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Analysis of the ratio between the plasticity of clay and the expansion capacity by changes in humidity and temperature

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Abstract. Clay is a cohesive material that varies in volume due to changes in humidity and temperature. Its behavior is studied with physical and geotechnical characterization of the material. The experimental analysis of the expansiveness of clays is related to plasticity, which depends on the expansive minerals it contains. The objective is to analyze the relationship between the plasticity index and the expansion capacity due to changes in humidity and temperature; various types of clay from San José de Cúcuta, Colombia, were studied. Liquid limit and plastic limit were analyzed with which the plasticity index was determined. The test tube free expansion and calcination were carried out at 1000 °C to determine the volumetric change due to humidity and temperature, respectively. The clays with plasticity index of 10% - 20% presented expansion by humidity of 5% - 10% and by calcination of 0% - 10%, which indicates low expansion; while the clay with plasticity index of 20% - 40% presented expansion by moisture of 20% - 50% and by calcination of 25% - 50%, which indicates moderately high expansion. The results show that there is a relationship between plasticity index and the expansion capacity due to changes in humidity and temperature.

1. Introduction
Clays are unstable materials that present variation in their volume due to wetting and drying processes, or by calcination at temperatures above 1000 °C. The behavior of clays is uncertain, and it is only possible to know it when the material is physically and geotechnically characterized. The study of clays is widely used in the field of civil engineering because the presence of this material makes building construction difficult due to its volumetric instability. However, there is a lack of studies that correlate the physical and geotechnical properties of clays with the expansive capacity due to variation in humidity due to wetting and drying cycles with expansion by calcination at temperatures above 1000 °C.

The clays with the highest expansive capacity occur in areas with warm and tropical climates [1]. This is due to low rainfall and evapotranspiration processes, contributing to post-deposition patterns of the soil [2,3]. The volumetric change by wetting and drying cycles is presented by the electronegativity imbalance that originally occurs in a clayey tissue in solid state, this process is balanced when water exchange cations surround the clay sheet, generating a double diffusion layer (hydration caused by the surface of the clay crystal, adsorbing water molecules) [1].

On the other hand, the volumetric changes due to calcination of clays occur when the material is exposed to relatively high temperatures. This process is due to the fact that the clay, which is basically silica, contains properties of pyroplasticity and viscoplasticity, that is, when the temperature increases, the clay reacts and becomes a viscous mass that, when the internal gases react, produces closed internal porosity, generating expansion of specimens [4].

Various studies have been carried out on the study of the expansiveness of clays due to changes in humidity. Pérez, *et al.* (2021) studied the behavior of volumetric change by humidity and drying cycles of montmorillonite clay [1]. Sridharan (2014) studied the clay mineralogy and physicochemical mechanisms that govern the behavior of fine soil [5]. Ruge, *et al.* (2019) performed a mineralogical, microstructural and porosymmetric analysis in clay soils to determine the mineral composition that controls the potential swelling of clay soils [6].

On the other hand, the study of the expansivity of clays by calcination at temperatures higher than 1000 °C is related to the production of light aggregates. Cáceres, *et al.* (2019) carried out studies on the expansion of clays for the production of light aggregates, starting from an exhaustive review and ending with the evaluation of the expansion capacity of clays with the addition of wastewater [7]. Sánchez, *et al.*, 2019, on the other hand, study the influence of the variation of the calcination time in the expansion of the clays [8]. Likewise, Gang Lee (2016) studied the swelling mechanism of clay to make light aggregate according to the size of the particles [9]. Likewise, Loutou and Hajjaji, 2017, studied light aggregates based on clay residues through thermal transformations and physical-mechanical properties [10]. The aforementioned studies are based on the study carried out by Riley, 1951, who made a theoretical and experimental correlation between the capacity for expansion of clays by calcination and their chemical composition, presented by means of a ternary diagram of prediction of expansiveness. [11].

Considering the presence of expansive minerals that affect the behavior of clays when they are subjected to changes in humidity and temperature, the present research work aims to study the relationship between the plasticity index, determined by the limits of Atterberg (liquid limit and plastic limit), and the expansion capacity due to changes in humidity and temperature of 10 clays from the city of San José de Cúcuta, Colombia.

2. Methodology

In this section, the method used to determine the plasticity index of the study clays is presented, as well as the process that was carried out to measure the expansion due to humidity and temperature changes of the clay materials that are the focus of study.

