Artificial Soil Development for Geotechnical Properties Evaluation

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ABSTRACT

The hydraulic and mechanical properties of soils depend of physical and chemical interaction between particles. The artificial soil pretends to decouple the interparticle interaction effects. These material is obtained from sodium silicon dioxide can be used in the laboratory for modeling geotechnical problems. This paper presents an inert material development. Images of scanning electron microscopy (SEM) and chemical compositions of soil have been determined by Energy Dispersive Spectroscopy (EDS). The materials designed have indices and physical properties equivalent to silty loess. Artificial and natural soils are compared in plasticity indices, particle size and maximum dry unit weight in Standard Proctor test. The mechanical characterization was made by one dimensional compression tests and hydraulic properties are tested. The potential of artificial soil material in geotechnical laboratory tests are discussed.

KEYWORDS: Natural loess soil, artificial soil, geotechnical properties.

INTRODUCTION

Large geological areas are covered by silty-clay loess soils (Zarate 2003). Their macroscopic behavior is related to formation process (Iriondo 1997). Hydraulic and mechanical performances of soil are based on chemical composition and particles structures (Arrúa et al. 2012). The chemical compounds with higher capacity reaction are organic materials, iron, aluminum and clay. These materials and their interaction with the particles determine the behavior mechanism.

The micro-structural instabilities have been extensively studied in loessic soils (Mitchell and Soga 2005, Lu and Likos 2004, Francisca et al. 2010, Arrúa et al. 2011). The collapse phenomenon controls the soil-structure relationship and foundation design. The cementation by presence of carbonate has been one of the highlights for many researchers, as the cause that prevents sudden decreased volume, but not much has been said about chemical degradation on interparticle links. The chemical components released into soil by human activities are the major cause of site contamination. In most cases the technical and economic consequences are irreversible. Both stress-strain relationship and volume of fluids infiltrates in soil mass are important geotechnical engineering aspects. The design of artificial and transparent soil, can be used in laboratory scale to study of soil structure interaction and contaminant transport problems.

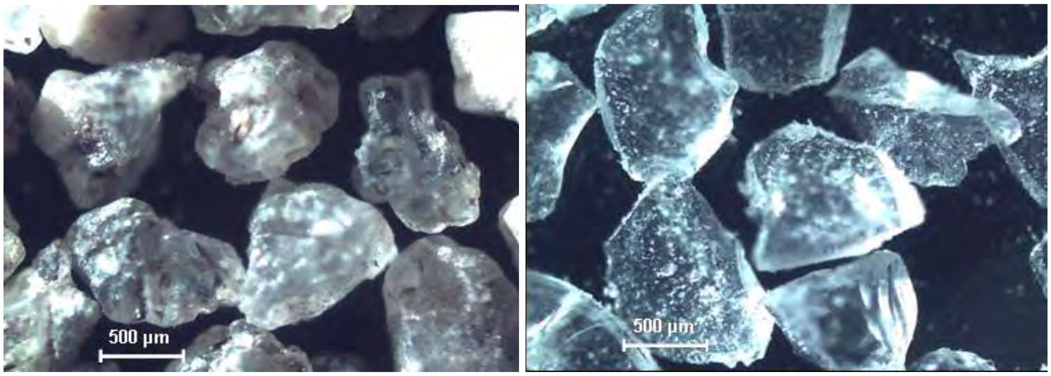
Frequently, silica gels are used to simulate artificial granular soils, but it has some limitations, for example: plastic deformation occur for low confining pressure, particles are fragile and can break or change color, mechanical property are not satisfactorily simulated for fine sand, de-airing internal pores is impractical for quantities that are required for large scale test and are hygroscopic materials (Iskander et al. ab 2002, Sadek et al. 2002, Iskander 2010). Granular soil from Córdoba Argentina can be made with sodium silicon dioxide. Figure 1 shows (a) sand particles from central area form Argentina and (b) silicon dioxide particles with sodium used to produce artificial soil with equivalent geotechnical properties to loessic soil. Figure 1 shows that both materials present similar uniform size and angularity. The principal difference between natural and artificial soil is the presence of chemical components which gives the material opacity or transparency.

