Journal of Rock Mechanics and Geotechnical Engineering 6 (2014) 257–268

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full length article

Effects of loading–unloading and wetting–drying cycles on geomechanical behaviors of mudrocks in the Colombian Andes

Mario Camilo Torres-Suarez [a,*], Adolfo Alarcon-Guzman [a], Rafael Berdugo-De Moya [b]

[a] *National University of Colombia, Bogota, Colombia*
[b] *North University, Barranquilla, Colombia*

A R T I C L E I N F O

Article history:
Received 28 February 2014
Received in revised form
5 March 2014
Accepted 10 March 2014
Available online 16 May 2014

Keywords:
Mudrocks
Degradation processes
Suction changes
Stress–strain behavior
Vapor equilibrium technique (VET)

A B S T R A C T

The mudrocks in the Colombian Andes, particularly those exhibiting low cementation (bonding), are susceptible to degradation when the environmental conditions change, which are challenging issues for engineering works. In this paper, the changes in physico-mechanical properties of mudrocks were monitored in laboratory, and some influential factors on the mechanical competence of geomaterials were studied. The geotechnical characteristics and experimental designs were developed from physical, chemical, mechanical and compositional points of view. In the tests, the techniques such as vapor equilibrium technique (VET) were employed to apply wetting–drying cycles and to control relative humidity (suction-controlled) and loading–unloading cycles through ultrasonic wave velocities technique. The results show that the main failure mechanisms for the laminated mudrocks start on the microscopic scale by fissures coalescence, exhibiting physico-chemical degradation as well; the global geomechanical behavior presents a state between a ductile, like rock, and a fragile, like soil. The obtained results can provide engineering values according to monitoring laboratory set, when compared with in situ conditions.

1. Introduction

The mechanical behaviors, in particular the degradation of geomaterials, have traditionally been met with suitable ways of scaling effects of environmental factors, which determine the behaviors and responses of samples representative of the physical environments.

In fact, the behavior of a sample in laboratory could be substantially different from that of in situ rock mass. It would be very important to compare the structures of these two scales, attempting to incorporate, in the experimental program, all the environmental factors that influence the response of a rock mass of a clayey nature, especially of a laminated structure.

The studied material in this context is sedimentary rock composed of microscopic particles (diameter less than 75 μm) of clayey nature, in addition to the characteristics of degradability associated with its chemical–mineralogical composition. Although the material is “over-consolidated” clay in geological times, it presents a goal-stable character in most cases by finely laminated structure, whose resistance is mainly due to time that has withstood the weight of sediments above confining, and, to some extent, to the formation of “contacts” between particles or any minor amounts of any type of agent binder that may be present (bonding).

Digenetic consolidation processes experienced by the geomaterials are associated with events involving movements of the earth’s crust, including tectonic and massive erosion. Without considering the surface modeling due to engineering practices such as the construction of underground and shallow works, the mechanical properties of the material at the “beginning” of their training (stress–strain history) may have been affected. Therefore, the geomaterial develops different degrees of susceptibility to new processes, which arouses the interest in dealing with the present investigation (Fig. 1).

This work is based on a given susceptibility state of geomaterial and discusses the mechanisms that control the loss of mechanical behavior of sedimentary mudrocks, which are responsible for many stability problems in engineering works, such as underground and shallow excavations, foundations and fillings for various engineering structures. It is considered that within the

---

* Corresponding author. Tel.: +57 1 2440220.
E-mail addresses: camilogeotecnia@gmail.com, camilogeotecnia@yahoo.es (M.C. Torres-Suarez).

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jrmge.2014.04.004

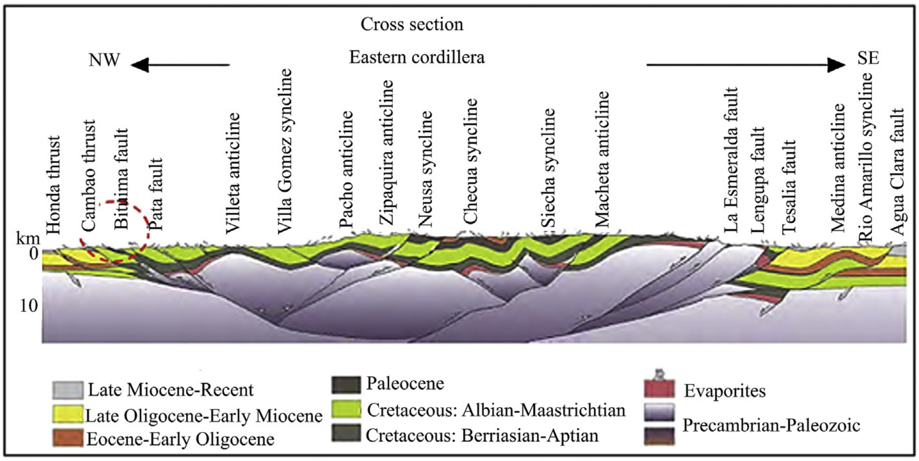


Fig. 1. Cross-section of the Eastern Cordillera of Colombia. From Hydrocarbon National Agency – HNA (Barrero, 2007).

mechanisms influencing the deterioration of the mechanical properties of these geomaterials, these are wetting–drying (w–d) cycles and unloading, usually associated with loading–unloading (l–u) cycles.

Obviously, these mechanisms are also developed in different scales and affect the material in a variety of ways. It is recognized that the physico-chemical degradation is the main agent to the structure of materials, little detectable by starting at the micro-structural level sometimes. In addition, the hydro-thermo-physico-chemical factors should be involved with mechanical effects of geomaterials.

In summary, it is a process of "accelerated" weathering, in comparison with that experienced by strongly cemented and consolidated geomaterials, such as the igneous and metamorphic rocks. These processes are significantly complex in characterization and even more in modeling, and also arise in different scales of observations, in which an experimental program is required to attend this wide diversity of processes and phenomena associated with properly delimited control variables.

This paper aims to elucidate part of phenomena of degradation of laminated mudrocks in the Colombian Andes, which is proposed:

(1) To explore and identify the main morph-structural features of rock formations in field, where laminated mudrocks predominate.
(2) To characterize the studied material, both in field and laboratory, from the physical, chemical and mineralogical points of view, and to determine its composition and relationships with its mechanical behaviors.
(3) To determine the main effects of degrading actions such as w–d and l–u cycles on the mechanical behaviors of geomaterials through implementing advanced laboratory techniques.
(4) To suggest models of mechanical behaviors which can properly describe the degradation phenomena through modeling laboratory tests.
(5) To propose practical technologies aiming at the characterization of mudrocks and the physico-mechanical behaviors during the construction of engineering works.

In the context, it is important to recognize the principal properties of the geomaterial as shown in Table 1.

2. Geo-engineering characterization of laminated mudrocks in the Colombian Andes

As the mudrocks are the geomaterials of sedimentary in nature, and particularly in this case with laminated structure, they have low void cementation and even little digenetic consolidation. Basically, they are formed in Andean tropics, regional environments of tectonic strongly active in mountainous region. Thus a careful process of identification and characterization of their constituent elements (Fig. 2) is required, for instance the scanning electronic microscopy (SEM) from the National University of Colombia, Bogota head in 2007.

2.1. Introduction to the characterization of mudrocks

In a broad sense, the characterization of a geomaterial must include determination of chemico-mineralogical composition, physical properties and indices, and basic aspects of their mechanical responses to normal loads, usually related to site-specific construction. Furthermore, the mechanical behavior of material in question is complex in its forecast, since it cannot be simulated by conventional models or features of goal-stable structure, thus some additional elements are required for engineering purposes.

