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Physical, chemical and microstructural characterization of two problematic soils from the Paraguayan Chaco

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Technical Note

Keywords
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Dispersive soils
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Soil characterization

Abstract

It is not uncommon for Geotechnical Engineering works to be carried out under unfavorable conditions that compromise the earth-stability. In this context, the Paraguayan Region of Chaco is notably known owing to the presence of problematic soils that possess dispersive characteristics and/or present high amounts of soluble-sulfates content. Geomaterials of such nature affect mainly the road infrastructure earthworks due to, respectively, their promptness to erosive phenomena when in contact with water and swelling owing to the grown and hydration of expansive minerals such as ettringite and thaumasite, when treated with calcium-based materials. Therefore, present research presents a detailed characterization of a dispersive soil and a sulfate-rich dispersive soil, both collected in the Western Region of Paraguay. Physical, chemical and microstructure tests were carried out in order to verify and explain the deleterious behavior observed in both soils.

1. Introduction

It is not atypical for engineering earthworks to be carried out under adverse geotechnical conditions due to the existence of problematic soils (Ingles & Metcalf, 1972; Mitchell, 1981; Behnood, 2018). That is, soils which are not suitable for a particular purpose without the application of any kind of improvement/stabilization technique. Distinct issues may lead soils of different natures to earth-stability problems, such as high swell or shrinkage potential, dispersibility tendency, amongst others. Those drawbacks are usually related to the soil' overall structure (fabric, composition and interparticle forces) and the way it interacts to the medium (Mitchell & Soga, 2005; Miguel et al., 2020).

In this sense, the Paraguayan region of Chaco (Western Region) is notably known for the presence of soils that may present either dispersive characteristics and/or sulfate-rich expansive soils (Quiñónez Samaniego, 2015; Consoli et al., 2016, 2019, 2020, 2021; Rocha et al., 2016; Scheuermann Filho, 2019; Miguel, 2020, Miguel & Festugato, 2021). These imply constant damage to local infrastructure, especially on road embankments which require persistent maintenance interventions owing to erosive and swell related issues. Generally, dispersive soils are distinguished by its high amounts of monovalent cations (mostly Na^+) adhered to the surface of the clay particles (Ryker, 1977; Elges, 1985). This yields in the predisposition of such soils to phenomena of external and internal erosion (piping) when in contact with water, since the level of electrochemical forces of attractive character is low as sodium is lightly charged and weakly adhered to the clay minerals (CRC, 2001). Thus, it is not uncommon to observe severe erosive phenomena, such as tunnel erosion, in sodic soil areas (Sparks, 2003).

The complications related to sulfate-rich soils, in turn, are associated to the presence of sulfates that may interact with calcium-based stabilizers and yield the precipitation of hydrated calcium alumino-sulfate minerals, which might grow, hydrate and expand, causing the heaving of the treated soil (Sherwood, 1962; Hunter, 1988; Kota et al., 1996; Roy et al., 2003; Little & Nair, 2009; Knopp & Moormann, 2016; Consoli et al., 2019; Scheuermann Filho et al., 2020). This happens in a hydrated alkaline environment, through the reaction between the calcium ions (from the stabilization agent), the available sulfates and the aluminates from the clay minerals. Thus, the stabilization of such soils with conventional materials (e.g. Ordinary Portland Cement and hydrated lime) may lead to inconvenient pathologies. Moreover, sodium sulfate (Na_2SO_4), magnesium sulfate ($MgSO_4$) and calcium sulfate ($CaSO_4 \cdot H_2O$ – gypsum) are commonly encountered in such soils and may be natural compounds or secondary sources from the oxidation of sulfides (Puppala et al., 2003; Talluri, 2013; Talluri et al., 2013; Harris et al., 2004).