Oxides of aluminum, iron and calcium provide the color of sand. Those types of oxides are not present in silicon dioxide and consequently the opacity is low. This work pretends to present an alternative to reduce the cation exchange in soil matrix. The chart presented for Mitchell and Soga 2005- Uday et al. 2013 are used to compare individual grains on visual estimation of Roundness (R), Sphericity (S), and Regularity (ξ). This paper presents the manufacture of artificial soil obtained from sodium silicon dioxide for experimental procedures in laboratory. Size distribution and loess soil structure are reproduced. This work presents the results of particle size distribution, particle morphology, chemical composition, compaction test results, mechanical and hydraulic behavior are presented.

EXPERIMENTAL PROCEDURE

The natural soil used as reference material, is CL-ML from Argentine central region. Grain-size distribution includes fine sand (1%-10%), silt (50%-80%) and clay (2%-15%). The chemical compositions of loess are mainly SiO_2, Al_2O_3, Fe_2O_2 y CaO. Oxides average soil components are SiO_2 =58%; Al_2O_3= 17%; Fe_2O_2 = 7%; CaO = 9%; MgO = 3%; K_2O = 4%; Na_2O = 2%. In natural conditions the water content ranges from 12.7% to 23.0%, the dry unit weight (kN/m^3) is 12.5 to 13.5, Specific gravity is 2.65 to 2.67, Atterberg limits are: liquid limit 23% – 30% and plasticity index 4.2% – 4.9% (Arrúa et al. 2005, Aiassa et al. 2011).

The chemical compositions of artificial soil, presented in this paper, are mainly SiO_2, Na_2O, MgO, CaO. Oxides average artificial soil component are SiO_2 = 80%; Na_2O = 11%; MgO = 4%; CaO = 3%; Al_2O_3 = 1%; Fe_2O_2 = 1% (Vogel 1994, Shelby 2005).



(a) (b)

Figure 1: Grain morfology. (a) Sand (b) Sodium silicon dioxide

The inert soil was produced by a ball mill with stainless steel drum. The internal diameter of the drum is 19,05 mm, and spins at 81 rpm. The electric motor specifications are 124 J s-1 and 1500 rpm. The device has a speed reduction system by belts and pulleys. The artificial soil water content can be modified in the laboratory as required. The dry unit weight can be obtained without trouble in a range of 11 to 15 (kN/m^3). The specific gravity is 2.4 to 2.5, liquid limit 24% to 28% and plasticity index 2% to 4%.

The desired inert soil grain size can be achieved by different time of milling. An acceptable approximation to the natural soil grain size distribution used in this work is accomplished using artificial material passing sieve No. 20 and retained on No. 30 after milling for 60 minutes. The material obtained by milling is then dried in an oven to 105 ºC during 24 hours. Then, the material was classified in particle diameter by mechanical sieving using sieves No.10, No.20, No.40, No.60, No.100, No.200 (ASTM, 2012). (ASTM, 2012). From grain size distribution curves performed on three samples of silty loess obtained at different depths, the artificial soil percentage for each particle size was defined (Natural soil A=1,0m; Natural soil B=2,0m y Natural soil C=3,0m). Then, the material was mixed mechanically to obtain the particle size distribution shown in Figure 2.

The particle morphology, roughness and roundness have been determined by a Scanning Electron Microscope (SEM) and the chemical components of loess and artificial soil have been determined by an Energy Dispersive Spectroscopy analysis (EDS). For this purpose, samples of natural and artificial soil were preserved for 48 hours at 220°C, in order to cause ignition of the organic matter.

The laboratory compaction test were measured by standard test method using standard effort (ASTM D698) commonly referred as Proctor Standard. The compaction curve presents the relationship between dry unit weight (γ_d) and water content (ω). The optimums were obtained from approximation curves.

