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Relationship between Monitored Natural Slaking Behaviour, Field Degradation Behaviour and Slake Durability Test of Marly Flysch Rocks: Preliminary Results

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Abstract

According to various studies, the degradation of marly lithologies that constitute heterogeneous rock masses such as flysch, can trigger and condition many slope instabilities. However, not all marly lithologies degrade in the same way, exhibiting considerable differences in the rates and ways of degradation. Therefore, it is very important to know the degradation behaviour of different lithotypes against environmental conditions, characterizing their weathering patterns and quantifying their rates of deterioration. This issue has been widely studied trough different approaches: a) through laboratory tests, mainly based on the slake durability test (SDT); b) through the study of monitored natural slaking behaviour; and c) by means of the characterization of in situ observed patterns and natural degradation rates. The main aim of this work is to link these different approaches used to perform this characterization. For this purpose, an experimental test, in which various samples have been exposed under monitored natural climatic conditions for 12 months and have been characterized through the study of the fragment size distribution curves of the degraded particles, has been developed. Additionally, these samples have been also classified based on the Potential Degradation Index (PDI) determined through laboratory tests. Finally, the *in situ* weathering behaviour profiles have been also logged. Preliminary results of this research suggest the existence of a clear relation between the different classes of degradation stated by the Potential Degradation Index (PDI), the behaviour of the fragments retained in the drum along the SDT cycles, the slaking behaviour under natural climatic conditions and the weathering behaviour patterns and rates observed at weathered profiles in the field.

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Keywords: Marly flysch rocks; Slake Durability Test; Slaking behaviour patterns; Natural slaking behaviour;Field degradation behaviour

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1. Introduction

According to several authors, heterogeneous rock masses such as flysch, which are formed partly by marly lithologies, exhibit slope instabilities related to the degradation of this marly lithologies. However, not all marly lithologies degrade in the same way, exhibiting considerable differences in the way of degradation and especially in the deepening rates of alteration. Therefore, it is very important to know the degradation behaviour of different lithotypes against environmental conditions, characterizing their weathering patterns and quantifying their rates of deterioration.

This is an aspect of great importance, especially in linear infrastructures that coursing through these types of rock masses, such as roads and railways, as many slopes are generated. In these slopes, which are permanently exposed to the atmosphere, instabilities resulting from differential erosion/degradation are very habitual. This implies that must be implemented corrective measures, that to be fully effective they must be preventive [1, 2]. Otherwise, these instabilities result in meaning maintenance and repair costs, and may pose a significant safety hazard. In addition, degradation processes, such as ravelling and erosion, should also be considered as failure modes themselves, rather than just triggering factors. For this reason, the problem of slope stability over time should also be considered, in case they are not protected against weathering processes [3].

The instability processes involving these slopes excavated in heterogeneous rock masses and associated to differential weathering and erosion are mainly caused by the degradation of marly lithologies. In this regard, it is noteworthy that on slopes with only 25% of degradable marly lithologies instabilities, associated with differential degradation processes can be developed [4].

For all these reasons, researchers have attempted to quantify the weathering susceptibility of clay-bearing rocks, which may destabilize heterogeneous slopes by means of differential erosion/degradation. However, the slaking resistance, closely linked with weathering susceptibility, depends on different parameters commonly cited in literature as permeability, porosity, adsorption, mineralogy, microscopic texture, microfabric, presence of microfractures, etc. [5–14]. It implies that the characterization of slaking behaviour in weak rocks using a single parameter becomes extremely complex [11, 13].

Moreover, not even the marly calcareous rocks degrade following a unique pattern. Considerable differences in the manner of degradation and time taken to degrade the rock may be observed [1, 2, 14, 15]. Therefore, it is particularly important to link the weathering behaviour observed in the field with the slaking parameters obtained in the laboratory. This can be done, for example, by using weathering patterns and weathering profiles [14, 15].

As it is well known, the indices obtained from slake tests are widely used to characterize the behaviour of different types of rock in a qualitative manner, although its use to predict the quantitative behaviour of rocks under field conditions, is highly questionable [16, 17]. In this context, Rincón et al. [18] investigated the reliability of using microtremor H/V spectral ratio, derived from microtremor signals, and image entropy, obtained from image analysis techniques, for quantifying the varying degrees of disintegration of in situ weak rocks.