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Therefore, the present research intends to comprehensively characterize two problematic soils from the Paraguayan Chaco. The first is a highly dispersive soil and the second is a sulfate-rich soil which also presents an intermediate dispersibility propensity. For this, both soils were assessed by means of its standard physical properties (i.e. grain size distribution, Atterberg limits, compaction characteristics, amongst others), chemical composition and mineralogical constitution. In addition, regular tests aiming to determine the dispersibility potential and the soluble sulfates content were also performed.

2. Experimental program

The experimental program was carried out on three parts. First, the physical properties of both soils were characterized. Next, the total soluble salts (TDS) and water-soluble sulfate contents were determined. Finally, the microstructure of both soils was assessed by means of X-Ray diffraction tests and scanning electron microscope images (SEM). Both soils come from the Paraguayan Chaco region, which is located in the Western Region of Paraguay. The dispersive soil was collected nearby the Villa Hayes town, which is 31 km from the north of Asunción (capital of Paraguay). The sulfate-rich dispersive soil, in turn, was collected in the city of Filadelfia, which is 467 km northwest from Asunción.

2.1 Physical properties

Table 1 summarizes the physical properties of the studied soils, while Figure 1 presents the grain size distribution obtained for both soils via the hydrometer method (ASTM, 2017a). Both soils can be classified as a lean clay (CL) accordingly to the Unified Soil Classification System (ASTM, 2017b). The compaction curves of the soils are presented in Figure 2 and were obtained through the employment of the standard effort accordingly to the ASTM D698 standard (ASTM, 2012). Hence, the maximum dry unit weight attained for the dispersive soil was equal to 18.05 kN/m^3, at a moisture content of 15.70%, while the greatest dry unit weight was 18.20 kN/m^3 for an optimum moisture content of 13.50% for the sulfate-rich dispersive soil.

In order to determine the dispersive characteristics of both soils, the Crumb Test and the Pinhole test were performed in either. The first was carried out in according to the ASTM D6572 standard (ASTM, 2020) and basically consists in observe the turbidity of a portion of distilled water due to the presence of crumbs of soil. That is, if the soil possesses dispersive features its particles deflocculate and go into suspension as the crumbs begin to adsorb water. Therefore, the dispersive grade (I to IV) is based upon the turbidity of the water attained once the test is finished. The dispersive soil was classified as a highly dispersive soil (grade IV) as a dense and profuse cloud of suspended clay colloid was seen along the test. The sulfate-rich soil, in turn, was classified as an intermediate dispersive soil (grade II) since

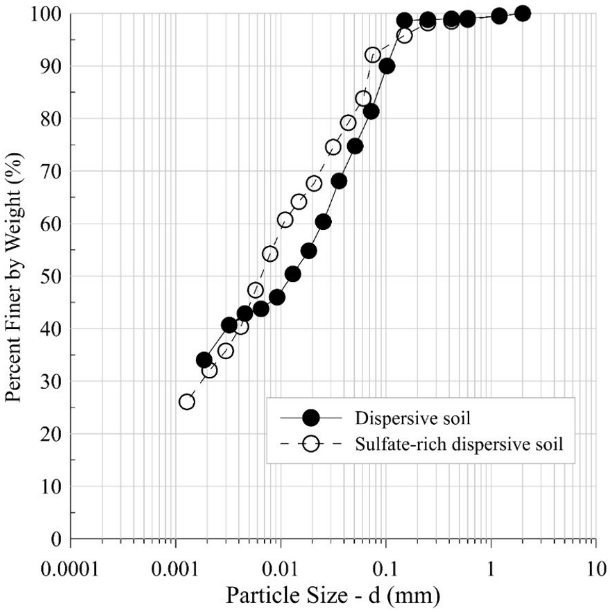

Figure 1. Grain size distribution of the studied soils.

Table 1. Physical properties of the soils.