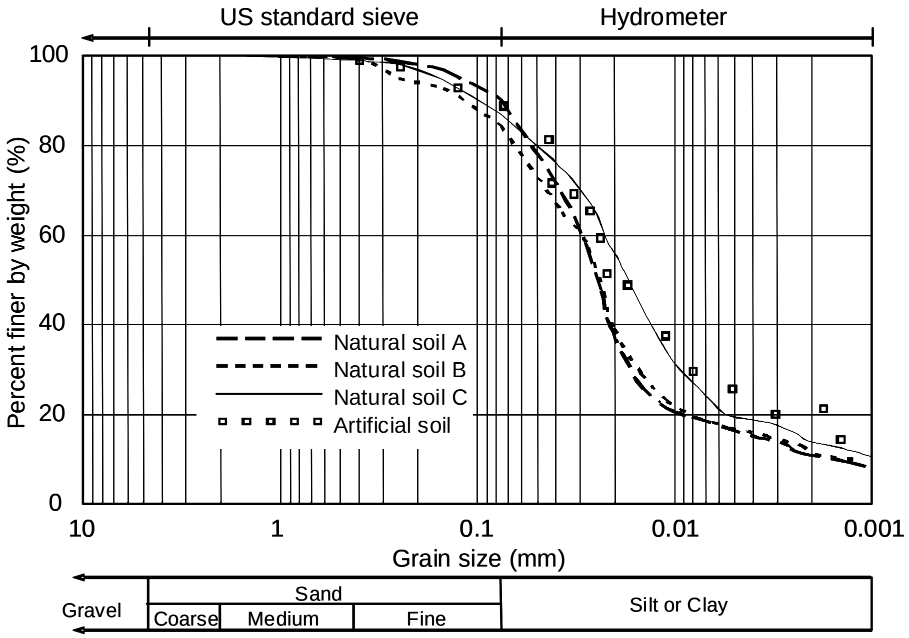


Figure 2: Grain size distribution. Natural loess soil and artificial soil

The mechanical behaviour was studied from confined compression test. The samples were remoulded under different static compaction level and constant water content of 21%. The tests were conducted in eight load stages. The compression coefficients were defined on oedometric stress-strain curve by the equations (1):

$$C_r = \frac{(\varepsilon_2 - \varepsilon_1)}{log\left(\frac{\sigma_2}{\sigma_1}\right)} \quad ; \quad C_c = \frac{(\varepsilon_8 - \varepsilon_7)}{log\left(\frac{\sigma_8}{\sigma_7}\right)} \tag{1}$$

Where C_r = reload compression coefficients, C_c = load compression coefficients. The subscripts indicate the load step considered in the coefficients calculation. The segments of the curve defined by the coefficients C_r y C_c allow obtaining the yield pressure P_f according to equation (2).

$$P_f = 10\,exp\left(log(\sigma_7) - {}^{Cr}\!/_{Cc}\,log(\sigma_1) + (\varepsilon_1 - \varepsilon_7)/\,Cc\right) \tag{2}$$

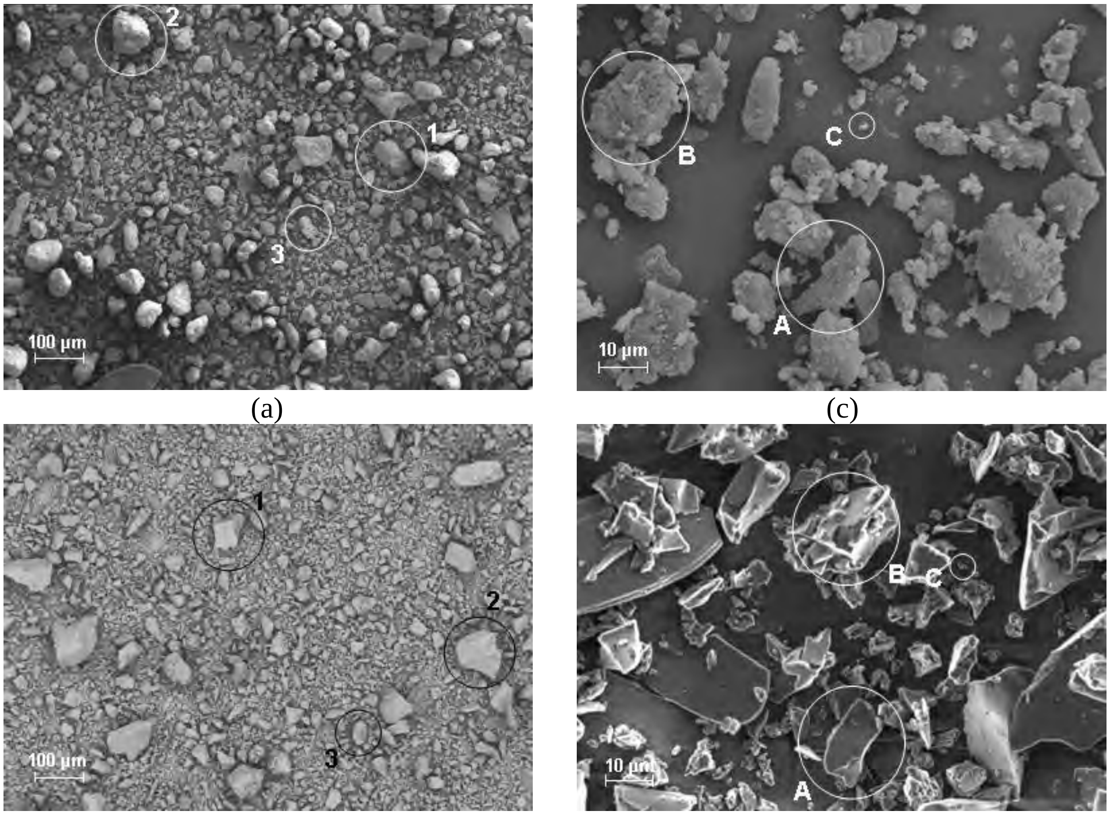
Relationships between applied pressure of 100kPa (σ^{100}) and strain (ε^{100}) defined the oedometric modulus $E_{edo}{}^{100}$.