Characterization activities of a geomaterial should not be performed by a standard or just as a simple fulfillment of requirements set out in standards or building codes. The adopted method must meet the specific needs of the project and especially the uncertainties associated with the lack of knowledge of the intrinsic characteristics of the material about the eventual response to actions during its useful lifespan. Therefore, non-destructive techniques are suitable in the initial stages of the characterization.

Many landslides and mass movements have taken place in dealing with argillaceous rock formations, even more when these are unavailable little or no cemented laminar, where the ground movements are initiated soon after certain excavation activities or simple exposure of the geomaterial to environmental changes.

The characterization of rocks presented here is part of the approach of the scales of observation, i.e. micro-, macro- and mega-structure, since it is found that various processes of damage or structural defects of geomaterials take place equally in different spatio-temporal scales (Torres and Alarcon, 2007), and consequently the geomaterial characterization must obey the real behaviors expected on the scale (Fig. 3).

This method includes the characterization of the material in terms of its mineral components, chemical processes and

Table 1
Index and global physico-mechanical properties for the mudrocks.

Basic parameters (Mohr–Coulomb)			Rigidity parameters				Advanced parameters				
Cohesion, c (MPa)	Internal friction angle, φ (°)	Dilatancy angle, ψ (°)	Rigidity modulus of ref. at 50%, E_{50}^{ref} (MPa)	Oedometric rigidity modulus of ref., $E_{\mathrm{oed}}^{\mathrm{ref}}$ (MPa)	Unload–reload modulus of ref., $E_{\mathrm{ur}}^{\mathrm{ref}}$ (MPa)	Exponent modulus, m	Unload–reload Poisson's ratio, n_{ur}	Mean normal stress of ref., p^{ref} (MPa)	Earth lateral coefficient at rest, normally consolidated, K_0^{nc}	Failure ratio, F_{r}	Tension stress, s_{tension} (MPa)
0.5	30	0	0.28×10^4	0.05×10^4	0.56×10^4	Variable	0.2	10	0.5	0.9	0

Fig. 2. The laminated structure of mudrocks (×50 times). SEM from National University of Colombia in 2007.

thermal associates, formation of microstructure and its influence on the mechanical behavior, as well as the main recent geomaterials characterization techniques, combining auxiliary geosciences such as geochemistry, geophysics and the geomechanics of materials.

Also, in the environment field (in situ), it is important to identify the main geological, geo-morphological and geo-structural features of the studied material through systematic application of methods and conventional procedures to identify geological structures (and the application of appropriate type of geological strength index (GSI)), in addition to geophysical field testing and the determination of the natural environmental conditions.

Comparing the characteristics of geomaterials determined in laboratory with those in field, it is feasible to establish relations of the expected behaviors and thus help to better explain the material response to certain actions during execution of engineering works. This is consolidated in a proposal of laboratory-field interaction, allowing in the future for optimizing modeling of these actions in a way representative of what is really happening to the material.

2.2. The characterization results of mudrocks

Identification and characterization of argillaceous rocks, laminated and little and/or no cemented as well as strongly degradable, are required before careful observation of the behaviors of these geomaterials in terms of the observation scales, i.e. scale of rock mass (mega-scale), samples in thin sections of the material (micro-scale) and laboratory (macro-scale).

Within this framework, it is feasible to integrate different elements and factors that affect the engineering behaviors of geomaterials, such as mudrocks studied in this work since they are naturally degradable, which are exposed to changes in environmental conditions during its geological history.

Based on the idea, it was proposed to advance a series of identification activities of constituent elements and minerals, which are naturally degradable by the actions such as pore water pressure, which soften and wash these soluble minerals. Consequently, its porosity is increased, leading to loss of

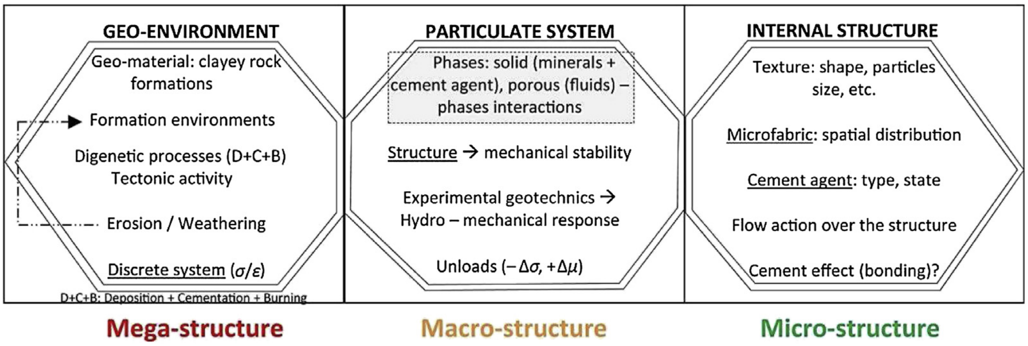


Fig. 3. Spatio-temporal scales relationship and key aspects to start laminated mudrocks studies (Torres and Alarcon, 2007).

structure integrity. Techniques implemented for this purpose are of recent engineering application and therefore require a high dose of integration between different disciplines related, such as geochemistry, hydrology, geology, geomorphology and sedimentology, etc.

In the characterization of rocks, it is necessary to scale macroscopic rocks that exhibit a strong lamination, which also gives a strong anisotropic character in terms of their hydro-mechanical behaviors, a perennial tendency to fail for those flat laminations. This feature represents an additional difficulty when attempting to extract intact samples, because stress relief and temperature changes can have immediate effects on the degradability of the samples.

In terms of physical indices of mudrocks, it is predictable for rocks in degraded state that they behave as such changes in humidity, leading to sensitive changes in unit weight. The range of drastic moisture changes of geomaterial is relatively small, with plasticity index of 10 and liquid limit of 30. Values for a muddy soil are evidently scattered since that material has a tendency to behave like liquid.

The presence of minerals such as pyrite is a factor that induces higher degradability of material, since iron sulphide is oxidized intensely, increasing the acidity of pore water and deteriorating the contacts between particles and therefore strongly deteriorating material structure. Even relative acceleration deteriorating rates are observed, depending on geological conditions and temperature changes. This in part can explain the changes in properties such as the density of the geomaterial.

Through a trial of slurry prepared with different water contents subjected to l–u cycles in a conventional oedometer, it is feasible to estimate the stress–strain history of the material possibly, at least from a point of view of lithostatic loads, which could have been submitted during geological times, as well as the events of large-scale removal in a condition similar to that occurred during its formation process (Fig. 4). The major changes are rising in rigidity of the geomaterial at different moisture contents. The point, reflecting geological history of material (in terms of lithostatic load), was obtained to extend intrinsic compression line (ICL) to an unloading path, coinciding with the point that reflects the actual state for the material (in situ).

Finally, through application of the suggested method, a reduction factor of mechanical properties can be proposed based on the determination of factors associated with wave parameters and spatial dimensions, which predominate in different observation scales of the environments considered (Torres, 2005).

3. Description of the wetting–drying cycles (controlled suction cycles)

The laminated mudrocks in the Colombian Andes are sedimentary rocks, which are more susceptible to degradation physico-chemically when compared to other rocks. In fact, the shale makes up more than 50% of the sedimentary rocks on the earth's surface and emerges in large regions of the territory in Colombia, dominated in the eastern mountains of the country. Environmental factors most affecting their mechanical behaviors are the w–d cycles, which will be treated in detail.

At the level of the in situ rock mass, the w–d cycles in combination with l–u cycles will destroy the structure of materials, as well as by the large-scale events experienced in geological history. Consequently, this will lead to variations in mechanical properties of rocks, i.e. the reduction of strength and stiffness degradation. This paper tries to determine the effects of the w–d cycles on the engineering behavior of mudrocks.

