Modeling of Deformations of Fine Clayey Soils Stabilized Using Sugar Cane Molasses: Extension of the Ferber Model

Nice Ngouallat Mfoutou, Narcisse Malanda*, Jarlon Brunel Makela, Paul Louzolo-Kimbembe

Polytechnic National Superior School, Marien Ngouabi University, Brazzaville, Congo

*Corresponding author: narmalanda@gmail.com

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Abstract

This work presents a theoretical study based on the instability of fine soils stabilized with sugar cane molasses. Indeed, this stabilization is only effective during the dry season in the town of Nkayi due to the scarcity or non-existence of rainfall. This being the case, let us suppose that humidification influences the intrinsic parameters of the earth materials (suction, porosity) and even the stabilization capacity of the molasses, we can try to understand the instability phenomenon that occurs within the structural matrix of the material when it is solicited during periods of heavy rainfall. The current models which study the deformation of the proposed fine soils, relate the inter-aggregate voids, the intra-aggregate voids, the stability index, the suction of the soil material and the relative humidity of the environment. Also, the theoretical study of these models shows that the inter-aggregate voids increase with relative humidity, the intra-aggregate voids decrease with increasing relative humidity and the stability index decreases with increasing relative humidity. Similarly, inter-aggregate voids decrease with increasing suction, intra-aggregate voids increase with suction and the stability index increases with suction. However, with the extension of Ferber's model, the breaking point of the earth material is obtained using these same models, i.e. this minimum point beyond which the adhesion forces in the aggregate and between the aggregates become low to ensure cohesion between the aggregates in the material for a long time. All in all, this point is significant for Pr \( \left( H_r = 35.768\% \right) \), \( e_{\text{ag}} = 0.5262 \), \( e_{\text{ag}} = 0.078 \), \( e_{\text{ag}}/S = 0.0005 \) and \( S = 146 \text{ MPa} \) (suction value) and is defined as the breaking point below which the cohesion of the aggregates is not evident. This proposed model mathematically translates both the effects of relative humidity and suction on voids in earth materials. It also explains the deformations that take place in earth materials at the microstructure level (intra-aggregate voids and inter-aggregate voids) under the effect of moisture or suction.

Keywords: fine clay soils, sugar cane molasses, modelling, aggregate, void, deformation

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1. Introduction

Sugar cane molasses is dumped on dirt roads in Nkayi town, including access roads to the production sites of the agricultural sugar refinery company (Saris), to mitigate the effects of raising soil dust as vehicles pass by. Molasses showed remarkable cohesive behaviour on aggregates of fine clay soils. Malanda et al (2017), for example, observed an increase in the strength of compacted raw earth briquettes stabilised with molasses [1,2]. However, molasses is soluble in water and soil stabilisation using this product is only suitable in the dry season, when rainfall is remarkably scarce given the climate of the study area [3,4]. Thus, the stabilisation is destroyed when it comes into contact with rainwater. Malanda et al (2017) also observed dispersions of characteristic compressive and tensile strength values and data on drying kinetics, which are fairly acceptable and reliable for bricks with the same amount of molasses and the same curing time [1,2]. So, suppose that the storage conditions of the bricks, especially relative humidity, influence the intrinsic parameters of the materials (suction, porosity) and even the stabilising capacity of the molasses, what would be the effect of humidification on the soil and the materials stabilised with molasses?

This is because when stabilising soils or clay bricks, molasses is added to the water content of the optimum Proctor. We therefore consider that the molasses constituent molecules circulating in the pores through the
water, is found in the water film absorbed by the clay particles in the soil and in the water meniscus between aggregates and between particles. The possible interactions between the molasses molecules and the clay particles in the soil contribute to the suction and thus the adhesion forces of the particles and aggregates in the soil material.

Ferber (2005), developed a mathematical model linking the microstructural parameters of earth materials (void indices) with the water content in the material to explain the swelling phenomenon at the microstructure level [5].