The permeability was valuated using rigid-wall permeameter by falling head test. Distilled water was used as fluid. The natural and artificial soil samples were molded to equal void ratio (e = 1) and initial water content (ω_{ini} = 15%).

RESULTS AND DISCUSSION

Shape and Chemical Composition

Figure 3 presents a SEM images taken with 100µm and 10µm scales of the natural and artificial soil. Twelve equivalent geometric characteristics particles have been identified. The purpose of this representation is to compare the morphology of particles. Random spatial distribution of the particles of natural and artificial soil show remarkable similarities. The numbers 1, 2, 3 and letters A, B, C shows similar materials. Natural soils present rounded border with porous surface generated by smaller particles agglutination with larger attractive forces (Figure 3 (a)-(c)). The particles 1, 2, 3, are size like fine sands or silts. In artificial soil the surface is smooth and the borders are angular and irregular. The particles A and B, have a size silt, while particles C are like clays.



(a) (c)

(b) (d)

Figure 3: Soil and artificial soil grain size distribution at 100µm and 10µm. (a) – (c) Natural soil. (b) – (d) Artificial soil

The Energy Dispersive Spectroscopy presented in Figure 4, shows the differences in the chemical compounds present in the natural soil and artificial soils. The percentages of silica and sodium are the most abundant in the artificial soil. A level content of Ca (5.9%) and Mg (2.6%) are presented. The natural soil has aluminium compounds, potassium, calcium and iron that are primarily responsible of colouring and mechanical and hydraulic behaviour.

The shape and connection between particles are inherent soil characteristic related to macroscopic mechanical properties. The morphology describes at large scale the sphericity level, and the texture in smaller scales reflects the local roughness. Tabla 1 presents the morphology and chemicals compounds of natural and artificial soils. Note that Roundness (R), Sphericity (S) and Regularity (ξ) are similar.

The classical geotechnical classification identifies both materials as ML. The amounts of clay particles are equivalent in size; however in artificial soil surface adhesion is not generated. The differences between the liquid limits and plasticity index are small. The specific gravity of the artificial soil is less than natural soil, which may be due to lower content of iron, aluminium and potash.