3.1. Introduction to the behavior by wetting–drying cycles

After a series of identification and engineering characterization of laminated mudrocks, i.e. on the scales of rock mass (mega-scale) in field and in laboratory (macro-scale), various procedures using the suggested method are required to investigate the effects of w–d cycles on these geomaterials.

Different alternatives, varying from the more traditional cycles with techniques to induce the slaking of the material to the most recent cycles based on the application of steam generated by chemical solutions, are exerted on the material with the same degradation effect. The vapor equilibrium technique (VET) has been implemented to meet this purpose. The VET allows implementing monitoring systems of changes in the properties of the geomaterials involved. In addition, it has a close relationship with the suction level experienced by the material, given that the chemical solution in question was developed to a certain relative humidity (RH) level but keeping other variables of the process constant.

A new technique is then applied to control the degraded materials subjected to the action of chemical solutions used. The stress state of the geomaterial is identified and the changes in their rigidity can be measured by determining elastic wave velocities during each of the phases under w–d cycles.

The experimental set-up in this investigation is based on an experimental design previously established, consisting of different samples of laminated mudrocks under w–d cycles through the VET. This technique not only allows the suction changes of the geomaterial, but also the monitoring of structure changes by measuring wave speeds. The technique is implemented to apply suction-controlled cycles consisting of prepared saturated salt solutions, which can generate different degrees of RH in closed environments. For this purpose, the salt solution was calibrated initially, in a way that its effect on specimens was previously identified, and in a sense whether these specimens were moistened or dried.

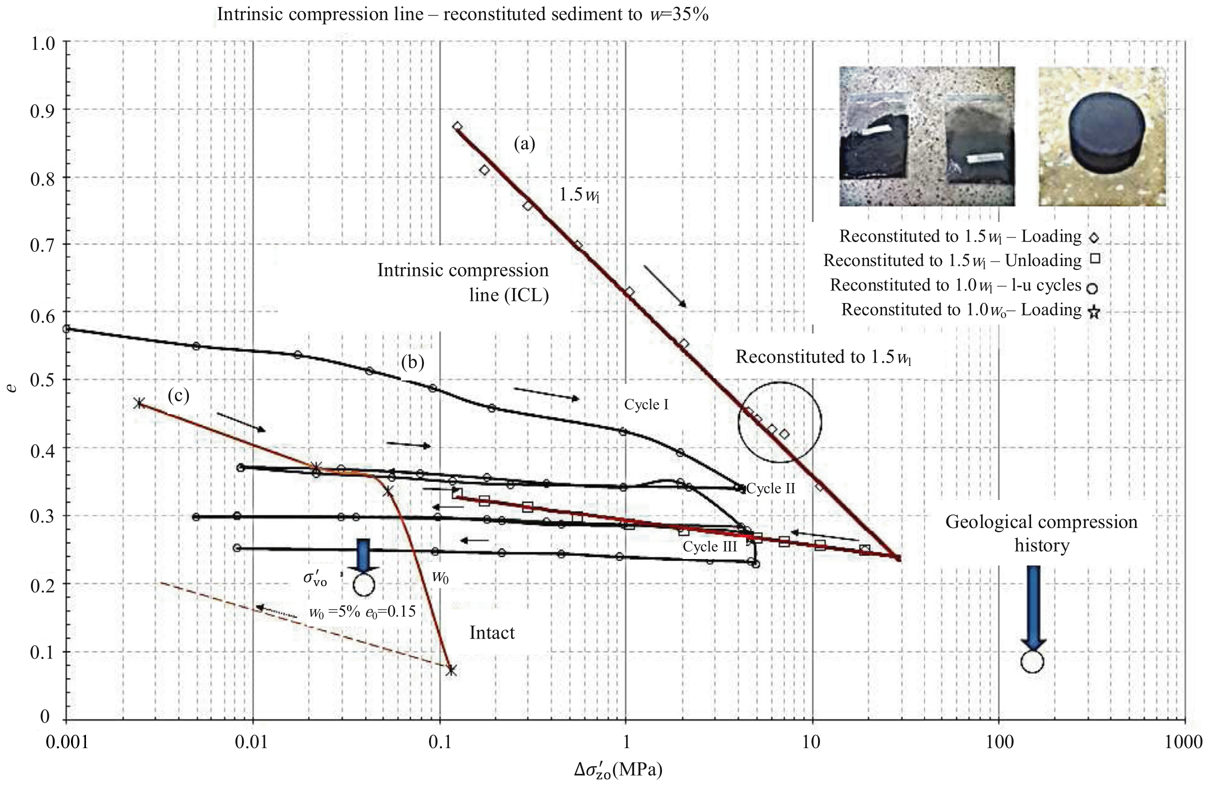


Fig. 4. Intrinsic compression curve for reconstituted mudrocks to moisture: (a) 1.5w_l; (b) w_l; and (c) w_n (Hernández and Torres, 2008).

During the implementation of the environmental conditions to the test materials, the changes in their physico-mechanical properties should be previously known, as they underwent w–d cycles. The weight of samples and other speeds of ultrasonic pulses were also measured in each stage through those samples (Fig. 5).

Generally, the intensely degraded samples went through all w–d cycles, and we obtained the variation of physical properties and reduction of mechanical properties. It is also advised that the VET is suitable for simulating environmental actions that affect the masses of mudrocks, not depending on the scale of the material in field. It is suggested that this tool is conducive to simulating weathering processes in laboratory that can be complemented by techniques such as centrifuge test. It can also model other environmental variables, e.g. solar radiation, precipitation, wind, even if they affect the material differentially due to the scale in which samples are commonly work.

Fig. 5. Samples during suction cycles imposed by the VET.

3.2. Conclusions about the behavior by wetting–drying cycles

Among the traditional techniques to evaluate the change of mechanical properties of geomaterials, in particular argillaceous rocks, there are the so-called trial slake-durability in different modalities, such as the modified form of Wood and Deo (1975), slaking in jar and the most recent in a No. 10 mesh rotating, or suggested modifications of covering the samples with tape micropore to reduce hydraulic gradient and slow material slaking.

All of these techniques induce rapid sample degradation, especially when the rocks are excessively soft and degradable. In this sense, this is the technique that implies not to submerge sample into water and permits monitoring of physico-mechanical changes during w–d cycles. Additionally, the effect of water on immersed samples has not been carefully evaluated, and sometimes it is the case that contributes to the process of deterioration of the material by the chemical nature of this.

A recent technique to evaluate the effects related to environmental actions, where changes in RHs are involved, is known as VET, and it is widely used by soil scientists to evaluate the moisture retention capacity of those geomaterials, determining points (humidity) as the dew, wilting, etc. A few projects in rock engineering are known to apply this technique, although in soil mechanics there have important developments in unsaturated soils.

When applying a RH in a controlled manner through using certain salt solutions to induce chemical materials subjected to these potential, the total suction applied to the samples is controlled at the same time under suction–RH relationship (Kelvin's Law). In this study, we used salt solutions with RH ranging from 40% to100%, which as a result means suctions varying between 120 MPa and 1.5 MPa.

The test design is composed of five groups of specimens, 13–16 elements in total, under the action of four prepared saline solutions in laboratory condition. It is expected that some samples are dried and others are humidified, depending on the saline solutions submitted initially (S1, S2, S3, S4 or S5). After a period of time when thermodynamic equilibrium, i.e. a "constant" humidity, is reached, the solutions were changed after a cycle completed, basically in a cycle of 20 days in each phase (Fig. 6).

Some of the specimens were subjected to one cycle, others to two and some of more than three, with a total of 150 days approximately. Other specimens undergoing three w–d cycles were subjected to a final phase of dampening up to 380 days, with the purpose to assess change in the physico-mechanical properties of specimens, as of intensely degrading materials.