Thus, in this study, we have proposed a model based on Ferber's model linking inter-aggregate voids, intra-aggregate voids, the suction of the earth material and the relative humidity of the environment. We have also defined a parameter: the soil microstructural stability index as the ratio between the index of intra-aggregate voids and the suction.

The aim of this work is to carry out a theoretical study of these models, then to extend it to the stabilisation of fine soils using molasses in order to try to understand the effects of relative humidity and suction on the cohesion of the aggregates of stabilised earth materials, and at the same time the instability of the soil.

2. Unsaturated Porous Medium

2.1. Study Area

The town of Nkayi where the studies were carried out is located about 250 km from Brazzaville, the capital of Congo. The study area extends from 4°9'56"S longitude and 13°17'34"E latitude.

2.2. Definition of Unsaturated

The mechanics of porous media has been theorised mainly by Coussy (1991). According to him, the porous medium consists of:
- the interstitial space or connected porous space;
- the matrix composed of grains and occluded porous spaces.

The saturated porous medium is the superposition in time and space of two continuous media: the porous medium and the fluid.

Saturated soils are composed of a solid phase (the matrix) and a fluid phase (the liquid saturating the pores). Unsaturated soils, on the other hand, have a third gaseous phase (usually air) which shares the pore volume with the liquid phase (usually water):
The presence of the gaseous phase in the pores results in a negative pressure, considering the atmospheric pressure as the origin of the pressures. This negative pressure is called suction.

2.3. Suction

From a mechanical point of view, suction is the intensity of the attraction exerted by the soil on the pore water [6]. The total suction of a clay soil is composed of the matrix suction and osmotic suction.

2.4. Bone Suction

Osmotic suction \( S_{osm} \) is related to the phenomenon of osmosis; it is the attraction by water concentrated in dissolved salt on less concentrated water. It exists when the water is a saline solution. In the case of an unsaturated medium, modellers generally do not take this component into account [6], which is why total suction is assimilated to matrix suction.

2.5. Matrix Suction

Matrix suction \( S_m \), groups together the capillary and adsorption phenomena [6].

\[ S_m = S_C + S_{ad} \]

\( S_m \): Matrix suction,
\( S_C \): Capillary suction due to the presence of water,
\( S_{ad} \): Adsorption suction due to adsorption of sugar cane molasses.

- The phenomenon of adsorption is observed in the case of clays and fine clay soils: it is mainly due to bonds of a physico-chemical nature, such as hydrogen bonds. This component is taken into account in our study because of the adsorption phenomenon of sugarcane molasses.
- Capillarity corresponds to the presence of capillary menisci between the pores.

This component is often taken into account [6].

3. Ferber Model

This model is based on the definition of the aggregate, the quantitative description of the porosity of the aggregate and the quantitative description of the voids in the rest of the volume [7].

3.1. Microstructural Parameter of the Ferber Model

The microstructural parameters of the Ferber model are [7]:
- Intra-aggregate voids index \( e_{iag} \),
- Inter-aggregate gap index \( e_{iag} \),
- Overall floor void index \( e \), with \( e = e_{iag} + e_{iag} \)

3.2. Assumptions of the Ferber Model

Ferber’s hypotheses are [7]:
1: the aggregate is saturated;
2: the volume of intra-aggregate voids \( V_{iag} \) is assimilated to the volume of water \( V_{\omega} \), within the aggregate;
3: the inter-aggregate voids are occupied by air, \( e_{iag} = e_{iag} \)

3.3. Ferber's Model Equations

The equations of Ferber's model are given below [7]:

3.3.1. Intra-aggregate voids index \( e_{iag} \)

\[ e_{iag} = \frac{V_{iag}}{V_{\omega}} = \frac{\rho_{\omega}}{\rho_{d}} \]

With, \( \rho_{\omega} \): the average density of solid particles;
\( \rho_{d} \): density of water;
\( \omega \): overall mass water content of the soil;
\( V_{\omega} \): Volume of water;
\( V_{iag} \): volume of solid particles.