Parameter	Sulfate-rich dispersive soil	Dispersive soil
Liquid limit (%)	32	43
Plastic limit (%)	16	19
Plastic index (%)	16	24
Unit weight of the soil grains (g/cm^3)	2.69	2.74
Percent finer by weight sieve #200	92%	91%
Mean particle diameter, D_{50} (mm)	0.0064	0.013
Maximum dry unit weight (kN/m^3)	18.2	18.05
Optimum moisture content (%)	13.5	15.7
USCS classification	CL	CL
Organic matter (%)	1.24%	0.20%
Crumb Test	Grade 2 (intermediate)	Grade 4 (highly dispersive)
Pinhole Test	D1	D2

only a slight reaction took place, which resulted in a barely visible colloidal suspension.

The pinhole test was performed according to NBR 14114 standard (ABNT, 1998) on soil samples molded to the maximum dry unit weight (at the optimum moisture content) attained in the compaction tests (Figure 2). The test consists in opening a small hole (1 mm of diameter) at the entire length of cylindrical specimens (38 mm in diameter and 38 mm in height) of the compacted soil. These specimens are then subjected to constant hydraulic heads during time intervals equal to 5 minutes. After each interval, the average flow rate and turbidity of the water is checked. Hydraulic heads of 50 mm, 180 mm, 380 mm and 1020 mm are employed. For instance, the test firstly initiates with a hydraulic head of 50 mm that is subjected to the sample during a defined volume and time, after either elapsed time or volume collected, is able to classify the soil according to its effluent turbidity and flow rate. Additionally, the hole enlargement must be verified, highly dispersive soils tend to easily erode, therefore, enlarge the initial hole size. In case of results do not fit with the NBR 14114 requirements, then the hydraulic head must be raised and the procedure repeated with the next hydraulic head. Consequently, as greater is the dispersibility of the soil, greater is the flow rate and the turbidity of the water. Namely, the soil particles in dispersive soils tend to be carried by the water flowing, which is responsible to increase the diameter of the hole and, as a consequence, the flow rate and the turbidity of the water. Accordingly, the dispersive soil was classified as a dispersive soil (D2), while the sulfate-rich dispersive soil was classified as a highly dispersive soil (D1).

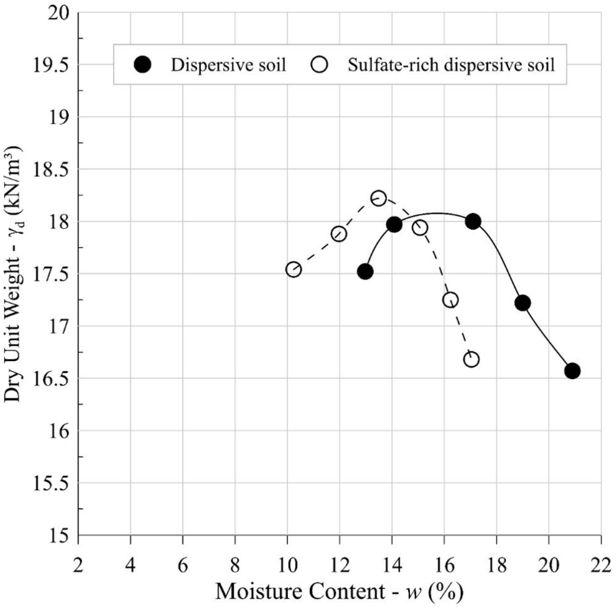

Figure 2. Compaction curves.

Table 2. Soluble salts content.

Parameter/Elements	Sulfate-rich dispersive soil	Dispersive soil
Na (cmol/kg)	44.91	13.90
K (cmol/kg)	0.21	0.50
Ca (cmol/kg)	15.80	0.60
Mg (cmol/kg)	4.53	0.20
TDS (*Total Dissoluble Salts*)	65.45	15.20
PS (*Percent Sodium*)	68.60	91.40
SAR (*Sodium Adsorption Ratio*)	14.09	21.98
pH	8.54	8.52