According to the results in each phase, the saline solutions S1 (NaCl, $RH \approx 97.8\%$), S2 ($NaNO_3$, $RH \approx 75\%$), S3 (K_2CO_3, $RH \approx 50.5\%$) and S4 ($CaCl_2$, $RH \approx 41.1\%$) were employed. The tendency shown in Fig. 6 reflects that under similar water content for all conditions, the previously determined changes in physical properties are significant; the initial suction was determined according to the relations between water content at exploration depth and RH under the same condition.

In order to understand physico-mechanical changes under w–d cycles (controlled suction), a detailed monitoring of the properties of test materials was conducted, with initial moisture content and specific weight G_s. The first index was a numerical procedure while the second G_s measurements were conducted on different materials, ranging from intact rock to the most altered one.

Although the initial humidity determined for the major of specimens taken from boreholes oscillated around 4%, it is evident that this could be altered to some extent with elapsed time from the moment when the boxes were placed with the rock cores, or even when the process of characterization of materials began. This parameter variation had a standard deviation of 0.33%, and variation coefficient of 8.66%. On the other hand, the unit weight of the specimens was approximately 25 kN/m^3, less than that determined in pre-experimental stage of the work which was more than 30 kN/m^3, since this material was more superficial and thus was thought to contain more amount of disseminated pyrite.

3.2.1. Changes in index and physical properties

From the systematic measurement of the changes in the unit weight of the specimens with w–d cycles, we assumed that the weight of solids remained constant, which is considered valid for the technique applied (VET) during the three w–d cycles. An equation was then determined for each phase of each w–d cycle through a simple iterative numerical procedure, allowing to estimate the volumetric changes of geomaterials.

Change in G_s was determined upon various materials resulted from different environments, such as in situ rock mass or completely degraded river-bed geomaterial, soils derived from mudrocks, which were then compacted in laboratory and others like that. It is found that this parameter G_s varies from 2.82 for intact condition to 2.36 for the most degraded, averaging 2.76 after three w–d cycles applied.

Changes in various environmental actions, e.g. RH, are cyclical and eventually are used to reproduce field conditions, which would be modeled in laboratory, at least partially. The iso-areas of RH with elapsed time for three w–d cycles are also established (Fig. 7).

At the microstructural level, the observations in the SEM were conducted under different water contents corresponding to w–d cycles (ESEM), showing clayey matrix with occasional appearance of cracks after intense drying cycles, allowing the growth of crystals of calcite to form "chicken leg".

This could explain in part the slight "structuring" effect observed after drying, and, on the other hand, the reduction of

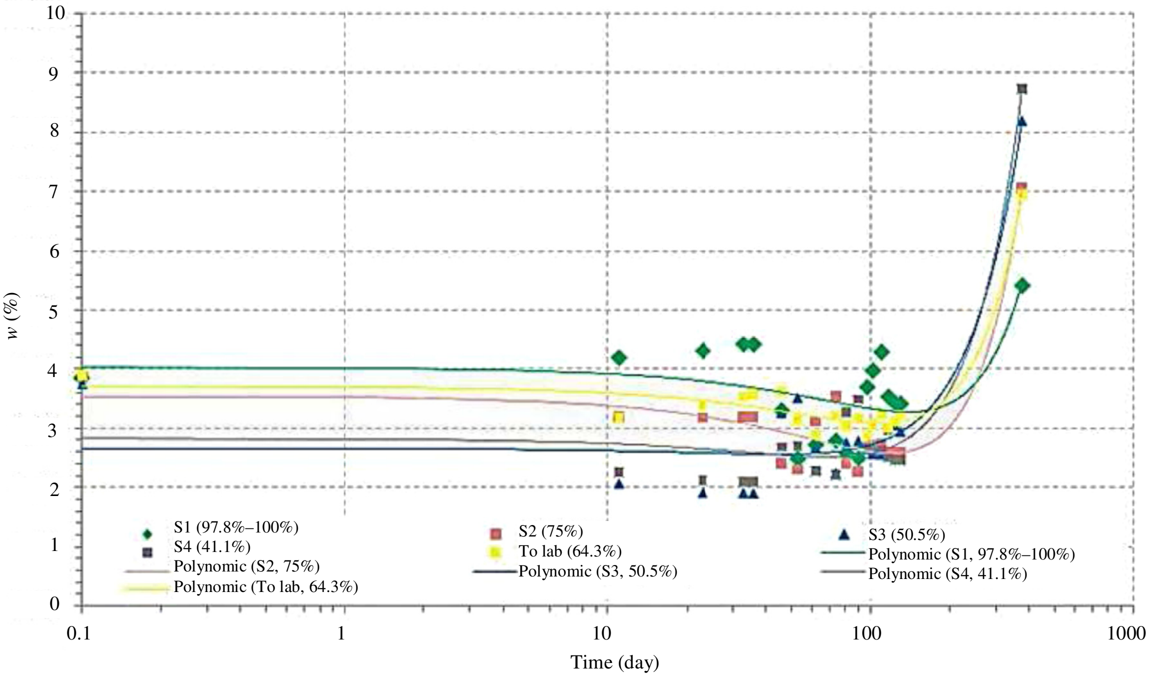


Fig. 6. Humidity vs. time functions for five groups of specimens according to initial suction (1st, 2nd, 3rd and final cycles).

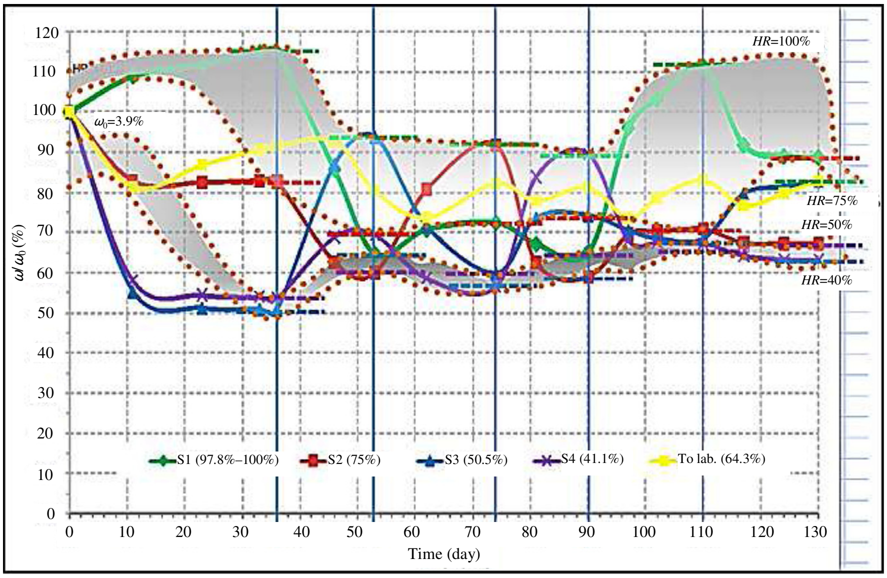


Fig. 7. Iso-areas of relative humidity vs. time for three w–d cycles.

resistance cycles, since the material fissuring is increasingly more. With the results ahead of electro-dispersed X-ray (EDX) analysis, the determination of slight changes in the contents of certain chemical elements, as larger amounts of Si and the presence of Sr in the most degraded samples regarding the least altered, was feasible.

Another way to identify effects on the material structure at the microstructural level was the implementation of the technique of nitrogen injection (BET technique) or sort-meter (adsorption/desorption curve). The BET technique can evidence the degrading actions in terms of a greater micro-porosity of the material that increased nearly 50% of w–d to the next cycle, an increase in the specific surface rising from 4.5 to 12 or 24 m^2/g of the intact condition to the degraded after a w–d cycle.