Erguler and Shakoor [19] proposed a new method to quantify the nature of rocks. This method quantifies the fragment size distribution of the slaked material in terms of "disintegration ratio". Similarly, Cano and Tomás [15] developed the potential degradation index (PDI). Nevertheless, the field slaking behaviour is influenced by factors that cannot easily be simulated under laboratory conditions. The time of exposure is a main factor, as slaking under natural field conditions is a long-term phenomenon compared to short-term laboratory tests, giving rise to different results [20, 21]. For this reason, Gautam and Shakoor [22] proposed a methodology, based on disintegration ratio, to quantify slaking behaviours of clay-bearing rocks during a one-year exposure to natural climatic conditions. This methodology has been validated by other researchers, such as Vivoda et al. [23] and Vivoda and Arbanas [24], endorsing this method as an alternative to traditional slake indices. Gautam and Shakoor [13] also compared the slaking of clay-bearing rocks under laboratory conditions with the slaking under natural climatic conditions.

Similarly to the aforementioned studies, this work aims to evaluate the degradation of marly calcareous rocks by the Potential Degradation Index (PDI), analysing changes in the fragment size distribution curves obtained from the material retained in the drum after each slake durability test cycle, up to a total of five cycles [15]. This issue has been widely studied trough different approaches: a) through laboratory tests, based on the slake durability test (SDT); b) through the study of monitored natural slaking behaviour; and c) by means of the characterization of in situ observed patterns and natural degradation rates. However, the main aim of this work is to link these different approaches used to perform this characterization. For this purpose, an experimental test, in which various samples have been exposed under monitored natural climatic conditions for six months and have been characterized through the study of the fragment size distribution curves of the degraded particles, has been developed.

2. Lithological and climatic framework of the study area

The selected study area is situated in South-eastern of Iberian Peninsula, in the coastal area of Alicante province (Spain) and corresponds to the named Surco flysch El Campello-Villajoyosa (Fig. 1). This area has been chosen because of the presence of numerous slopes with a great variety of outcropping lithologies. This flysch-like sequence is composed of pelagic sediments, predominated by sequences of grey marls and thin white marly limestones (hemipelagites) that constitute the rythmite with a clear predominance of the 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 [1].

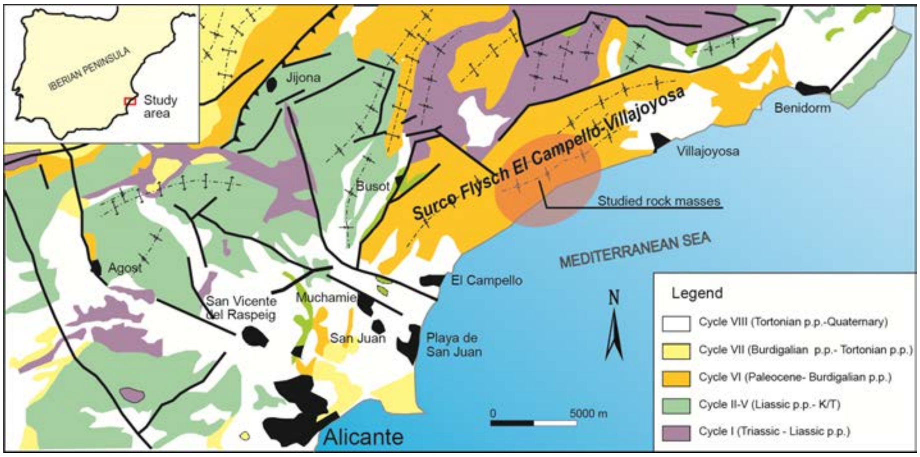

Fig. 1. Location and geological sketch maps of the study area (based on Vera [25] and Guerrera et al. [26]). The Shaded area indicates the location of the slopes studied in this work.

In a previous work, Cano and Tomás [15] defined by the first time the PDI, applying this index to the lithologies that outcrop on this study area. 117 intact rock samples extracted from all strata present in five selected slopes were analysed. These samples were described in detail at field and geologically classified as 16 lithotypes. Additionally, these samples were classified into 6 classes considering their durability according to the PDI.