2.2 Chemical properties

Table 2 present the results of the soluble salts contained in the pore water of the studied soils. The pore water extraction and the determination of the soluble salts content was carried out in according to ASTM D4542 (ASTM, 2015a) standard. The total dissoluble salts (TDS) is the sum between the content of the soluble salts, while the percent sodium (PS) and the sodium adsorption ration (SAR) were determined, respectively, with the following Equations 1 and 2:

$$\mathrm{PS}\ (\%) = \left(\frac{\mathrm{Na}}{\mathrm{TDS}}\right) \mathrm{x} 100 \tag{1}$$

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{0.5\ \mathrm{x} \left(\mathrm{Ca} + \mathrm{Mg}\right)}} \tag{2}$$

Those parameters are an indicative of the soil' dispersive potential, as the presence of sodium cations can be seen as the main reason for the dispersion observed amongst clays. Thus, both soils can be classified as dispersive accordingly to Sherard et al. (1976) diagram, which is illustrated in Figure 3 and relates the dispersibility to the TDS and PS. Moreover, soils that present SAR values greater than 13 are defined as dispersive by the United States Department of Agriculture (2017), which is the case for both soils studied herein.

Table 3 presents the water-soluble sulfates content for the sulfate-rich dispersive soil. The determination of the sulfates content followed the recommendations of the ASTM C1580 standard (ASTM, 2015b), and yielded a total of 14229 ppm. There is not exactly a precise value of sulfates content that can be taken as critical, as the researches on the area point out that there are other important factors that affect the ettringite formation in the stabilized soil, such as availability of water and soil mineralogy (Hunter, 1988; Mitchell & Dermatas, 1992; Dermatas, 1995). However, based upon previous researches, was stated that soluble sulfate contents higher than 3000 ppm may require special attention for soil stabilization purposes (Mitchell & Dermatas, 1992; Dermatas, 1995; Berger et al., 2001; Harris et al., 2004; Little & Nair, 2009a, b; Jones et al., 2010). Furthermore, it's a consensus that amounts higher than 10000 ppm are serious and demand specific considerations (Hunter, 1988; Berger et al., 2001;

Table 3. Soluble salts content.

Soluble salts	Sulfate-rich dispersive soil
$CaSO_4$ (ppm)	5372
K_2SO4 (ppm)	93
$MgSO_4$ (ppm)	1351
Na_2SO_4 (ppm)	7576
$NaHCO_3$ (ppm)	215
NaCl (ppm)	7396
Total of salts (ppm)	22003
Total of sulfate salts (ppm)	14229

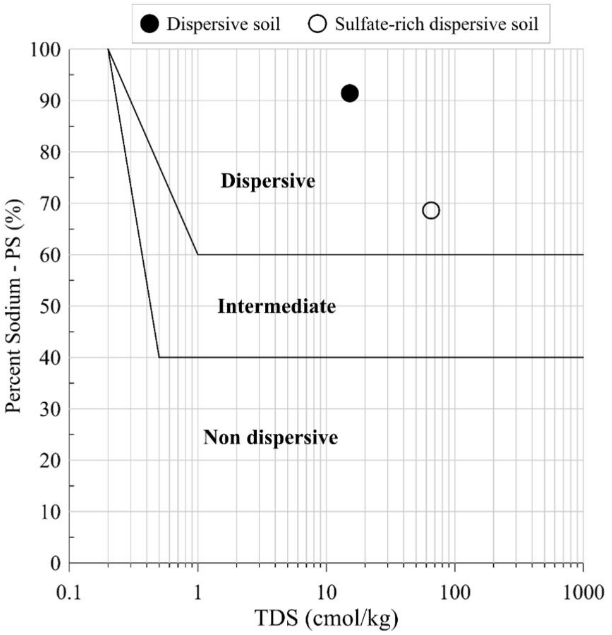

Figure 3. Diagram of identification.