In the meantime, mercury injection porosimetry (MIP) technique is used to identify changes in porosity and the linkage of these changes with the pore sizes, i.e. macro-pores (>60 μm), meso-pores (10–60 μm), micro-pores (1–10 μm) and simple pores (<1 μm). At the same time, the changes in unit weight were determined using the penta-pycnometer. It is found that, for a w–d cycle, the real unit weight was 28 kN/m^3, while that after two cycles fell to 27.8 kN/m^3. In this case, the porosity was from 0.53% to 0.42% after two cycles.

All of these changes took place with variations relatively less than the water content of the material with the cycles, which varied between 1.5% and 9%, indicating thus a relative variability between −2.5% and 6% of “initial” values.

3.2.2. Changes in mechanical properties

Due to complexities implied in determining changes in geomechanical properties of this kind of laminated mudrocks, strongly degradable by their high susceptibility to change in environmental conditions, an indirect measurement of stress–strain properties was implemented through systematic measurement of velocities of elastic waves, V_P and V_S, in each of the stages crossing the specimens during w–d cycles (Fig. 8). In Fig. 8, 1.5, 40, 94, 123 are suctions in MPa for each phase of each w–d cycle applied by VET, and numbers before hyphen are the numbers for specimens.

This technique could advance a comparative analysis of the waves speeds on the two scales of the same lithological sites (mega-scale and macro-scale), for the particular case of mudrocks studied. A previously suggested procedure that involves statistically analyzing dimensional data of the rock mass and rock specimens was applied. It is found that these two scales are in relation of 1:0.03 (laboratory vs. in situ), suggesting that in situ geomechanical properties represent approximately 38% of those determined in laboratory.

It is also found that, after w–d cycles, almost all specimens tend to have a common percentage of relative deterioration in shear modulus (G), after three cycles, that is approximately 60% of the initial value. Such a result is important because independent of absolute value was obtained for each specimen, and thus the deterioration of the material structure is evident. This was checked by comparing the degradation of the modulus from its maximum value registered (G_{maxreg}), which does not necessarily correspond to the initial one.

3.2.3. Behaviors of geomaterials in situ vs. laboratory

We initially assessed the in situ behaviors of geomaterials in terms of variability of water content with depth. Please note that in general each of the specimens properly reflects the effect of the cycles and the curves move with elapsed time, either to one side or the other from the initial condition, which depends on a phase of drying or wetting underwent (Fig. 9).

The determination of the variability in resistance to compression is achieved through using a model that relates this property of sedimentary rocks to the speeds of waves. Results show that it varies between 8.0 MPa in intact condition and less than 0.1 MPa in conditions subjected to three w–d cycles, similar to muddy soils.

4. Description of the loading–unloading conditions

The laminated mudrocks in the Colombian Andes are geological materials with anisotropic behavior, precisely due to their fine laminated nature, which occurred during the processes of deposition of clay sediments (cretaceous age), associated with processes of consolidation and compaction and burial (digenetic) turn that allowed the formation of masses consistent with some degree of mechanical strength, by which are referred to as “soft rock”.

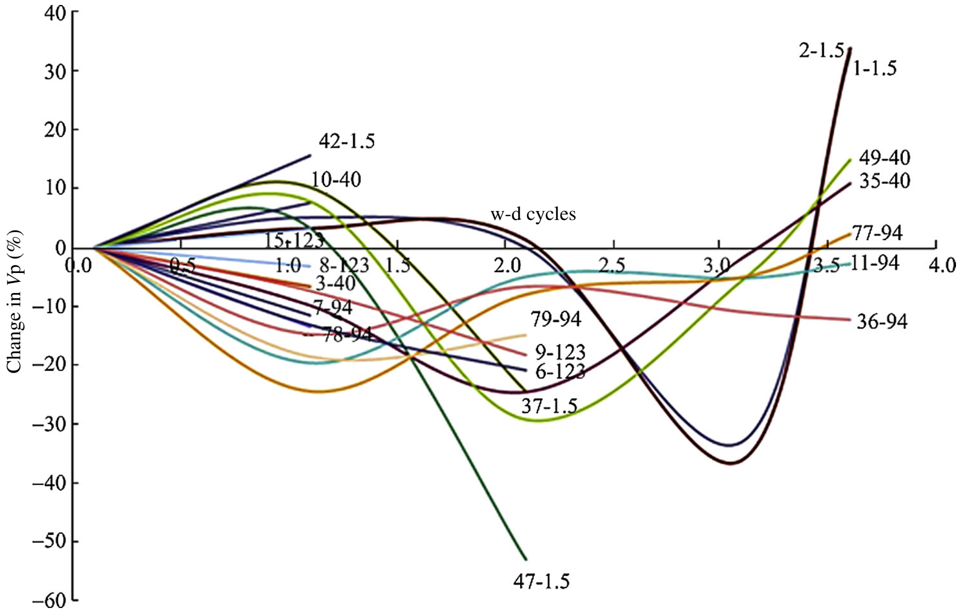


Fig. 8. Relative change in V_P from initial conditions vs. three w–d cycles.

The digenetic processes during the formation of these rocks took place also in marine or epicontinental (beach line) environments, usually under anaerobic conditions and calm water, where fine clay sediments underwent high lithostatic loads. This ultimately allowed generating digenetic links (bonds), providing the necessary material coherence so that it behaves mechanically as a rock.

In this section, we focus on the effects of specific actions such as the l–u cycles, a part relating them with intrinsic processes that could traverse the material during its geological history, and others are associated with anthropogenic actions by construction procedures, i.e. shallow and underground excavations which can induce significant changes in geomechanical properties of mudrocks.

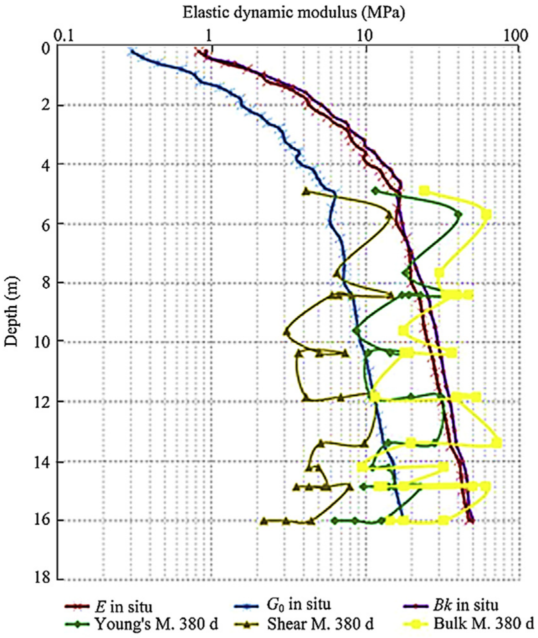


Fig. 9. Elastic modulus variability vs. depth, for in situ and laboratory (w–d for 380 days) conditions.

4.1. Introduction to behavior by loading–unloading cycles

The unloads have been recognized as one of the factors leading to the deterioration of rock masses of clayey nature (even large discharges can alter the very hard rock masses), in particular since the resistance and consistency of these geomaterials are largely just the preloads experienced during the geological history. Cyclic events of loads and unloads passing through the materials that make up the earth's crust are related to digenetic processes and erosion, which induces certain susceptibility or predisposition to degrade back to experience this type of actions due to engineering works (e.g. excavations, cuts and fills).