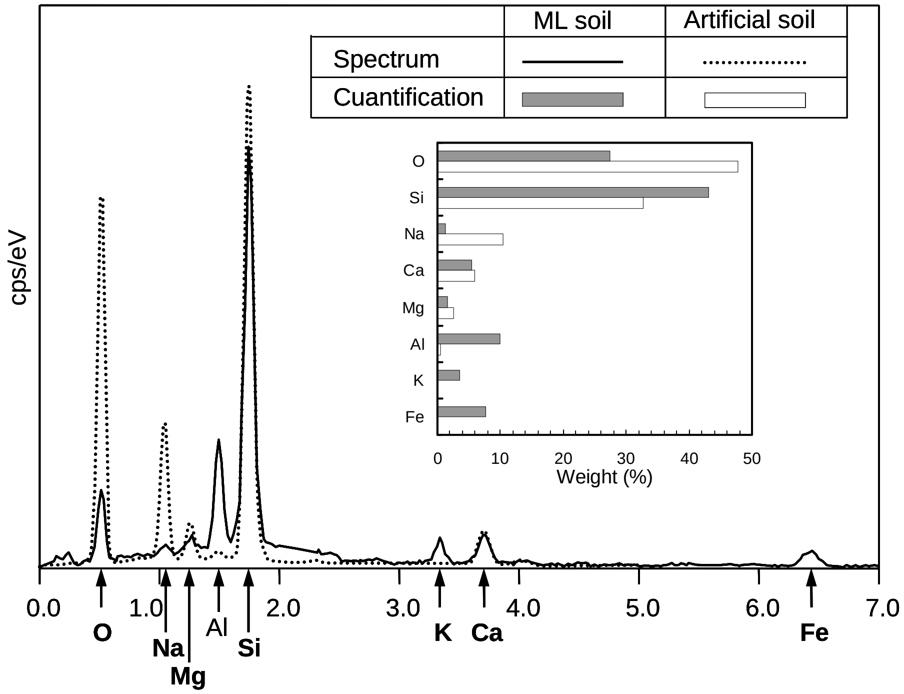


Figure 4: Energy Dispersive Spectroscopy test (EDS)

Maximum Dry Unit Weight

Compacted soils are frequently used in engineering works. The relationship between water content (ω) and dry unit weight (γ_d) is used to define the optimum water content (ω_{opt}) for maximum dry unit weight (γ_{dmax}) under constant effort. Figure 5 show results for natural and artificial soils. The natural soils has a compaction curve shape like silty soils, with $\omega_{opt} = 18.5\%$ and $\gamma_{dmax} = 17.2$ kN/m^3. The artificial soil has a compaction curve shape like sandy soils, with similar ω_{opt} and $\gamma_{dmax} = 15.8$ kN/m^3. The difference detected may be associated to different specific gravity of materials and reduced interaction between artificial soil particles.

Table 1: Morphology and chemical composition of natural and artificial soil

Description	Natural soil	Artificial soil
	Particle shape	
Roundness (R)	0.40	0.37
Sphericity (S)	0.57	0.52
Regularity (ξ)	0.48	0.44
	Geotechnical index	
PT200		
USCS	ML	ML
LL (%)	25.3	26.7
IP (%)	4.4	2.3
Gs	2.65	2.49
	Chemical Composition (weigth)	
O (%)	27.4	47.8
Si (%)	43.1	32.7
Na (%)	1.3	10.4
Ca (%)	5.4	5.9
Mg (%)	1.6	2.6
Al (%)	10.0	0.5
K (%)	3.5	0.2
Fe (%)	7.7	0.0