3.3.2. Inter-aggregate gap index \( e_{iag} \)

\[ e_{iag} = e_{air} = \frac{V_{iag}}{V_{\omega}} = \frac{\rho_{\omega}}{\rho_{d}} - 1 - \frac{\rho_{d}}{\rho_{\omega}} \]

With, \( V_{iag} \): inter-aggregate voids volume;
\( \rho_{d} \): the overall dry density of the sample;
e: the overall void index of the sample.

Equations (1) and (2) show that any variation in water content implies both an increase in intra-aggregate voids and a decrease in inter-aggregate voids.

4. Extension of the Ferber Model

4.1. Kelvin's Law: Sucking-Moisture Relationship

Suction is related to relative humidity by Kelvin’s law. According to this law, suction in a porous medium depends on temperature and humidity [8,9,10]:

\[ S = \frac{RT}{Mg\gamma_{\omega}} \times \ln(Hr) \]

With,
\( \gamma_{\omega} \): the density of water \((9,81 \text{ kN.m}^{-3})\),
g: the acceleration of gravity \((9,81 \text{ N/} \text{kg})\),
M: molecular weight of water \((18,016.10^{-3} \text{ Kg.mol}^{-1})\),
T: absolute temperature (K),
and R: the ideal gas constant \((8,3143 \text{ J.mol}^{-1}.\text{K}^{-1})\).
\[ \frac{RT}{Mg} = 137,837 \] at \( T=20^\circ \text{C} \) [10].

Throughout this study we consider the material to be unsaturated, so the volumetric weight of water \( \gamma_{\omega} = 1 \)
N/cm$^2$ is used in our calculations for further work.

A slight variation in the amount of water in the material causes variations in suction. The relation (3) becomes:

$$\Delta S = -\gamma_w \frac{RT}{Mg} \ln(Hr)$$  \hspace{1cm} (4)$$

The combination of the Kelvin (3) and Ferber (1 and 2) relationships gives us the following relationships between suction, void indices and relative humidity.

4.2. Relationship index of intra-aggregate voids ($e_{ag}$) as a function of relative humidity ($H_r$) and suction ($S$)

Relations (3) and (1) give:

$$e_{ag} = S \frac{Mg^2 \omega \rho_s}{RT \ln(Hr)}$$  \hspace{1cm} (5)$$

With, $\omega$: Initial water content of the soil or earth material.

4.3. Relationship Index Inter-aggregate Voids ($e_{iag}$) as a Function of Relative Humidity ($H_r$) and Suction ($S$)

Relations (5) and (2) give:

$$e_{iag} = \rho_s \frac{1}{\rho_d} S \frac{Mg^2 \omega \rho_s}{RT \ln(Hr)}$$  \hspace{1cm} (6)$$

4.4. Relation microstructural stability index ($\frac{e_{ag}}{S}$) as a function of relative humidity ($H_r$)

The relation (5) gives:

$$\frac{e_{ag}}{S} = \frac{Mg^2 \omega \rho_s}{RT \ln(Hr)}$$  \hspace{1cm} (7)$$

With, $\rho_s=$2660 Kg/m$^3$

4.5. Assumptions of the Extension of the Ferber Model

1: The initial water content of the soil or earth material is negligible, the material is unsaturated ($\omega = 0.001\%$);
2: the aggregate is saturated;
3: Sugarcane molasses behaves like a salt solution.

5. Theoretical Results of the Extension of the Ferber Model

We will test the models using the suction and relative humidity values from the Kelvin relation (4).