The effects of l–u cycles would be more obvious, if several states of alteration (degradation) of the material, which was previously induced by w–d cycles through the VET, are evaluated as several boundary conditions are applied, i.e. confined compression (triaxial) under axial and lateral compression (axial extension) or unconfined compression. With this purpose, a technique seldom used in rock mechanics was implemented to load the specimens up to a certain stress level, previously evaluated in a way that the material does not fail; then unload it to the reference stress established initially and finally reload it till failure. Sometimes several intermediate loading–unloading–reloading (l–u–r) cycles were made in order to fatigue the material and thus to evaluate construction procedures that may occur in practice.

We designed and manufactured two velocity transducers for P and S waves, which are attached to the compression system (Hoek cell) available in laboratory. These transducers are manufactured with steel of high resistance to support the stress induced by the l–u–r cycles mentioned above. In total, we performed about fifty mechanical tests in different models established (Fig. 10).

4.2. Conclusions about the behavior by loading–unloading–reloading cycles

Initially we presented some general considerations about what may involve the yielding of geomaterials under the actions of l–u–r cycles, because unloading has been previously recognized as

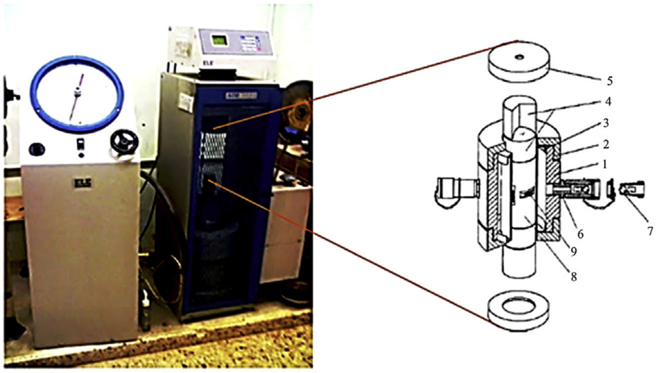


Fig. 10. Compression machines and confine unit, ELE International® and basic assemblage for chamber pressure, between 7 MPa and 70 MPa. Pieces 4 are changed by wave velocities transducers (Torres®).

one of the mechanisms that can induce deterioration of materials, especially those subjected to very high-level stress, such as underground excavations in hard rocks, thousands of meters deep.

Although the laminated mudrocks under study are currently on the surface, the sediments that formed them took place several kilometers deep, over time and by tectonic action. Due to this process, the rock stored a large amount of energy of deformation (Bjerrum, 1967), which is likely to move when the rock masses experience stress relief that may be associated with both w–d cycles and unloads.

In order to assess any changes in physico-mechanical properties of these materials under unloads, a unconventional technique in rock mechanics was required to implement in laboratory applied by l–u–r cycles under various forms of compression loads, i.e. unconfined and confined, with paths of axial or lateral compression (simulating test of axial extension).

Contrary to the above-mentioned situations where the w–d cycles were applied, the direct measurement of the specimens' deformations with compression loads applied became feasible, followed by electric type strain-meter attached to the walls of the cores. It can have the data related to the variation of strength and deformability when the l–u–r cycles were applied. However, in part due to procedural difficulties as well as the alteration conditions of various test specimens, sometimes the deformability data were complicated in reflecting the developments of geomechanical properties' change.

This modification allows to compare the variability of deformability (Young's modulus E, shear modulus G, bulk modulus Bk, and Poisson's ratio ν), in terms of P and S waves velocities with which the related loads of axial and lateral compression with unit deformations are obtained by the electric strain-meter adhered to the walls of test specimens. It is not always true that the moduli obtained with the first and other equipments are the same, since the first relates to loads of acoustic characters (ultrasonic pulses), sent by the emission and captured by the receiving transducer at the other end of the specimen, and the second is in direct relation to compression loads applied during the execution of the mechanical tests.

In such a way, some specimens after the first w–d cycle were then subjected to compression, others with two previous w–d cycles were also tested in compression machine and finally some of those after three previous w–d cycles were also submitted to the above charges. In relation to the mechanical tests above-mentioned, some specimens were subjected to unconfined compression loads, while others to confined compression loads: axially and laterally.

In order to evaluate the physico-mechanical changes of the testing material during l–u–r cycles, some properties such as water content were investigated. The specimens were weighed before and after the test and the average variation was assumed for the purpose of determining the weight with which to establish its suction level during the mechanical test, whereas its variability was low (less than 2%) and in some cases there was no change.

4.2.1. Changes in index and physical properties

The appropriate equations were used to determine the average value of humidity of the specimens during the test, and the changes in specific volume, which depend essentially on the void ratio estimated from a numerical procedure, also developed in this work. The initial condition of the test was assumed in terms of the readings of the strain-meter. It shows that the above-mentioned changes in G_s were considered to be insignificant, and not changes in the material structure were observed in association with the development of cracks and sliding planes which were some thin sections. Thus it would enable to identify a pattern of behavior mainly due to the scale on which these observations were made.

Moreover, observations of samples by means of the SEM allow demonstrating that the generation of surfaces at the macro-scale is seen as polished but at the micro-level, it is obviously altered with mechanical actions. A way to evaluate the change in the material structure under the l–u–r cycles consists of the measurement of sound waves velocities before and after applying the mechanical actions. During the pre-experimental research, an exercise of this kind was made, from which a reduction by close to 26% of the average value in V_P between intact specimens and specimens after failure by unconfined compression stress was determined.

Finally, it is manifested that the index and physical properties changes associated with the l–u–r cycles are relatively less in comparison with those related to the w–d cycles, but not those properties in view of engineering sense such as consistency, slaking, specific gravity and volumetric change, etc. The results of chemical–mineralogical analysis are not evident since the mechanical loads are applied in a short period (a few hours) and therefore the development is not complete.

4.2.2. Changes in mechanical properties

As suggested previously, changes in geomechanical properties associated with l–u–r cycles are relatively simple in its determination, given that the specimens are monitored through electrical strain-meters attached to its side surface. These strain-meters basically have components attached in two directions, i.e. one longitudinal to the axis of the rock core and the other in transverse direction. However, the direction of the planes of natural sedimentation of material is at 30° with respect to the axis.

It is noted that the preliminary tests of compression failure loads on a mudrock specimen are not subjected to preconditions of alteration. The speed of P waves exhibits a sustained increase of 20% from the beginning of the test until the end, while that of S waves remains essentially constant. This is reflected in the modulus of deformation. The Young's modulus (E) and bulk modulus (Bk) also increase from 20% to 25%, while the shear modulus (G) although seems to remain constant, actually it exhibits from a nearly 30% increase of its initial value to the maximum.

Lateral deformation modulus elsewhere, i.e. the Poisson's ratio (ν), exhibits a relative increase of 40%, showing that this material is degraded progressively when undergoing compressive loads. These results are based on the analysis presented below, as a summary that are described before (Fig. 11).

5. Hydro-mechanical coupling analysis

For nearly half a century, the laminated mudrocks in the Colombian Andes exhibited a complex engineering behavior, at the same time they were misunderstood, due in part to the insufficient scientific research. This misfit prevented us from characterizing materials in their natural condition, and still led to the delayed development of testing procedures that might be suitable for assessing the change in geomechanical properties.

This investigation responds, to some extent, to a yearning for professionals related to the area of geotechnics. For decades, those who tried to approach this material must adhere to inherent limitations in the evolution of equipment and tools as implemented on this work. This section presents an integrated analysis of various factors and variables that have been considered during the investigation process, in particular in relation to the effects associated with w–d and l–u cycles. It has been determined that such actions represent the factors of increasing incidences in deterioration that the mudrocks have experienced.