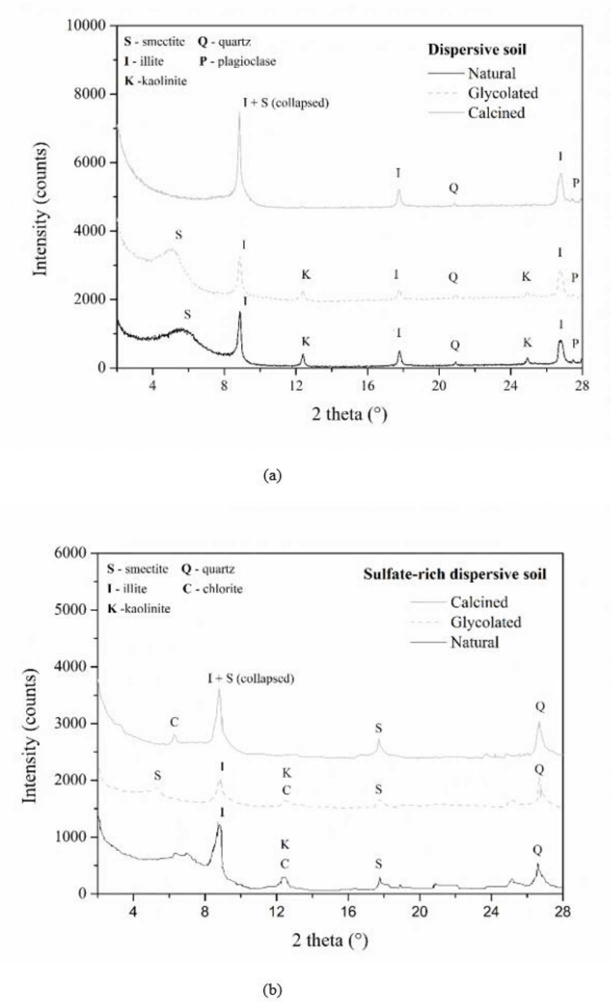

Figure 4. (a) XRD of the dispersive soil (b) XRD of the sulfate-rich dispersive soil.

Little & Nair, 2009a, b), which is the case of the sulfate-rich dispersive soil studied herein.

2.3 Microstructure

In order to assess the soils' mineralogy, with emphasis to the clay minerals, X-Ray diffraction tests (XRD) were carried out on the fractions finer than 4 µm of both. Therefore, for each soil, this fraction was isolated by means of a special process that encompassed (i) the disintegration using an orbital mixer along 14 hours, (ii) disintegration via ultrasonic tip during 5 minutes in a liquid solution and (iii) separation of the finer portion via decantation during a pre-defined time which was calculated based on the Stokes' law. Right after, plain slides were prepared by pipetting the soil on them. In order to precisely check for expansive minerals and/or minerals from the kaolinite group, three samples were tested within each soil. Namely, a sample with the natural soil, a glycolated sample aiming to verify the existence of expansive minerals (smectites) and a calcined sample (calcined at 550°C) intending to assure the existence of minerals that collapse its structure at that temperature. The tests were conducted on a Siemens (Bruker AXS) D-5000 diffractometer, equipped with copper anode tube and operated at 40 kV and 35 mA. The angular range adopted varied from 2° to 28° 2θ at rate of 0.02°/s.

The XRD results for the dispersive soil are depicted in Figure 4a, while the results for the sulfate-rich dispersive soil are exhibited in Figure 4b. For the first, the following minerals were identified: quartz (47.6%), illite (4.1%), kaolinite (3.4%), plagioclase (14.8%), K-Feldspar (19.3%) and smectite (10.8%). For the second, in turn, the presence of quartz (33.9%), albite (24.5%), chlorite (17.4%), illite (14.5%), barium orthoclase (5.5%) and gypsum (4.2%) were attested. However, those quantities are merely semi-quantitative as they were based upon the Reference Intensity Ratio method (RIR).