In this work, 20 samples were selected from the same five slopes (Fig. 1). These samples correspond to 8 marly lithotypes, representing the defined lithotypes and the 6 existing durability classes. Additionally, for the slightly marly limestones lithotype and class five, 2 samples were selected due to their wide variation of PDI values. The selected samples for the development of the weathering degradation analysis were described in detail at field and fully characterized in the laboratory. They were geologically classified as: a) Slightly marly limestones; b) Marly limestones; c) Silty calcareous marls; d) Silty marls; e) Calcareous marls-marls; f) Sheet silty marls; g) Soft marls and h) Sheet marls. However, for this preliminary study, only 11 samples were analyzed, two for each of the first five classes and one for sixth. Regarding the studied lithotypes, the six defined classes are the following: Sheet Marls (1), Calcareous marls – Marls (4), Sheet silty marls (1), Silty calcareous marls (1), Marly Limestones (2) and Slightly marly limestones (2).

In the study area, located on the Mediterranean coast of Alicante, the rainfalls are scarce, irregular and random. The summer drought extends from three to five months, with few rainy days. At the end of this period, the autumnal heavy downpours cause numerous episodes of flooding. Cloudiness and fogging is also scarce, so the number of clear days is very high, with nearly 2900 hours of annual sunlight. The annual average temperature is 18.3°C and practically there is no meteorological winter [27]. The potential evapotranspiration is high, with a Thornthwaite index of 896 mm, so there is a strong water deficit during most of the year [28].

Additionally, this area is characterized by the absence of frosts and high temperature gradients [27] and as a consequence the weathering of the different lithologies is mainly caused by drying-wetting cycles due to rainfall and atmospheric moisture. Furthermore, no evidence of rock weathering caused by salt precipitations was observed in the slopes which were studied. Inasmuch as the slaking consists of the disintegration of clay-bearing rocks due to their interaction with water, which is common when they are exposed to the atmosphere, due to climate of the area, the weathering potential was expected to be related to their slaking properties.

3. Methodology

As commented above, the main aim of this study is to link the different approaches used to perform the weathering characterization of marly calcareous rocks. To the aim of validating the link between the slaking behaviour under monitored natural climatic conditions and the weathering patterns observed at field, it should be noted that, the maximum distance between the study area and the located zone where the controlled experiment is performed is 20.5 km in a straight line, so the weather can be considered very similar.

First of all, the selected samples have been characterized and classified based on the Potential Degradation Index (PDI) proposed by Cano and Tomás [15] which is calculated from a modified parameter (i.e. DRP) based on the "Disintegration Ratio" (DR) proposed by Erguler and Shakoor [19]. PDI is based on the change in the DRP ratio between the five slake cycles. The combined use of the PDI, together with the analysis of the behaviour of retained fragments throughout the five cycles of the slake durability test (changes in size and shape) has allowed a classification of the slake behaviour of these lithologies. From the three factors proposed by Cano and Tomás [15] (roundness, number of fragments, and fragment size), the qualitative study was performed on the fragments retained in the drum during the different cycles of the slake durability test. Using these standard factors, six slaking behaviour patterns were distinguee based on the changes observed in the fragments. It should be noted that the unique textures present in these marly lithotypes is compact (Table 1).

Complementarily, an experimental test, in which various samples have been exposed under monitored natural climatic conditions for six months, has been developed. In this test, the slaking characterization has been evaluated through the study of the fragment size distribution curves of the degraded particles, similarly to Gautam and Shakoor [22].

For evaluating the slaking behavior of the marly samples under monitored natural climatic conditions, 20 replicate samples of each rock, weighing 450–550 g, were prepared, for a total of 240 replicate samples. The replicate samples were prepared following the ASTM specifications for Slake Durability Test [29]. However, in order to minimize breakage of the samples by high temperatures, the samples were oven dried at 50°C until they reached a constant weight. All replicate samples were similar shape, size, and weight and the sharp edges and corners were rounded as far as possible.

Ten samples of each studied marly were placed in separate 30x19x5 cm aluminium plates. To allow easy and quick rainwater drainage, several 8 mm diameter holes have been made in the bottom of the plate and the whole base was covered by a 1 mm mesh plastic mesh. The plates were placed on wooden pallets that were located on the flat roof of the building of the laboratory of Civil Engineering of the University of Alicante (Spain). Thus, the samples were exposed to natural climatic conditions from January 29, 2016 to July 29, 2016 (Fig. 2).