2.1. Determination of the plasticity index of the clays studied

The plastic limit and liquid limit of the 10 clay samples were studied; the plastic limit is known as the point at which a material goes from a semi-solid state to a plastic state. While the liquid limit is the point at which the clay sample stops from a plastic state to a liquid state [12]. The plastic limit is determined with the mass of clay that passes through the 40 sieves, that is, the clay sample with particles smaller than 0.42 mm. The clay is kneaded into cylinders 8 g in mass and 3.18 mm in diameter. The sample is rolled between the palm of the hand and a smooth surface that will not absorb moisture until it begins to fracture. On the other hand, the liquid limit is determined with the Casagrande standard test, for which two sections of clay are subjected to a number of impacts in a cup or spoon known as the Casagrande pan until the two sections touch [13].

The plasticity index depends on the liquid limit and the plastic limit. It is determined by subtracting the value of the plastic limit from the liquid limit. The plasticity index is expressed in Equation (1); a low plasticity index indicates that a small increase in the moisture content of the soil transforms it from a semi-solid to a liquid condition, that is, it is very sensitive to changes in humidity. Meanwhile, a high plasticity index indicates that for a soil to pass from a semi-solid state to a liquid state, a large amount of water must be added [13].

$$\mathrm{PI} = \mathrm{LL} - \mathrm{PL}, \tag{1}$$

where PI is the plasticity index, LL is the liquid limit, and PL is the plastic limit.

2.2. Free expansion test in specimen
The free expansion index is defined as the increase in volume that a soil undergoes without external restrictions when it is submerged in water [14]. To determine the free expansion index, a 5 g portion of clay is taken and poured into a 100 ml capacity cylinder, filling it with distilled water, and 5 g of clay with kerosene is poured into another cylinder to complete 100 ml. Kerosene is used because it is a non-polar fluid that does not generate volumetric changes in the clay. The sample is allowed to settle for a period of 24 hours to allow the volumetric equilibrium of the samples; after 24 hours a reading is taken of the volume reached in the test tubes. Equation (2) shows the expression to calculate the free expansion index.

$$\mathrm{FEI} = \frac{\mathrm{V_w} - \mathrm{V_k}}{\mathrm{V_k}}, \quad (2)$$

where, FEI is the free expansion index, $\mathrm{V_w}$ is the volume read from the cylinder with clay and distilled water, and $\mathrm{V_k}$ is the volume read from the test tube with clay and kerosene.

2.3. Calcination test
According to Sánchez, 2019 [8], there is no relationship between the expansion capacity and the exposure time of clay pellets to temperatures above 1000 °C. Therefore, for the clay calcination test, a static heat treatment will be applied at a temperature of 1100 °C with a burning time of 5 minutes. The burning curve starts from room temperature and goes to 600 °C in a time of 2 minutes, this in order to release gases that can cause the mixture to break down, these gases are produced by the combustion of carbon compounds. Then the clays are brought for 3 minutes at a temperature of 1100 °C where iron oxide (Fe_2O_3) reacts causing the release of oxygen [8]. Equation (3) shows the expression to calculate the calcination expansion index.

$$\mathrm{CEI} = \frac{\mathrm{V_f} - \mathrm{V_i}}{\mathrm{V_i}}, \quad (3)$$

where, CEI is the calcination expansion index, $\mathrm{V_f}$ is the volume read after the calcination process, and $\mathrm{V_i}$ is the volume read before the calcination process.

3. Results
The prediction of the expansiveness of the clay is complex and requires the analysis of several variables; the plasticity index has proven to be one of the most important characteristics for the characterization of a hyperactive clay material, that is, its volume varies due to external changes. In addition, the physical analysis of the liquid limit and plastic limit can be correlated both with the expansivity by calcination and by changes in moisture of the clays. In the following sub-sections, the results obtained in the laboratory are presented and the relationship that exists between the physical-geotechnical properties of the clays with the expansion capacity they have due to changes in humidity and temperature in the material is indicated.

The plasticity index defines the plastic field of materials and represents the percentage of moisture that the clays must have to be preserved in a plastic state. This value allows determining the settlement parameters of a clay material and its potential expansiveness. Table 1 shows the chemical compounds of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and other fluxing oxides (Rx). In addition, it presents the liquid limit and the plasticity limit together with the calculation of the plasticity index of the 10 clay samples studied.

The clays studied are mainly composed of SiO_2 of 56% - 70%, Al_2O_3 of 17% - 25%, Fe_2O_3 of 4% - 12%, and other fluxing oxides of 4% - 9%. Chemically, clay exhibits volume changes due to calcination when it has high indices of silica and alumina, compounds that generate the material's viscoplasticity. In addition, the iron oxide must be eliminated to avoid the instability of the material, so it must be raised to a temperature of 600 °C to calcine said compound. However, it has not been shown that there is a correlation between the chemical properties and the geotechnical properties of clays. It is evidenced that clay samples 1, 2, and 7 have the lowest plasticity index, which indicates that these samples require a low amount of water addition to go from being a semi-solid to having the condition of a liquid.

Table 1. Plasticity index of the clays studied in the city of San José de Cúcuta, Colombia.

