Effect of wetting/drying and heating/cooling cycles on geomechanical behavior of mudrocks in the Lutitas de Macanal formation

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Abstract. The mudrocks are weatherable materials, an intrinsic condition of mineralogy and sedimentary formation. In the Eastern Cordillera of the Colombian Andes lies this rocky material, which implies the degradation of physical and mechanical properties in the face of environmental factors, such as changes in humidity and temperature that are intensively propitiated in the tropical climate of the region, factors not considered in the design of civil works. The present study determines an experimental procedure in laboratory to reproduce the effect of the cycles of wetting/drying and heating/cooling in conditions and periods similar to the original ones of the geomaterials, by means of the steam equilibrium technique and thermal change, the processes were carried out on rock cores extracted from the Lutitas de Macanal formation that emerges in the municipality of Pajarito, Boyacá, Rancheria sector, Colombia. The results quantitatively determined the degradation of Young's module and the resistance to uniaxial compression with the applied treatments, having a greater effect on the heating/cooling cycles in a period equal to that of wetting/drying generating greater damage to the rock due to pronounced cracking.

1. Introduction
All The mudrocks are geomaterials known as compaction shales developed during diagenetic pressures, mainly because they have supported the weight of overlying sediments, in other words, these rocks have poor or non-existent cementation and deteriorate very quickly once exposed to atmospheric agents [1]. The particles of these rocks are so small that they cannot be easily identified and, for this reason, these rocks are of inferior quality within the set of sedimentary rocks, their properties are not satisfactorily characterized and correlated, given their particle size and microscopic character, being difficult to explore, sample and test [2-4]. The mudrocks with the same description of mineralogical composition can have very variable results, since they are intimately linked to the formation genesis and the microstructure composition [5].

The disintegration and/or decomposition of rocky materials on the surface are meteorization processes that are controlled by climate variables such as temperature [6] and humidity [7], producing mechanical fracturing of the rock. The characterization of the effects of physical meteorization, such as moisture in rocks, are usually studied with saturation processes by immersion and quick drying in...
the kiln [8-12]. In addition, other investigations are oriented to the abrupt environmental changes of wetting/drying (W-D), heating/cooling (H-C) and freezing/thawing cycles [13-15].

Previous studies have identified that changes in humidity and temperature generate degradation of the physical and mechanical properties of the rocks, but this evaluation in many cases is carried out using methods such as saturation and rapid kiln drying that imply violent changes in the conditions of the samples; for mudrocks the previous laboratory procedures are neither representative nor applicable [1]. Considering the above, the present article aims to determine the effect of laboratory reproduction of environmental agents such as the W-D and heating-cooling H-C cycles, taking into account the respective time periods in which these factors influence the study site.

2. Methodology
The methodological process developed in research is described below.

2.1. Study area and field data
The study site is located in the eastern mountain range of the Colombian Andes, on the formation Lutitas de Macanal (Kilm), rocks characterized by being a set of black fissile shales that were deposited in a marine environment, of shallow waters in a closed basin [16]. The samples of analysis are located on the upper limb of this formation member C (see Figure 1).

Figure 1. Point of study and local geology.

The point of study lies in the geographical coordinates; Latitude 5°26'37.16 "N and Longitude 72°42'33.61 "W. The rocky massif has a laminated structure, the orientation and inclination of the strata is 313/15°. This area is subjected to intense tectonic activity influenced by two local faults; these normal faults cross the rock mass near the N-S sampling point with a tendency towards SW, observed in Figure 1. The characterization of the rock mass finds four families of discontinuities, a rebound number (RN) of 16 in the Schmidt hammer test. The classification of the rock mass gives a class IV RMR quality index with a value of 27 points. Relative humidity (HR) fluctuations in the area of interest vary between 54% and 87%, according to the Corinto meteorological station of the “Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM)” [17], located 15 km from the area of interest. The insolation temperature was measured in the field with a laser thermometer (Xueliee GM320), obtaining average minimum and maximum data of 8 °C and 52 °C, respectively.