At the end of each month, one replicate sample from each of twenty marly calcareous rocks was removed and taken to the laboratory to obtain the grain size distribution curve. The samples were oven dried on the same way that the original samples (i.e. 50ºC). The grain sieve analysis was made manually and carefully in order to minimize the breakage of the particles during sieving in order to avoid the modification of the grain size distribution curves. The sieving procedure adopted for determining fragment size distribution curves was the same than that used for soils [30], using standard sieves whose aperture sizes were 40, 31.5, 25, 20, 12.5, 10, 6.3, 5 and 2 mm. The results were plotted in semi-logarithmic scale, in order to show the fragment size distribution of samples before and after each test cycle. The curves from the different cycles were plotted on the same plot, in order to easily identify changes in the samples after each slaking cycle. The used sieve apertures were shown on the x-axis in semi-logarithmic scale, and the percent passing (by weight) on the y-axis. After obtaining the grain size distribution curves, these samples were placed back on the roof for the remainder of the year. It should be note that in this preliminary study only the curves for the first six months have been analyzed.

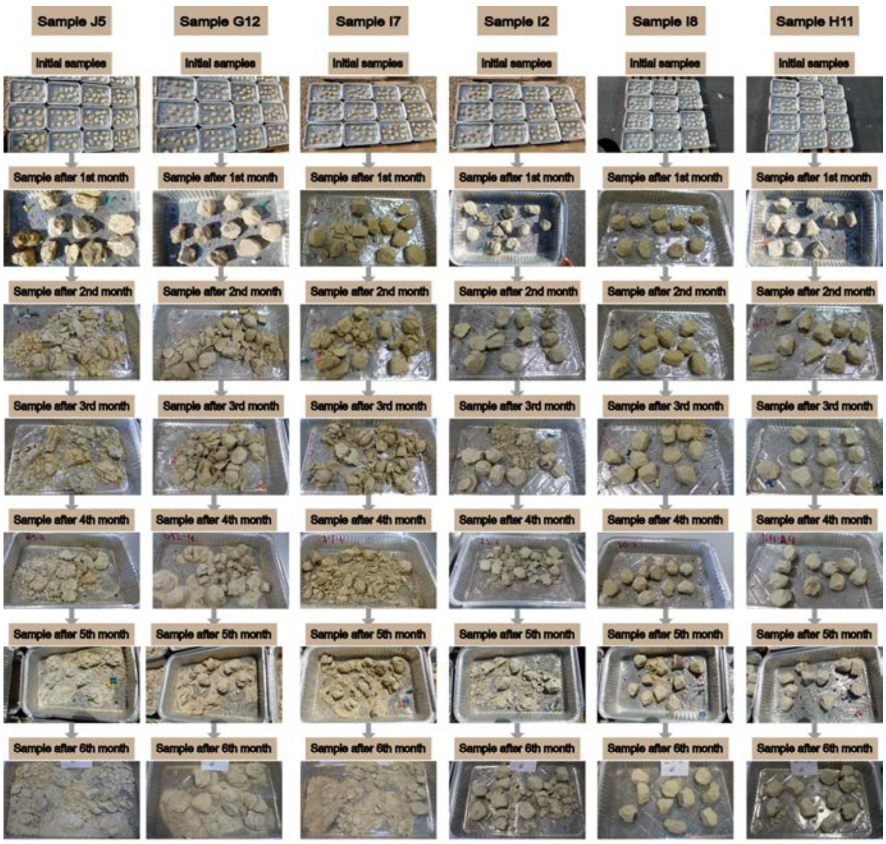

Fig. 2. Evolution of selected samples trough six months of exposition to natural climate conditions. The samples J5, G12, I7, I2, I8 and H11 are respectively representative of very low to high classes of durability based on slake PDI.

The performed methodology consists in an adaptation of the methodology of PDI [15], replacing grain size distribution curves after each cycle of slake durability test for the obtained curves of monthly analysis. First of all, the disintegration ratio (DRP) is calculated:

$$D_{RP} = \frac{A_C}{A_T} \quad (1)$$

where A_C is the area under any size distribution curve and A_T is the total area encompassing the whole range of fragment size distributions (Fig. 3).