Table 1. Example of suction and relative humidity values from the Kelvin relation [9]

| Suction (Mpa) | Relative humidity (%) |
|---------------|-----------------------|
| 0             | 100                   |
| $10^{-2}$     | 99.9993               |
| $10^{-1}$     | 99.927                |
| 1             | 99.227                |
| 70            | 60                    |
| 126           | 40                    |
| 221           | 20                    |
| 317           | 10                    |

From relations (5), (6) and (7), it is possible to calculate the void indices ($e_{ag}$ and $e_{iag}$) and the stability index $\frac{e_{ag}}{S}$ with, $\rho_s =$2600 Kg/m$^3$ et, $\rho_d =$1620 Kg/m$^3$, T=20 °C and $\omega =$0.001%. The values obtained are as follows:

Table 2. Values of the vacuum and stability indices calculated from the extension equations of the Ferber model and suction and relative humidity values from the Kelvin relation.

| Suction (Mpa) | Hr (%) | $e_{ag}$ | $e_{iag}$ | $\frac{e_{ag}}{S}$ |
|---------------|--------|----------|-----------|-------------------|
| 0             | 100    | 0        | 0.6049    | 4.0182.10$^{-4}$  |
| $10^{-2}$     | 99.9993| 4.0182.10$^{-4}$ | 0.6049    | 4.0182.10$^{-4}$  |
| $10^{-1}$     | 99.927 | 4.0188.10$^{-4}$ | 0.6049    | 4.0188.10$^{-4}$  |
| 1             | 99.227 | 4.0245.10$^{-4}$ | 0.6045    | 4.0245.10$^{-4}$  |
| 70            | 60     | 0.0316   | 0.5733    | 4.5195.10$^{-4}$  |
| 126           | 40     | 0.0632   | 0.5417    | 5.0163.10$^{-4}$  |
| 221           | 20     | 0.1365   | 0.4684    | 6.1769.10$^{-4}$  |
| 317           | 10     | 0.2548   | 0.3501    | 8.0364.10$^{-4}$  |

The results in the form of a graph are presented below. All graphics were obtained using MATLAB software.

5.1. Theoretical solution of the equation of microstructural stability index ($\frac{e_{ag}}{S}$) as a function of relative humidity ($H_r$)

The function graph $\frac{e_{ag}}{S} = f(H_r)$ is generated using MATLAB software. The resulting graph shown below.
This curve shows that the structural stability of fine flooring decreases with increasing relative humidity. The stability index makes it possible to assess the stability of the soil structure. The higher the stability index, the more stable the fine soil structure is, i.e. the cohesion of the particles within and between aggregates is sufficient.

5.2. Experimental theoretical curve Index of stability \( \left( \frac{e_{ag}}{S} \right) \) as a function of relative humidity \((H_r)\)

The experimental theoretical curve \( \frac{e_{ag}}{S} = f(H_r) \), obtained from Values \( \frac{e_{ag}}{S} \), calculated from the extension equations of the Ferber model (5), (6) and (7) and from suction and relative humidity values from the relation of Kelvin (Table 1). The experimental theoretical curve obtained is as follows:

Figure 4. Theoretical curve, \( \exp \left( \frac{e_{ag}}{S} \right) \) as a function of \( H_r \).

According to the mathematical and theoretical experimental curves of the stability index as a function of relative humidity, the stability of the aggregates in the material decreases with increasing relative humidity. Indeed, the higher the stability index, the more stable the structure of the fine soil is, i.e. the cohesion of the particles within and between aggregates is sufficient;

- from \([10 - 40]\) % relative humidity, the stability index varies from \([8.0364 - 5.0163] \times 10^{-4}\), this rapid decrease is due to the rapid accumulation of water in the macropores. However, the structure of the material is stable. The intensity of humification is not sufficient to break the adhesion forces between the aggregates;
- from \([40 - 60]\) % relative humidity, the stability index varies from \([5.0163 - 4.5195] \times 10^{-4}\), the decrease in the stability index slows down, water seeps into the micropores, and the material structure begins to lose its stability. The adhesive force between the aggregates starts to lose its intensity;
- from \([60 - 100]\) % relative humidity, stability index varies from \([4.5195 - 4.0182] \times 10^{-4}\), stability index reaches its most basic value \(4.0182 \times 10^{-4}\) and becomes constant, material structure becomes unstable, adhesion between aggregates is broken, material is saturated.