2.2. Characteristics of the material
According to the materials analyzed below, a description is presented.

2.2.1. Sampling and sample preparation. Blocks of mudrocks were extracted from the rock mass to obtain in the laboratory cylinders of 34 mm in diameter and height/diameter ratio of 2. The cores of muddy rock have a vertical disposition according to the orientation of the stratification, that is, perpendicular extraction to the sedimentation plane.
2.2.2. **Physical and mechanical characteristics.** The physical and mechanical properties of the geomaterial can be evidenced in Table 1. The influence of the water when it has contact with the material, was made with the durability and desleimiento test with the wood and doe’s modified method [18,19], consisting in applying five cycles of saturation by immersion and later drying to the furnace, the desleimiento index calculated was low; with a is of 2.2%.

| Table 1. Physical and mechanical properties of mudrocks. |
|----------------------------------------------------------|
| Specific gravity  | Dry density (Kg/m3) | Void ratio | S-speed of wave (m/s) | Point load resistance (kPa) | Liquid limit (%) | Plastic index (%) |
| 2.77             | 2377                | 0.151     | 432                  | 30                           | 25.7            | 6.3              |

2.2.3. **Mineralogical characteristics.** The knowledge of the material was complemented with the mineralogical characterization by means of X-ray diffraction tests (XRD) and petrography by thin sections, with these methods of analysis it was identified that the rocky sample has a plastic-clay compositional texture, of medium gray color, laminar partition and poor fisility, the grain sizes of the average composition were 89% of sizes smaller than (5 μm) and 10% of sizes near (50 μm). The minerals found are shown in Figure 2 and Figure 3.

![Figure 2. Photographs Panoramic micrography illustrating relationship, granulometry and shape of the components. Quartz (1), goethite (2), clay (3), shamosite (4), opaque pirit (5), opaque carbonaceous matter (6), crossed and parallel nicols (XPL and PPL) respectively. Magnification 100X.](image)

![Figure 3. XRD test results, finding quartz, montmorillonite, moscovite and chamosite minerals.](image)

2.3. **Treatments of humidity and temperature changes in the laboratory**

The temperature changes were applied with a digital electric oven and a digital electric refrigerator with constant temperatures of 52 °C +/- 2 °C and 8 °C +/- 2 °C, respectively.

The moisture changes were carried out by means of vapor equilibrium technique (VET), these techniques work by transferring steam from a saline solution, in such a way that after a certain period of time a balance is achieved between the potential of the solution and that acquired by the soil.
[1,20,21], as it is observed in Figure 4 and Figure 5, using saline solutions inside hermetic containers, such as sodium chloride (NaCl) in the humid branch and calcium chloride (CaCl2) in the dry branch. The RH measurement inside the vessel was recorded with a hygrometer (AMPROBE TMA40-A). After placing several test samples in the containers with saline solutions, they do not change the weight with an accuracy of 0.01 gr after 20 days [1].

The change of RH versus temperature for a saline solution composed of water and NaCl varies very little [21], however, the RH of the CaCl2 solution is variable with temperature, for this, the dosages of CaCl2 were developed to obtain the RH of interest for each of the temperatures to which the rock cores are to be subjected, as they are in the refrigerator at 8 °C, ambient at 20 °C and oven at 52 °C, observed in Figure 4.

The changes of moisture and temperature on mudrocks nuclei were designed to consider environments that include H-C treatment, W-D treatment and simultaneous treatment of W-D and H-C, as shown in Figure 4. The previous treatments are executed in two cycles, to subsequently perform the uniaxial compression resistance test in compliance with the ASTM technical standard [22].

3. Results and discussion
During the W-D and H-C cycles, fissures and surface fractures were identified; these features on the mudrocks cores are of greater intensity in the treatments involving the H-C cycles see Figure 6. The reaction of the minerals to changes in temperature and/or humidity is due to volumetric changes [23], this characteristic being more repeated in the H-C cycles, due to the fact that they suffer this temperature differential on a daily basis. The above behavior validates the observations in the field where the rock expose to the surface presents fracturing and detachment of blocks.

Figure 4. W-D, H-C and simultaneous W-D and H-C treatment cycle.

Figure 5. Moisture change (W) with cycles in each treatment.

Figure 6. Superficial fissures with each of the treatments in two cycles of caused by: (a) H-C treatment, (b) H-C and W-D treatment and (c) W-D treatment.
3.1. Degradation of geomechanical resistance
The execution of the uniaxial compression test with measurement of the axial deformation on the mudrocks, allowed to determine and quantify the degradation of the resistance by changes in humidity and temperature, related to the modification of the internal structure of the material, especially the increase of pores [24]. The maximum compressive strength (σc) and Young's modulus tangential to 50% of the maximum strength (Et) are presented in Table 2. The test on each of mudrocks cores was carried out on the dry branch, after the corresponding cycle and treatment of H-C, W-D and simultaneous H-C and W-D. The arithmetic average of the results of σc and Et was calculated, identifying a reduction of the geomechanical behavior in each treatment applied (see Figure 7). In addition, there is the degradation percentage of σc and Et, this was calculated by comparing the average of each treatment and its cycle, with the average of the zero treatment.