Then, a logarithmic curve was fitted to the DRP values obtained for each sample and month. From this curve, the number of month required for a sample to reach 50% of the maximum possible degradation (DRP = 1) could be estimated. This number of cycles is denominated N50.

However, as it happened with PDI based on the slake durability test, owing to the fact that the slaking resistance of the rocks exposed at natural conditions in the study varied greatly, the range of N50 values was very large.

So the parameter denominated Natural Potential Degradation Index (PDIn) is calculated as:

$$PDIn = LnN_{50} \quad (2)$$

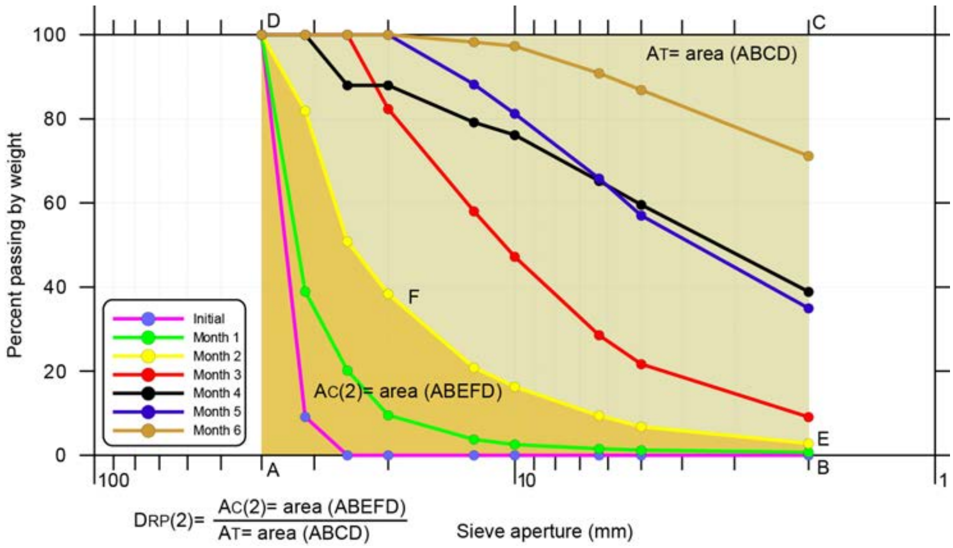

Fig. 3. Example showing the calculation of D_{RP} after monthly sieved analysis. In this case, after the second month D_{RP} (2).

Finally, the third way of approach to the weathering behaviour of marly rock consists on the study of field weathering behaviour profiles and weathering rates. The in situ observations of the different lithologies were made for rock that had been exposed to natural climatic conditions over a long period of time. The observed weathering patterns affecting the beds of exactly studied marly lithotypes are defined as follows (based on Cano and Tomás [14]):

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). The field weathering profile is comprised of the sum of different weathering patterns. It was observed that weathering profiles for the studied lithologies are FHIJK and EFG.

Additionally, weathering profile length (WPL) have been calculated according to Cano and Tomás [14]. Therefore, it is necessary to determine the original geometry of the slope. Then, the length of removed material (L_r), and the weathered lithology (L_w) of a layer affected by different weathering patterns (WP), until the bedrock was reached are measured. 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). The weathering rate (WR) may be calculated as ratio between WPL and the age (in years) of the slope (time from its excavation to the present).

Finally, to complete the work, a relationship between original slake PDI (PDIs) [15] and natural PDI developed in this study has been studied. Additionally, a link between natural PDI and weathering rate has also found.

4. Results, analysis and discussion

As described in the previous sections, changes in the DRP parameter throughout the monthly sieved analysis were evaluated for 11 samples for the six months (Fig. 3). The R^2 values were calculated for the logarithmic curves fitted to each sample. The fitting is appreciably good in general, despite being an analysis with only six months, with an average R^2 value of R^2 = 0.662 ± 0.0.279. However, the fitting considerably improves if only the curves of the samples corresponding to four first classes of durability defined according to the slake PDI are considered. In this case, $R^2 = 0.812 \pm 0.127$.