5.3. Superposition of the Theoretical Experimental and Mathematical Curves Stability Index as a Function of Relative Humidity

The experimental curve \( \frac{e_{ag}}{S} = f(Hr) \) (Figure 4) and its theoretical (mathematical) curve (Figure 3) have the same shape. The superposition of these two curves is given in Figure 5, the error values (SCE= 1.18 \times 10^{-9} and \( \chi^2 =1.94 \times 10^{-6} \)) are very small. Thus, the mathematical law adequately describes the experimental phenomenon. Intra-aggregate stability decreases with increasing relative humidity. It is therefore possible with this model to predict a value of the stability index knowing the value of the moisture content of the material and vice versa.

Figure 5. Curve \( \frac{e_{ag}}{S} \) as a function of \( Hr \).

5.4. Variations of the intra-aggregate voids index \( e_{ag} \) as a function of relative humidity \((H_r)\)

The curve of the intra-aggregate voids index as a function of relative humidity shows that the intra-aggregate voids decrease with relative humidity.

Figure 6. Theoretical curve, exp of the intra-aggregate voids index as a function of humidity.
At [10 - 40] % relative humidity, the suction in the material is high, the material is unsaturated and similar to dry. However, the aggregate is saturated because the water-clay interactions trap the water inside. Water occupies the intra-aggregate voids at the point of contact between the particles in the form of a capillary meniscus. The attractive forces between the particles due to the menisci are normal to the tangent planes at the point of contact of the particles and do not cause a rearrangement of the structure. They do, however, contribute to the consolidation of the granular skeleton of the material. Intra-aggregate voids are saturated and water is strongly bound to the clay particles. The accumulation of water due to the increase in relative humidity does not cause rearrangement within the aggregate. However, the accumulation of water around the aggregate causes water infiltration into the few available intra-aggregate voids. This results in a decrease in the intra-aggregate voids as a function of moisture;

From [40 - 100] [% relative humidity, the decrease in intra-aggregate voids slows down and stabilizes until it is zero. Thus, the available intra-aggregate pores are saturated.

5.5. Variations of the inter-aggregate void index ($e_{ag}$) as a function of relative humidity ($H_r$)

The following curve shows the variation of the inter-aggregate void index as a function of relative humidity. Inter-aggregate voids increase with relative humidity.

![Figure 7. Theoretical curve of the inter-aggregate voids index as a function of humidity.](image)

The rapid increase in inter-aggregate voids between [10 - 20] % relative humidity, due to the rapid occupation of the large pores (macropores) available between the aggregates, water molecules gradually occupy these voids and air is expelled from the material;

from [20 - 40] % relative humidity, the large pores are saturated with moisture, the moisture seeps into the small pores between the aggregates (hence the slowing down). Water accumulates around the aggregates and forms capillary menisci between the aggregates. However, the attractive forces between the aggregates due to the menisci are normal to the tangential planes at the point of contact of the aggregates and therefore cannot cause a rearrangement of the structure;

at [40 - 60] % relative humidity, there is a slight increase in inter-aggregate voids from [0.5417 to 0.5733], the inter-aggregate pores tend towards saturation. The more water molecules accumulate around the aggregates, the further apart they are from each other. Some inter-aggregate capillary forces are no longer normal to the planes;

at [60 - 100] % relative humidity, the inter-aggregate void values increase from 0.5733 to 0.6049. Inter-aggregate voids reach positive values and stabilise at 0.6049, inter-aggregate pores are saturated, above 100% relative humidity, the soil is in the quasi-saturated range. Inter-aggregate capillary forces are zero, the aggregates are flowing.