Table 2. Results of uniaxial compression tests to mudrocks cores subjected to H-C, W-D and simultaneous H-C and W-D treatments, up to two cycles.

| Treatment | Humidity (%) | Σc (MPa) | Average σc (MPa) | σc % degradation | Et (GPa) | Average Et (GPa) | Et % degradation |
|-----------|--------------|----------|------------------|-----------------|----------|-----------------|-----------------|
| 0         | 1.43         | 12.61    | 9.37             | 0.58            | 0.34     | 0.46            |                 |
|           | 2.10         | 6.57     |                  |                 | 0.34     |                 |                 |
|           | 1.33         | 8.93     |                  |                 | 0.47     |                 |                 |
| Cycle_1   | 1.17         | 7.82     | 6.94             | 25.9            | 0.52     | 0.45            | 3.5             |
|           | 1.69         | 3.48     |                  |                 | 0.39     |                 |                 |
|           | 1.27         | 7.99     |                  |                 | 0.58     |                 |                 |
|           | 1.44         | 8.49     |                  |                 | 0.31     |                 |                 |
| Cycle_2   | 1.55         | 2.95     | 4.72             | 49.6            | 0.31     | 0.38            | 17.5            |
|           | 1.48         | 4.25     |                  |                 | 0.50     |                 |                 |
|           | 1.23         | 8.61     |                  |                 | 0.55     |                 |                 |
|           | 1.65         | 3.09     |                  |                 | 0.18     |                 |                 |
| Cycle_1   | 1.41         | 1.44     | 3.74             | 60.1            | 0.21     | 0.29            | 38.1            |
|           | 1.75         | 2.08     |                  |                 | 0.35     |                 |                 |
|           | 1.78         | 7.70     |                  |                 |          |                 |                 |
| Cycle_2   | 1.57         | 1.94     | 3.63             | 61.3            | 0.18     | 0.24            | 48.6            |
|           | 1.79         | 4.31     |                  |                 | 0.21     |                 |                 |
|           | 1.67         | 6.44     |                  |                 | 0.36     |                 |                 |
|           | 1.97         | 1.81     |                  |                 | 0.21     |                 |                 |
| Cycle_1   | 2.15         | 2.04     |                  |                 | 0.25     |                 |                 |
|           | 2.22         | 1.26     | 1.92             | 79.5            | 0.17     | 0.24            | 47.5            |
|           | 1.57         | 2.47     |                  |                 | 0.31     |                 |                 |
|           | 1.20         | 1.13     |                  |                 | 0.11     |                 |                 |
| Cycle_2   | 1.31         | 1.73     | 1.71             | 81.8            | 0.23     | 0.17            | 64.5            |
|           | 1.10         | 2.26     |                  |                 | 0.15     |                 |                 |

Figure 7. Et vs σc, for H-C, W-D and simultaneous H-C and W-D treatments, cycle 1 and cycle 2.
The results of $\sigma_c$ and $E_t$ are closely related to the effect of the treatments applied, so that the fissures in the nuclei produce the degradation of the resistance of mudrocks. This degradation of the resistance to compression and of the modulus of elasticity, increases in the second cycle of each treatment (see Figure 8), the percentage of degradation is more intense in the treatment of H-C with values in the second cycle of 81.8% for $\sigma_c$ and 64.5% for $E_t$, followed by the simultaneous treatment of W-D and H-C is reduced by 61.3% for $\sigma_c$ and 48.6% for $E_t$, and finally, the treatment of W-D is reduced in less proportion with 49.6% for $\sigma_c$ and in 17.5% for $E_t$.

![Figure 8. Increase in the percentage of degradation in each treatment with the number of cycles. (a) degradation of compressive strength and (b) degradation of Young's modulus.](image)

4. Conclusions
Bearing in mind the humidity and temperature conditions of the study area, the environments in which the mudrocks of the Lutitas de Macanal formation is subjected were experimentally approached in the laboratory, using easily accessible equipment and the implementation of the VET, obtaining the comparison of heating/cooling cycle results in the same time periods as the wetting/drying cycles, i.e. 40 days, providing knowledge on the effect of temperature changes caused by daily insolation and cooling, and humidity changes between wet and dry seasons.

The experimental procedure shows that the mudrocks of the Lutitas de Macanal formation are mainly affected by thermal changes, suffering cracks and fissures, which resulted in a greater degradation of the resistance of the geomaterial, being this the main agent of physical meteorization, for a period of time equal to the changes of humidity.

The increase of the cycles in the treatments of H-C, W-D and simultaneous of H-C and W-D, reduces the resistance to compression and Young's modulus of mudrocks. The degradation in the response of the geomaterial is of greater slope in the first cycle and it is reduced in the second cycle for the H-C treatments and the simultaneous treatment of H-C and W-D, opposite case occurs with the W-D cycles.

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