The stress–strain behaviors of mudrocks degrade in a unique way compared to most other lithologies, due to the chemical–mineralogical composition. The degradation phenomenon of geomaterials has been studied by researchers in the world, but one should recognize that this work is pioneering, because it combines the characterization of natural materials of high complexity and considerable “fragility” on one hand, and suitable techniques to monitor the physico-mechanical changes in the material against the degrading actions, on the other hand.

5.1. Mechanisms of rocks failure

The main mechanisms of rocks failure are described: uniaxial tension, uniaxial compression, direct cutting and triaxial compression. Elements that control failure modes, intrinsic material, related systems, and measuring equipment, are indicated. For example, the uniaxial compressive strength is dependent on the shape, size, ratio of slenderness and intrinsic anisotropy of the material, as well as the relationship of stiffness between load plate and test specimen.

In addition, the specimens in terms of rock mechanics should meet dimensional requirements—physical integrity, e.g. small defects in flat faces or missing in the body of the test core, for the stress concentrations are induced involving the material conditional failure. This is one of the main difficulties to test soft mudrocks which are susceptible to landslides and surface defects.

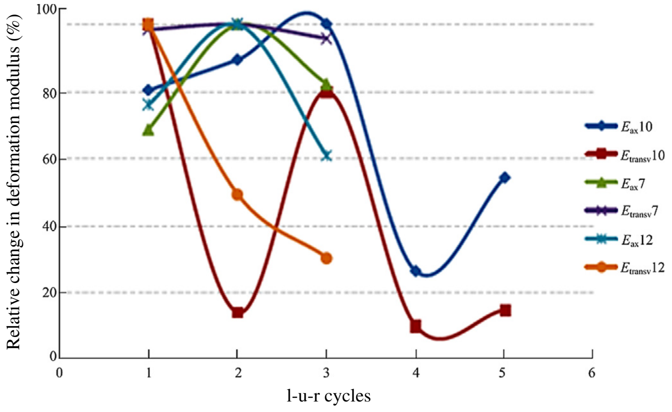


Fig. 11. Relative change in the deformation modulus, triaxial compression with one w–d cycle previous. The numbers next to moduli (E_{ax}, E_{transv}) are the confining pressures in MPa; “ax” is axial load and “transv” is transversal-lateral load.

However, as discussed previously, it is found that both unconfined and triaxial compression tests highlight the nature of the material and susceptibility to change in environmental conditions, including those related to the stress state (normal and shearing) and the suction caused by w–d cycles. Another aspect that could not be verified in this investigation is related to the post-peak behavior. A stress–strain type II curve due to the nature of the material is feasible (Wawersik and Fairhurst, 1970), associated with the release of a greater power than the required deformation to failure of the material.

Failure mode is related to formation of micro-fissures (defects) and their subsequent propagation, also called “coalescence”. Some detachments of material are generated in the direction of load applied, thus it seems appropriate to describe the physical degradation of these rocks. However, one should remember that the effects involve physico-chemical and morph-structural alterations that have been described above. This failure mode was preferentially observed during the experiments, both under l–u–r and w–d cycles, the latter in connection with changes of suction.

5.2. Stress–strain behavior of mudrocks

General concepts related to stress–strain behaviors of rocks are applied to the studied material, given that the chemical–mineralogical composition of shales from other latitudes is significantly different from that observed during this investigation. In this sense, argillaceous rocks degradation, widely studied across the world, appears to be more controlled in the micro-laminated structure-bearing Andean rocks in view of slake-durability properties as being believed until now.

Clay yielding expected surface occurs at center line K_0, while for soft rock and residual soils, one should focus more on the line representing isotropic consolidation of material. From this interpretation, the developed numerical models pose a structural arrangement based on packages of clay (added), surrounded by spaces with some material cement (bonding) and macro-structural voids. These models are not applied to the physical nature of the rocks of the study, whose structure is subjected to lithostatic loads.

Consequently, the determination of structuring parameters or expansion index is an even more complex task than obtaining representative specimens, due to the wide variability of physical conditions of test rock cores and also due to the limitations of equipment that does not allow the application of different paths of stress to identify such yielding surface. According to some authors, the soft sedimentary rocks exhibit a behavior similar to manifest soils transiting from a condition usually bonded to another overconsolidated, depending on the material intrinsic compression line.

Bonding can be represented, for the case of mudrocks with low to no cementation, by links of digenetic nature generated by lithostatic loads. Bonding can also be broken during unloading by erosive processes on a large scale or cut due to shallow excavations of engineering. However, it seems more complicated to model damage on links of this type to establish a damage law for cementation, physically characterized by its volume occupied.

5.3. Models of stress–strain behavior of argillaceous rocks

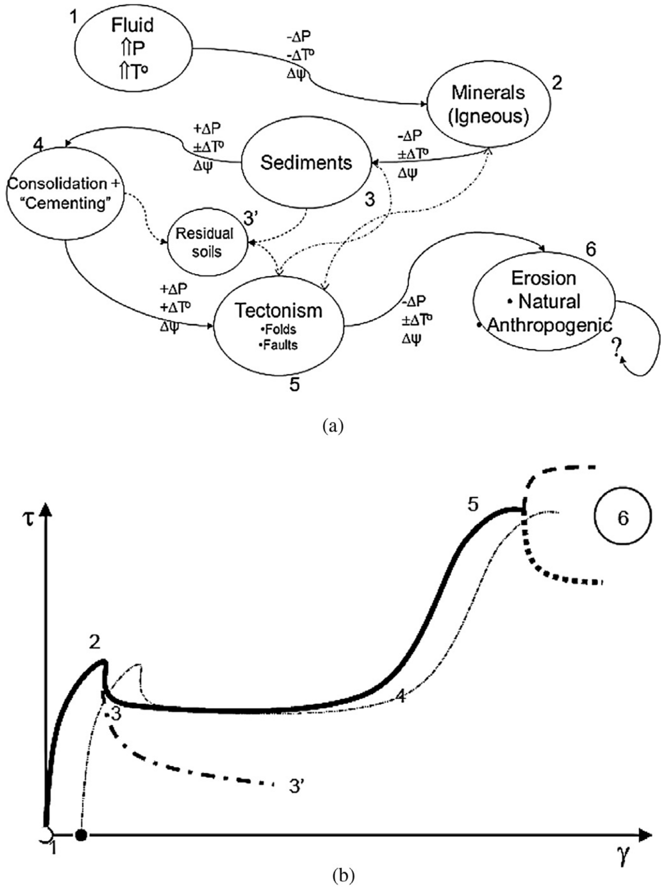
At this point, the stress hardening in the model and the soft soil is needed. The first is based on a relationship between triaxial rigidity and oedometer stiffness with applied stress by an exponent m, relativizing the stress with a reference pressure. The model works in a similar way to the so-called hyperbolic model, without considering the shape of the σ-ε curve as a hyperbola, but considering the relationship between rigidity modulus and deviator stress. The hardening model describes well the initial part of the $\sigma-\varepsilon$ curves of test rocks, but globally it fails.

The limitations of the numerical code do not allow adjustment of parameters that define the rigidity modulus, but that incorporated by user within certain prescribed limits.

5.4. Integrated analysis of wetting–drying and loading–unloading–reloading cycles in the stress–strain behavior of mudrocks

The analysis starts with observing the material through a geological–geomorphological process associated with deformational history in particular. And then, any structural changes experienced by the material based on these processes are identified at different scales of observation proposals, i.e. mega-, macro- and micro-scales, in the suggested framework of this work. The first relates to the scale of the rock mass, so the events that have affected the rock are studied in view of the tectonic and massive erosion of geomaterial.

On the macro-scale, the geomechanical properties are studied by testing the physico-mechanical characterization of samples in the laboratory. On the micro-scale, the chemical–mineralogical compositional factors are analyzed as well as the spatial distribution of components and phases in which they are organized, i.e. speaks of texture and their interaction with environmental actions that affect them. With a clear scale definition in this study, it is more practical to establish the relationships between them, and to determine incidental factors and to develop techniques that can be deployed (Fig. 12).



