock layers to be known when the excavation of a new slope is planned. Furthermore, the classification may be easily used and even adapted for similar heterogeneous rock masses and climatic conditions.

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