Sample	SiO_2	Al_2O_3	Fe_2O_3	Rx	Liquid limit	Plastic limit	Plasticity index
1	69%	21%	5%	5%	28.00	13.37	14.63
2	69%	20%	4%	7%	38.25	22.22	16.03
3	56%	25%	10%	9%	50.40	17.32	33.08
4	68%	18%	8%	6%	37.75	12.95	24.80
5	59%	20%	12%	9%	41.20	15.68	25.52
6	62%	20%	9%	9%	57.75	18.60	39.15
7	67%	17%	9%	7%	27.50	12.15	15.35
8	65%	21%	8%	6%	53.75	18.19	35.56
9	68%	20%	6%	6%	41.50	14.35	27.15
10	70%	19%	7%	4%	35.50	11.80	23.70

Depending on the plasticity index and the liquid limit, it can be determined if the plasticity of the clay is high, medium, or low. Figure 1 shows that all the materials studied are clays; being the samples denominated as 1 and 7 the clays with low plasticity, with a liquid limit of 28% and with a plasticity index of 15%, approximately. The samples designated as 2, 4, 5, 9, and 10 are clays classified with medium plasticity, with a liquid limit of 30%-50% and a plasticity index of 16% - 28%. Finally, the samples named 3, 6, and 8 are classified as clays with high plasticity, presenting a liquid limit of 50% - 58% and a plastic limit of 33% - 40%.

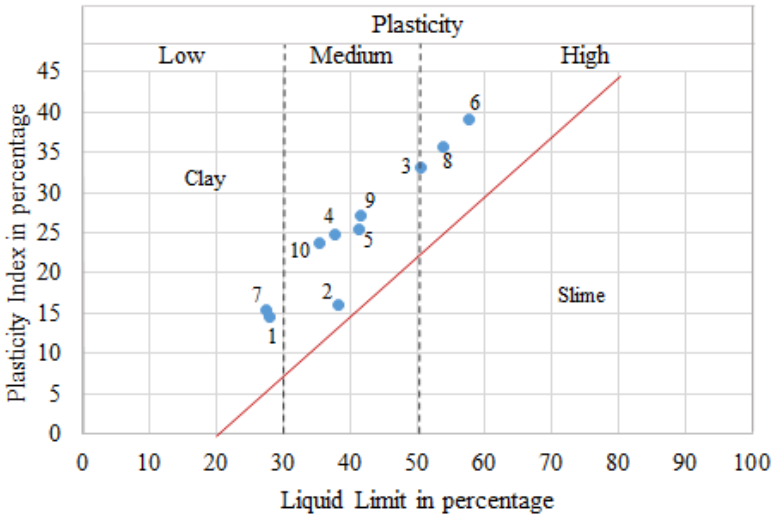

Figure 1. Determination of the plasticity level of the studied clays (low, medium, or high) according to the relationship between the liquid limit and the plasticity index.

Using Equation (2), the expansion capacity by wetting and drying cycles of the studied clays was determined. Figure 2 shows an increasing trend that relates the plasticity index and the free expansion index. A constant growth rate is evidenced, that is, as the clay increases its plasticity index, the expansion index due to changes in humidity increases 1.6 times. What has been described above shows a correlation between plasticity and expansion due to wetting and drying cycles of the clays. The calculation of the expansion index by calcination of the clay was carried out using Equation (3). Figure 3 shows the increasing trend of the expansivity due to temperature changes of the clays.

Clays exposed to calcination at temperatures above 1000 °C show expansion due to the production of internal pores due to the properties of pyroplasticity and viscoplasticity. The Figure 3 shows a constant increasing trend of the calcination expansion index with respect to the plasticity index. This indicates that the clay with greater plasticity will have a greater increase in volume due to sudden changes in temperature.

The studies in Figure 2 and Figure 3, presented previously, show that there is a directly proportional correlation between the plasticity of clay materials and their expansion capacity due to changes in humidity and temperature. The relationship between changes in humidity and the plasticity of the clay can be predicted because a clay with greater plasticity has a greater capacity to absorb water, which causes the clay to increase in volume. This can be identified in areas where there are constructions founded on clay terraces with high indexes of plasticity, since in these areas when there are rainy seasons, the constructions tend to be damaged because over-pressures are generated by the expansion of clay soils.

However, the swelling of the clay due to temperature changes related to the plasticity index is a bit more complex to analyze. Since so far, the studies carried out around the expansion of clays by calcination have focused on the analysis of the chemical composition. That is why this research shows that there is a correlation between expansion by calcination not only with the chemical composition, but also with the geotechnical properties. The high plasticity index indicates great water absorption capacity, which may be related to the pyroplastic instability of the clay when it is calcined, in addition, the high content of compounds such as silica and alumina provides the viscoplastic instability that is required. so that the clay expands by increasing the calcination temperature. That said, it is advisable to analyze clays from other parts of the world and identify if the same correlation presented in this work is present.