The relationship between the PDI based on slake durability test (PDIs) and the PDI calculated according to the monitored natural degradation (PDIn) is linear and good, providing $R^2 = 0.886$ and typical error of e = 4.974 (Table 1):

$$PDIn = 2.012PDIs - 5.776 \tag{3}$$

The J5 sample was collected from a slope whose excavation age is 15 years, the samples G5 and G12 are 5 years and the samples H1, H3, H7, H11, H14, I2, I7 and I8 are 40 years old. Once the weathering profile and length (WPL) of each bed that corresponds to each sample has been obtained in the field, knowing the age of the slope from which the samples were collected, we can calculate the weathering rate (WR) in terms of centimetres per year (Table 1).

Finally, a sigmoidal curve has been employed to fit the link between the natural PDI and the weathering rate with $R^2 = 0.764$ and typical error of e = 0.596 (Table 1):

$$WR = e - 5.776^{\left(-0.93+\frac{2.887}{PDIn}\right)} \tag{4}$$

The mineralogy was obtained using X-ray diffraction and Bernard calcimeter method. The phyllosilicate fraction was also analysed through oriented aggregate diffractograms, showing important contents of kaolinite, illite and mica and trace evidences of smectite in some samples.

Additionally, the slaking behavior patterns according to Cano and Tomás [15] was obtained. Table 1 summarize all the obtained information.

Table 1. Weathering behaviour classification of marly flysch lithotypes from Alicante. Each selected sample is representative of a category of durability based on slake Potential Degradation Index (and associated with a particular slake behaviour pattern (SBP). Additionally, mineralogy is shown for each studied sample. Slake PDI (PDIs), Natural PDI (PDIn) and weathering rate (WR) is also showed.

Sample	Lithotype	Mineralogy			PDIs	PDIn	WP	SBP	WR (cm/year)
		Cb	Phy	Qtz					
J5 (Very low)	Sheet Marls	76,6	16,9	6,5	1,04	0,88	F-H-I-J-K	C1	12,0
G5 (Very low)	Calcareous marls - Marls	72,3	19,6	8,1	1,96	1,08	F-H-I-J-K	C1	9,8
H7 (Low)	Calcareous marls - Marls	74,2	18	7,8	4,17	2,13	F-H-I-J-K	C2	1,6
G12 (Low)	Sheet silty marls	60,8	29,1	10	3,42	1,40	F-H-I-J-K	C2	7,4
H1 (Medium)	Calcareous marls - Marls	69,3	22,9	7,8	4,21	1,29	F-H-I-J-K	C3	1,5
I7 (Medium)	Silty calcareous marls	76,6	15,8	7,6	3,88	1,28	F-H-I-J-K	C3	1,4
I2 (Medium-high)	Marly Limestones	79,2	15,3	5,5	5,78	2,82	E-F-G	C4	1,6
H14 (Medium-high)	Calcareous marls - Marls	-	-	-	7,49	2,28	F-H-I-J-K	C4	1,6
H3 (High)	Slightly marly limestones	84,9	10,3	4,8	12,81	13,38	E-F-G	C5	0,5
I8 (High)	Marly Limestones	78,9	15,3	5,9	10,71	24,81	E-F-G	C5	0,3
H11 (Very high)	Slightly marly limestones	79,4	16,6	4,1	22,85	42,74	E-F-G	C6	0,5

Legend: Cb: Carbonates, dolomite plus calcite; Qtz: Quartz; Phy: Phyllosilicates. C1 to C6, are the different slaking behaviour patterns. EFG and FHIJK are the weathering profiles observed at field. Very low to high are classes of durability based on slake PDI.

5. Conclusions

In this work it have shown the preliminary results after a six months exposition to natural conditions of marly rocks. The obtained results are not definitive, as the climate variations of the western Mediterranean weather can exhibit strong precipitations during Spring and Autumn intensively affecting the rocks samples. However, the preliminary results allow to be optimistic about the existence of a relationship between the PDI index obtained by means of 5 slake durability test cycles and the new PDI based on the sieving of fragments of rocks after different natural conditions exposure cycles (PDIn). Additionally, this new index (PDIn) presents a tight relationship with the degradation rates evaluated on field. However, as Cano and Tomás [14] stated, this rate can be affected by different factors that can distort the computed value. Furthermore, there are some key aspects from the performed tests that should be analysed in depth as the ideal size of the samples, the optimum exposition time and the differences between the climatic monitored conditions and the actual conditions in the inner part of the slope.

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