(a)

(b)

Fig. 12. (a) Mudrocks formation processes (key → ΔP: pressure changes; ΔT: temperature changes; $\Delta\Psi$: structural changes; increasing [+]; reducing [−]). (b) $\sigma-\varepsilon$ curve sketch corresponding.

6. Discussion and conclusions

This section describes the main findings, conclusions and recommendations of this study on the basic behaviors of mudrocks, particularly those that exhibit low contents of cementation and a laminated structure, known as "lutites" in the middle and known as "shales" internationally. These two denominations are applicable to certain types of mudrocks.

Phenomenon of degradation of mudrocks is significantly complex and involves large interdisciplinary efforts and creativity when characterizing them with engineering purposes. It has been found that the actions, such as the exposure to changes in environmental conditions with respect to those during its geological formation, strongly influence the development of deterioration mechanisms, with mega-scale structural failure involved in rock masses.

Considering that research in our midst on degradation of mudrocks was poor compared to the large areas where they emerge, particularly in the Eastern Cordillera of Colombia, this work dedicated much to the establishment and implementation of methodological procedures that facility identification and characterization of this type of geomaterials.

The other essential issue was the implementation of actions that degrade the material through the implementation of techniques that systematical progress in advance would allow monitoring the material changes. This was developed through the application of w–d cycles in the first stage of the investigation, and finally with the implementation of l–u cycles, during simple and/or triaxial compression tests (Fig. 13).

Parallel to the experimental development of the study, the inspection of some variables that were considered essential was performed in the determination of degradation processes. In this sense, the application of non-destructive techniques such as pulse-wave-speed measurements, ultrasonic technique, to field and geophysical tests allowed us to establish reduced physico-mechanical properties between two scales, i.e. macro-scale in laboratory and mega-scale in field.

The works developed under observation (micro-) scales, such as photographs by microscope SEM and TEM, technical XRD, XRF, MIP, BET, analysis of thin sections, TGA, SDC, were critically important, which contributed to characterizing the studied material and fully understanding the geomechanical behaviors in various deterioration stages.

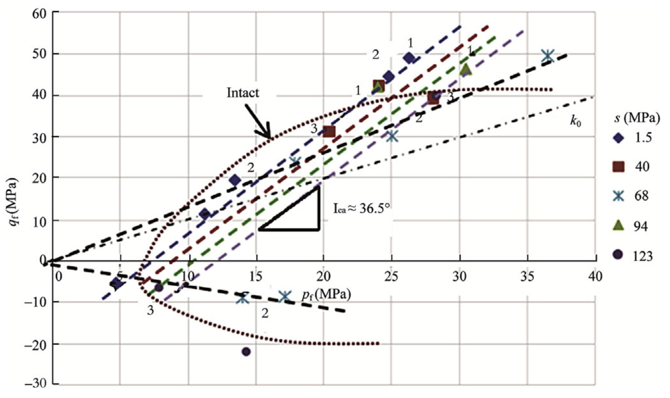


Fig. 13. Triaxial strength variation with suction and w–d cycles on the failure. q_f is differential stress at failure; p_f is mean normal stress at failure; and I_{ca} is the slope tendency at axial compression.

The work sought to elucidate part of phenomena of degradation of laminated mudrocks in the Colombian Andes, considering that are fairly complex materials and thus claiming full determination would be uncertain since the integration of complementary behaviors at different scales is still in the way. The main specific conclusions may be drawn as follows:

(1) This work is to investigate the geomaterials of rock and soil through monitoring the major changes experienced by the materials, but not through simply immersing rock fragments in (distilled) water until its full slaking, as performed by many researchers in rock mechanics. It considers that this may be one of the significant advances in the field of mudrocks, for determining geomechanical behaviors during the whole physical process in geomaterial degradation with similar characteristics is rarely reported.
(2) Scaling changes in environmental variables and their effects on the geomechanical behavior of rocks were achieved by the VET. In a sense, the application of this methodological procedure was proposed for the first time in the scientific research, i.e. the determination of scale factors or physico-mechanical properties reduction.
(3) The suction changes induced by the stress state variation of the material through changing the RH of the generated environments during w–d cycle scan affect significantly their structure when pressure intervals exceed 120 MPa. These w–d cycles are perfectly equivalent to the l–u cycles, since they affect the average effective stress in addition to chemical–mineralogical processes, which were observed through the SEM, IMP and BET during the w–d cycles.
(4) The l–u cycles constitute suitable mechanical tests to assess the effects of construction procedures, such as cuts, fills, excavations, and supporting that can affect these geomaterials. The geomaterial behaviors were susceptible to the uncontrolled release of deformation energy, and consequently failed, e.g. the mechanism of “progressive failure”, commonly observed in clayey materials. The destruction of the material begins on micro-scale and progresses to other scales. For this, real-time ultrasonic technique during various phases is considered, in addition to the systematic implementation of other techniques to monitor the physico-chemical changes induced by the prescribed degrading actions.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References

Barrero D. Colombian sedimentary basins: nomenclatura, boundaries and geology, a new proposal. Bogotá: Agencia Nacional de Hidrocarburos; 2007 (in Spanish).

Bjerrum L. Progressive failure in slopes of over-consolidated plastic clay and clay shales. Journal of Soil Mechanics and Foundation Division, ASCE 1967;93(SM5):3–49.

Hernández Ch, Torres MC. Ensayos de consolidación edométrica sobre lodos reconstituidos de rocas lodosas. Bogotá: Universidad Nacional de Colombia; 2008 (in Spanish).

Torres MC, Alarcon A. Some aspects of degradability of argillaceous rocks. In: Proceedings of the Preservation of Natural and Rock Weathering Workshop. London: Taylor and Francis Group; 2007. pp. 67–74.

Torres MC. Utilización de los métodos no destructivos para determinar propiedades físico – mecánicas en rocas sedimentarias. M.S. Thesis. Bogotá: Universidad Nacional de Colombia; 2005 (in Spanish).

Wawersik WR, Fairhurst C. A study of brittle rock failure in laboratory compression experiments. International Journal of Rock Mechanics and Mining Science and Geomechanics Abstracts 1970;7(5):561–75.

Wood LE, Deo P. A suggested system for classifying shale materials for embankments. Bulletin of the Association of Engineering Geologist 1975;12(1):39–55.

Mario Torres obtained MSc and a PhD from National University of Colombia, Bogota, Colombia. He is a professor of Geotechnical Engineering at the National University of Colombia in Bogota where he has been Leader of the Research Geotechnical Group – GIGUN of the University and member of the Colombian Geotechnical Society – SCG as well as the Engineers Colombian Society – SCI. He has been involved in geotechnical research, consulting and education for about 15 years. He is the author or co-author of more than 20 scientific and academic papers and he sits in the Editorial Board of several National Journals as Colombian Geotechnical Journal and the Journal of the Engineering Faculty of Gran Colombia University. He is a core member of TC on Hard Soils-Soft rocks of the ISRM. In recent years, he has been president of the Colombian Geotechnical Society (2010–2014 and 2014–2016), Secretary (2006–2008) and Vice-president (2010–2012) of the Board. Actually, he is the President of the Geotechnical Committee of Engineers Colombian Society, and participates in Expert Panels of Tunnels for ultimate generation of highways concessions in Colombia. As a professor and researcher, his work is focused on micro-mechanical degradation processes, tension states of rock masses and non-destructive techniques for characterization of rocks, with emphasis on establishing scale relation between rock mass properties and specimens properties.