Generally, clay that presents high expansion rates due to wetting and drying cycles, extracted and discarded because this type of soil damages the construction of civil works, however, with what has been demonstrated in the present research work, it can be concluded that Clays that present problems for the foundations of buildings can be treated and used for the manufacture of other types of materials, such as the manufacture of lightweight aggregates for hydroponic crops, gardening, light concrete, thermal and acoustic insulators, among others. Uses that can be given to the product from the calcination of clay with high plasticity indexes.

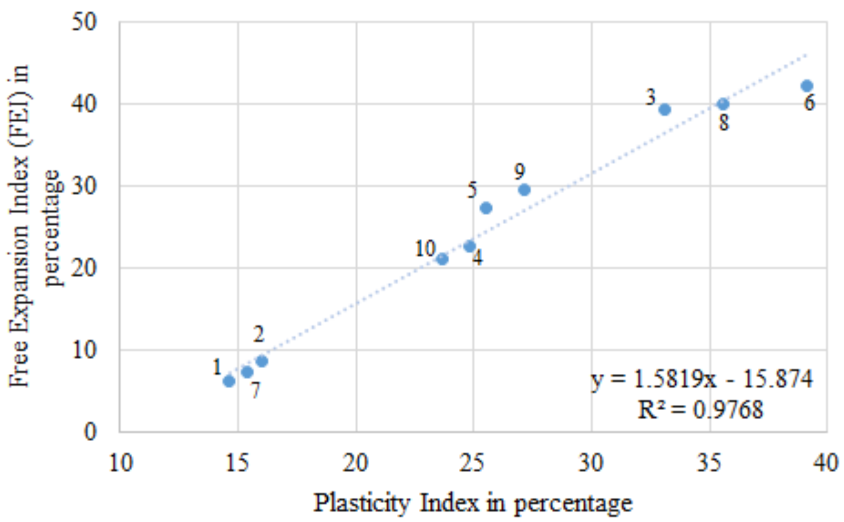

Figure 2. Ratio between the plasticity index and the expansion capacity by wetting and drying process measured by means of the free expansion test in a specimen.

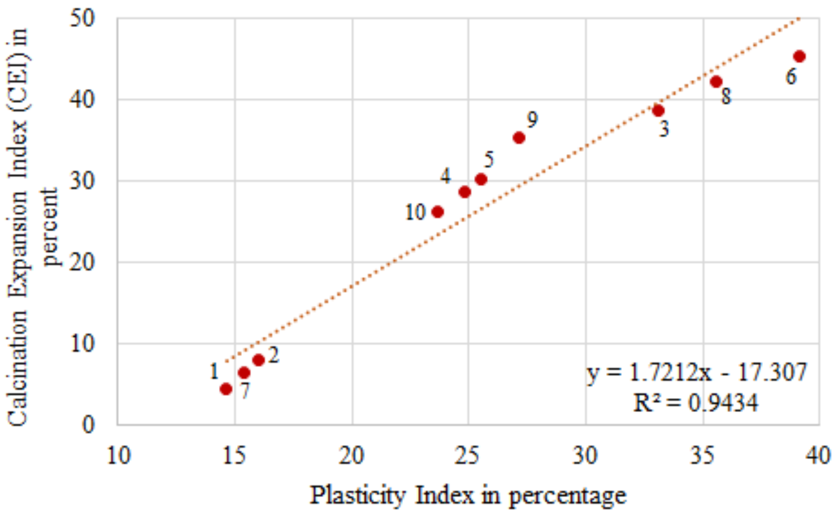

Figure 3. Ratio between the plasticity index and the expandability by calcination measured by means of a static heat treatment at temperatures above 1000 °C.

4. Conclusions

With the results obtained, it was determined that there is a relationship between the plasticity index of the clays and the variation in volume due to changes in humidity and temperature; clays with a plasticity index lower than 20% presented an expansion index due to humidity changes and calcination of less than 10%. The clays with a plasticity index of 20% - 30% presented an expansion index due to humidity changes of 20% - 30% and by calcination of 25% - 35%. Finally, the clays with a plasticity index of 30% - 40% presented an expansion index due to humidity changes and calcination of 35% - 50%. Which shows a constant growth trend.

The clays that present the highest expansion index due to humidity changes are the same ones that present the highest expansion due to calcination. This indicates that those clays that damage the soils where the constructions are founded and in turn affect the buildings, are the same clays that can be used for the production of other construction materials, such as light aggregates for hydroponic crops, gardening, lightweight concrete, thermal and acoustic insulators, among others.

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