5.6. Superposition of the curves of the void index (inter-aggregate ($e_{ag}$) and intra-aggregate ($e_{iag}$) and the stability index ($S$) as a function of relative humidity ($H_r$)

By superimposing these curves, it is possible to define the breaking point, as the intersection of the curve of inter-aggregate vacuum indices as a function of relative humidity and the curve of stability indices as a function of relative humidity. The breaking point $Pr(H_r, e_{iag}, e_{ag}/S)$
defines the relative humidity value and the minimum inter-aggregate void index value beyond which the structure of earth materials becomes unstable, the adhesion of soil particles in the material becomes weak to ensure longer inter-aggregate cohesion. The breaking point obtained is Pr(Hr=35.768%, $e_{ag}=0.078$, $e_{iag}=0.5262$). At the breaking point $1000 \times \frac{e_{ag}}{S} = e_{iag}$, then $\frac{e_{ag}}{S} = 0.0005262$.

5.7. Variations of the Stability Index $\left( \frac{e_{ag}}{S} \right)$ as a Function of Suction ($S$)

The curve below gives the variations of the stability index as a function of suction. The stability between the aggregates in the material increases with suction.

According to these curves:
- Intra-aggregate voids increase with suction. The water loss due to the increase in suction results in the contraction of the aggregate, which causes clay particles to divide in the aggregate. This multiplication of particles in the aggregate implies the multiplication of voids between the particles in the aggregate.
- On the other hand, the inter-aggregate voids decrease with increasing suction. The loss of water due to the increase in suction causes the aggregates to move closer together, which results in a decrease in the inter-aggregate voids with the increase in suction.

5.8. Variations of voids index ($e_{ag}$ et $e_{iag}$) as a function of suction ($S$)

The curves below give the variations of the void indices as a function of suction.

By superimposing these curves, it is also possible to define the breaking point, as the intersection of the curve of the inter-aggregate vacuum index versus suction and the curve of the stability index versus suction. The break point obtained is Pr ($S=146.1027$ MPa, $e_{ag}=0.0786$, $e_{iag}=0.5262$). At the breaking point $1000 \times \frac{e_{ag}}{S} = e_{iag}$, then $\frac{e_{ag}}{S} = 0.0005262$. We can see that, we find exactly the same values of the breaking point obtained in Figure 8.

5.9. Superposing the curves of the void index (inter-aggregate $e_{iag}$ et and intra-aggregate $e_{ag}$ and the stability index $\left( \frac{e_{ag}}{S} \right)$ as a function of suction ($S$))

5.10. Interpretation of Results and Discussion

The proposed equations mathematically translate the effects of relative humidity on voids in earth materials. There is therefore, a relative humidity value, a suction value and an intra-aggregate void index value, defined by the breaking point $P_r$ ($H_r=35.768\%$, $e_{iag}=0.5262$, $e_{ag}=0.078$, $\frac{e_{ag}}{S}=0.0005262$ and $S=146$ MPa), for which the
adhesion forces in the aggregate and between aggregates become weak, to ensure particle cohesion within the aggregate and between aggregates. This negatively affects the structural stability of earth materials and their mechanical properties (strength, consistency).

The mathematical law and the theoretical experimental law of the stability index as a function of relative humidity merge, the values of the error (SCE=1.18.10⁻⁹ and \( \chi^2=1.94.10^{-6} \)) are so weak. It is therefore possible to use this mathematical law for the prediction of the stability index value or relative humidity. For example, for relative humidity defined by the breakpoint \( H_r=35.768\% \), the mathematical law of stability index gives a stability index value of stabilité \( \frac{e_{ag}}{S} = 0.0003812 \).

While, the experimental theoretical results give a value of \( \frac{e_{ag}}{S} = 0.00037667 \), i.e. a value of \( \chi^2 = 5.3833 \cdot 10^{-8} \) and a value of SCE=2.0521. \( 10^{-11} \). Thus, the mathematical law adequately describes the experimental phenomenon.