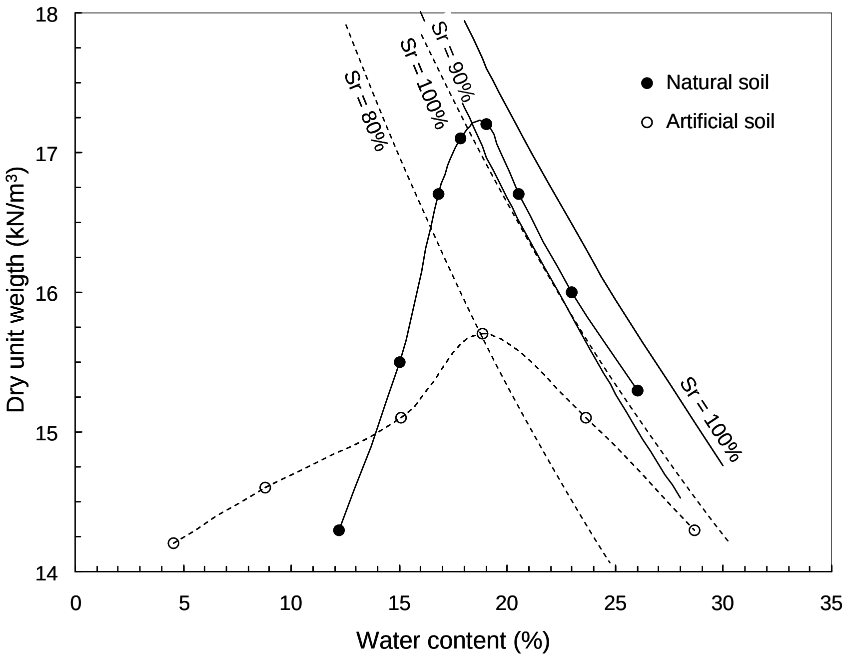
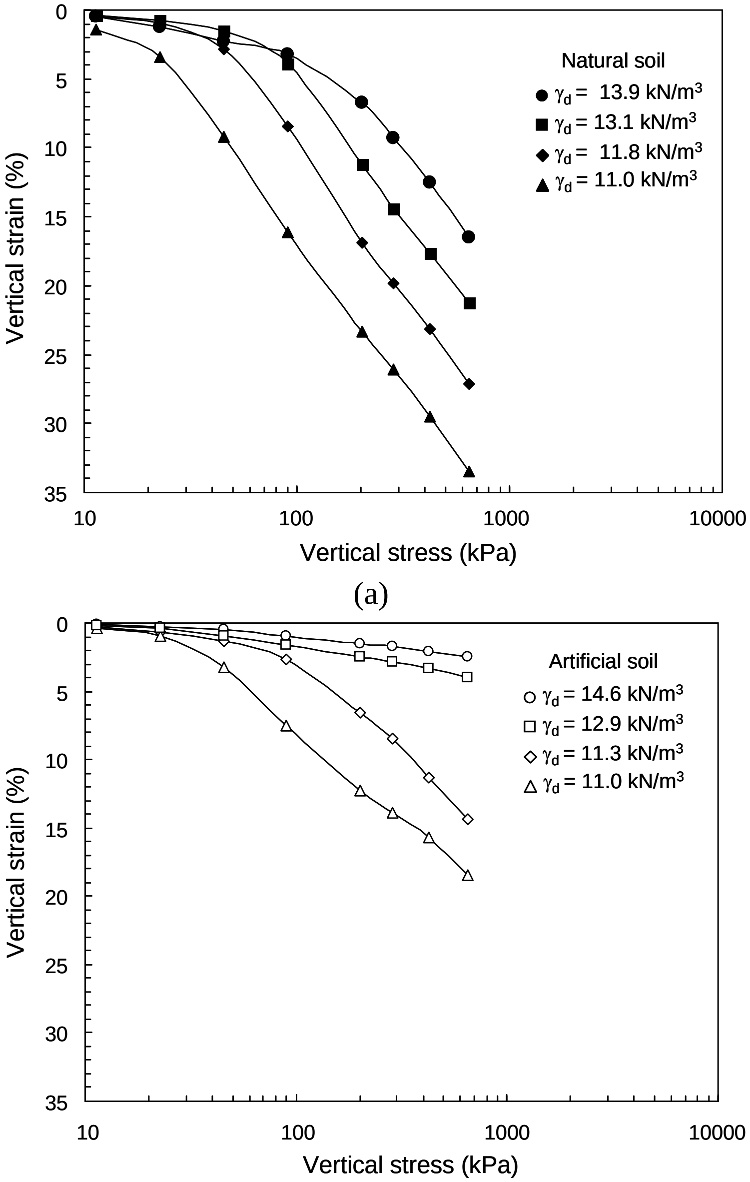


Figure 5: Water content vs. Dry unit weight

One Dimensional Compression Test

Both, artificial and natural samples have been molded with 25mm height and 65mm diameter. The test used was confined compression test on floating ring. All samples were prepared at 21% water content. The dry unit weight was varied. Compression characteristics were defined by applied stress of 11kPa, 23kPa, 45kPa, 90kPa, 202kPa, 286kPa, 425kPa, 648kPa. The load steps were made each 15 minutes. The test results are presented on Figure 6. For the two soils the strain is reduced while dry unit weight increased. However, the artificial soil is deformed less than the natural. Table 2 presents the compression parameters obtained from Figure 6.