Moreover, intending to visually assess the fabrics of both soils in a disintegrated state, scanning electron microscope (SEM) tests were carried out. Hence, Figure 5 presents the

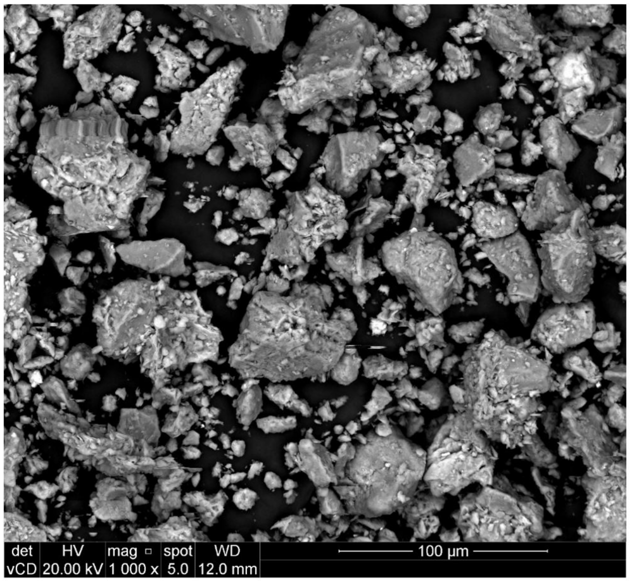

Figure 5. SEM image of the dispersive soil magnified 1000x.

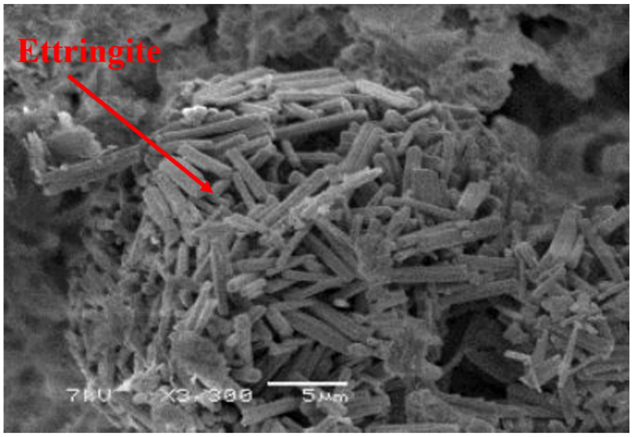

Figure 6. SEM image of the sulfate-rich dispersive soil magnified at 3300x.

SEM images of the dispersive soil, whereas Figure 6 exhibits SEM images of the sulfate-rich dispersive soil. In case of Figure 5, from dispersive soil, this figure focus on particle size and structure of clay minerals. The same approach was made to sulfate-rich dispersive soil, however, was also magnified the expansive minerals formation through calcium-based stabilizers addition, where ettringite crystals were depicted.

3. Conclusions

The present research intended to characterize in detail two problematic soils encountered in the region of the Paraguayan Chaco, from the data presented herein, the following assertions can be made:

- the results of the physical, chemical and mineralogical characterizations, when analyzed in conjunction, corroborate and explain the adverse behavior of the dispersive soil and of the sulfate-rich dispersive soil;
- the sulfate-rich dispersive soil is highly susceptible to ettringite/thaumasite formation when stabilized with calcium-based stabilizers as it possesses great quantities of soluble-sulfates and, as well, clay minerals that serve as an alumina source;
- both soils contain smectite, which is highly reactive and presents an elevated specific surface area, thus being capable to adsorb great quantities of sodium ions.

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Declaration of interest

The authors declare that there is no conflict of interest.

Authors' contributions

Hugo Carlos Scheuermann Filho: data curation, writing-original draft preparation. Gustavo Dias Miguel: conceptualization, methodology, validation. Lucas Festugato: supervision. Rubén Alejandro Quiñonez Samaniego: writing-reviewing and editing. Eduardo José Bittar Marín: writing-reviewing and editing.

List of symbols

TDS	Total soluble salts
SEM	Scanning electron microscope
CL	Lean clay
PS	Percent sodium
SAR	Sodium adsorption ratio
ppm	Parts-per-million
XRD	X-ray diffraction
RIR	Reference intensity ratio

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