Intra-aggregate voids increase with suction. On the other hand, the inter-aggregate voids decrease with increasing suction.

In fact, the loss of water due to the increase in suction results in the contraction of the aggregate, which causes the clay particles in the aggregate to divide. This multiplication of particles in the aggregate implies the multiplication of voids between the particles, thus increasing the intra-aggregate voids.

At the material level, the loss of water due to the increase in suction causes the aggregates to move closer together, resulting in a decrease in inter-aggregate voids with the increase in suction.

The stability index increases with the suction, in fact the increase in suction results in the expulsion of water, air penetration and consolidation of the granular skeleton. Thus, the higher the suction in the soil or earth material, the more stable the structure is.

The variation in suction due to variations in inter-aggregate void indices caused by variations in relative humidity could imply the degradation of the resistance of the earth materials, even though they have the same curing time and the same amount of sugarcane molasses. In fact, throughout the humidification of unsaturated material stabilised with sugarcane molasses, the organic molecules of the sugarcane molasses, interacting by external sphere with the external surface of the clay particles, move away from this external surface (of the clay particle) by progressive accumulation of water molecules due to humidification around the external sphere. The interaction between the organic molecules and the outer surface of the clay particles weakens (breaking point conditions reached), until it disappears completely (beyond the breaking point).

The results observed corroborate with those observed at the microscopic scale (MEBE) by Ferber, the experimental protocol consisted of placing the sample in a relative humidity of 90% in the initial state, then gradually increasing it to 100%. After observing the saturation of the sample, the relative humidity was lowered to 60% to dehydrate it. Ferber found three points, two of which are reported [11]:

- Moisture, in the first instance, manifests itself by the appearance of a grey-black film on the surface of the clay aggregates and, in the second instance, by the filling of the larger pores.
- Humidification and drying (increased suction) leads to particle movements and deformation of the inter-aggregate voids.

Elfacel (2013), studying the effect of relative humidity on the compressive strength of compact clay bricks, noted that the mechanical strength decreases with increasing humidity and that at 40% relative humidity the compressive strength is low, less than 10 MPa [12].

6. Conclusion and Prospects

A given relative humidity and a given suction, imposes on the floor any state of its microstructure. The variation of the relative humidity influences the stability of fine unsaturated soils and earth materials, acting on the intra and inter aggregate voids and on the matrix suction.

There are a relative humidity value (\( H_r=35.768\% \)) and an inter-aggregate void index value (\( e_{ag}=0.5262 \)), an intra-aggregate void index value (\( e_{ag}=0.078 \)), a stability index value (\( \frac{e_{ag}}{S} = 0.0005262 \)), defined by the breaking point beyond which earth materials and soils lose their cohesion due to humidification and a suction value (\( S=146 \) MPa) below which the cohesion of the aggregates in the earth material or soil is low.

The proposed models mathematically translate the effects of relative humidity and suction on voids in earth materials. They explain the deformations that take place in the soil or earth materials at the microstructure level (intra-aggregate voids and inter-aggregate voids) under the effect of moisture or suction. These models allowed us to define the breaking point \( Pr \) (\( H_r=35.768\% \), \( e_{ag}=0.5262 \), \( e_{ag}=0.078 \), \( \frac{e_{ag}}{S} = 0.0005262 \) and \( S=146 \) MPa), the minimum point beyond which the adhesion forces in the aggregate and between the aggregates become low, to ensure the cohesion of the aggregates in the material. This negatively affects the stability of the structure of earth materials and their mechanical properties; strength, consistency, etc.

The variation in suction and relative humidity related to variations in the intra-aggregate void indices could imply the variation in the strength of the briquettes, observed by Malanda et al (2017) [1], although the briquettes had the same curing time and the same percentage of molasses.

For the continuation of this work, it will be advisable to carry out an experimental study, which will consist of verifying the theoretical results obtained in this work. It will also be a question of applying these models according to the type of clay.

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