(a)

(b)

Figure 6: One dimensional compression test. (a) Natural soil (b) Artificial soil

Table 2: Properties of natural and artificial soil samples

One Dimensional Compression Test (ASTM D2435)									
Natural soil					Artificial soil				
γ_d (kN/m^3)	Cr	Cc	E_{eod}^{100}(kPa)	P_f (kPa)	γ_d (kN/m^3)	Cr	Cc	E_{eod}^{100}(kPa)	P_f (kPa)
11.0	6.46	21.44	581	28	11.0	2.11	14.61	1250	48
11.7	1.41	22.30	940	36	11.3	1.32	16.67	3333	110
11.8	1.31	21.49	1052	40	12.0	1.44	11.01	4000	130
12.4	1.22	19.40	1205	62	12.9	0.79	3.38	5555	95
13.1	1.19	20.08	2128	63	12.9	0.39	1.51	7000	140
13.9	1.12	18.30	2435	128	13.4	0.66	2.38	8333	100
14.2	2.44	21.61	2857	162	13.9	0.53	0.96	9090	90
14.5	0.81	16.71	3500	140	14.6	0.53	2.18	10000	100
15.3	0.72	16.23	4100	165	14.9	0.79	2.39	9500	95

The oedometer modulus at 100kPa increased whit dry unit weight. The interparticle bonds play an important role in the materials behaviour. Figure 7(a) shows that natural soils have oedometer modulus lower than the artificial soils. If we consider a linear relationship the slop are 2.2 and 0.83 respectively. The results dispersion is 1Mpa for natural soils and 2Mpa for artificial soils.

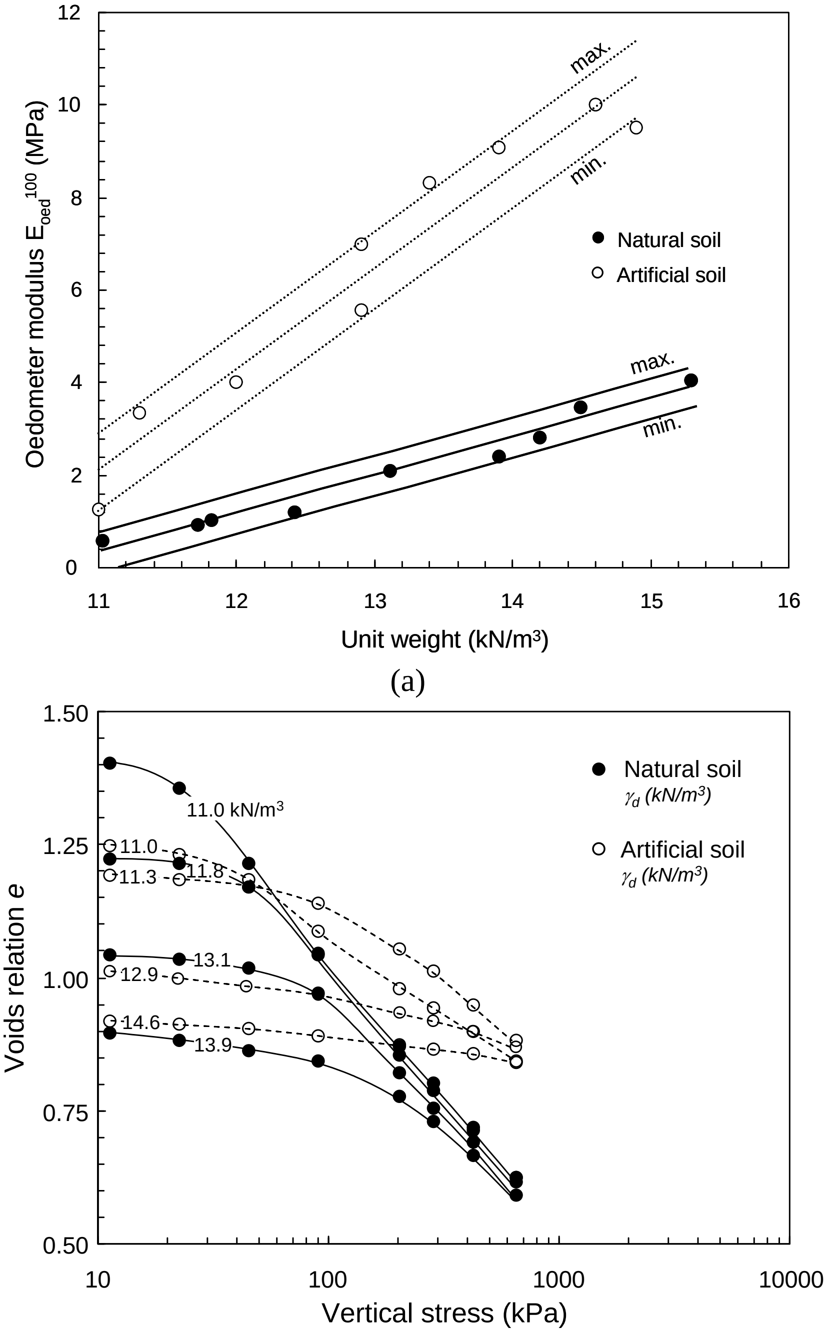
Due the specified gravity difference between materials, the dry unit weight could not to be a nice pointer. So, Figure 7(b) shows the relationship between stress and void relation. The final void relation is unique regardless the initial void relation value. The different final void relation could be explained by the different particle shape. The less sphericity and roundness observed on artificial soil could cause less specimen strain, due the interparticle locking.

Hydraulic Conductivity

The hydraulic behaviour of soil depends strongly, but not uniquely, of structure and chemicals composition. To permeability compare, specimens with the same void relation were made (e = 1). The fluid used was distilled water. The samples were prepared under static effort. The calculated dry unit weight was 12 kN/m^3, for artificial soil, and 13 kN/m^3, for natural soil. Figure 8 presents results. Similar values were obtained for two soils. The artificial soil permeability was 3x10^{-5} cm/s and for natural soil was 8x10^{-6} cm/s. The interesting of these results is the possibility of use artificial soils instead of natural soils for contaminant transport studies avoiding the fluid-particle interaction.

CONCLUSIONS

Artificial soil manufactured from sodium silicon dioxide can be used as inert material in laboratory tests for geotechnical purposes. Images from electron microscopy (SEM) indicate a soil structure equivalent to that of loess. The chemical composition has not presents iron oxides, aluminum or potassium. Geotechnical soil classification for artificial soil is (ML) and no interaction with the chemical matrix has been identified. The specific gravity is 2.49. The soil granulometry ML approaches, is obtained by grinding 1 hour to passing material retained T20 and T30. The Roudness (R), sphericity (S) and Regularicity (ξ) is 90% over the natural soil. The artificial soil have a maximum dry unit weight (standard Proctor) of 15.75 kN/m3, and degree of saturation of 80% at the optimum moisture content.



(a)

(b)

Figure 7: Mechanical behavior in one dimensional test. (a) Unit weight vs oedometer modulus (b) Vertical stress vs. voids relation

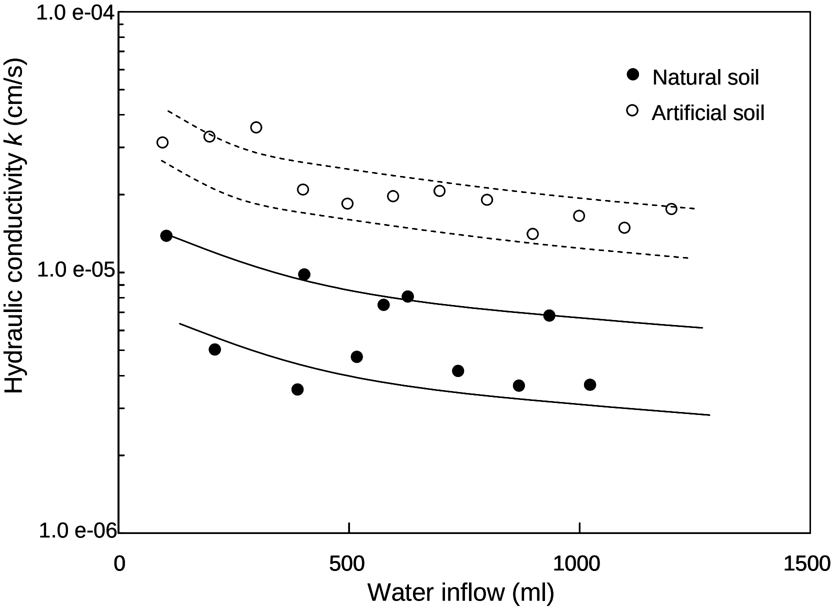


Figure 8: Permeability vs. volume inflow

Not identified a relationship between the dry unit weight and the yield pressure (P_f). The results dispersion for E_{eod}^{100} is 2 MPa. For loess soil void ratio achieved for a pressure of 648 kPa is e = 0.6. For artificial soil is e = 0.9. Infiltration in natural and artificial soil samples (*e* = 1) are in the same order of magnitude. This point has a particular importance because it is possible to have uncupled phenomena solute transport with the artificial soil developed in this work.

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