Unsaturated geomechanical and physicochemical characterisation of soils used for adobe blocks

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A mechanical and physicochemical characterisation of soil used for adobe block production is presented in this paper, considering a geomechanical framework. The main research objectives were to apply the partially saturated soil mechanics theory and obtain some of the soil's physicochemical characteristics. The soil used in this research was extracted from Putaendo, Chile, as it is representative of the vernacular building of that region. The soil was classified as fine sand, with little proportion of low plasticity fines. Further inspection showed a 7% content of organic matter. The unsaturated shear strength of the soil was obtained using a conventional shear box test, coupled with the soil-water characteristic curve (which was obtained using the filter paper technique) to estimate suction values. The soil-water characteristic curve had a similar shape as for other sands previously reported in the literature, but with a higher air entry and residual values. Results show that shear strength increases for drier soil samples, reaching an asymptotic value after the air entry suction of the soil. It is concluded that shear box tests without suction control can be used to estimate the unsaturated strength of soils and that the organic matter in soils can influence its cohesive strength, although further research on this aspect is required.

Keywords: Partial saturation, adobe blocks, earthen materials, organic content, shear box

1 Introduction

The mechanical behaviour of geomaterials is one of the principal concerns of the civil engineering discipline. Moreover, scientists are looking for alternative construction materials with lower environmental impacts that can help to mitigate the effects of climate change. In that regard, earthen blocks arise as a very sustainable material for the construction of residential buildings. Several researchers have studied their unconfined compressive strength, to use them to build safer and more environmentally friendly structures. However, the complex mechanics that occur in the three-phased material usually found in earthen materials (soil, water, and air) are not fully understood yet.

Earth blocks have been extensively studied in recent years, with a special emphasis on the evaluation of the effect of fibres and binders on their mechanical and physical properties [1]. Different authors have measured the changes in flexural and compressive strength due to the inclusion of plant [2], animal [3] and industrial fibres [2], and have concluded that fibres increase the toughness of the mixture [2], [3]. However, different results have been observed with regards to peak flexural and compressive strengths, with some authors measuring its increase [1], [4] while others observe its decrease [5]. One of the common points of the studies mentioned above is that most of them have employed a construction materials framework and measured failure properties, ignoring the soil mechanics perspective of the problem. In that regard, [6]–[8] have evaluated soil bricks under the soil mechanics framework. The first one observed that as the moisture content of the block increases, the unconfined compressive follows the opposite trend. This is in line with the increment of suction due to the reduction of water in unsaturated soils. On the other hand, [7], [8] considered an unsaturated soil mechanics approach to calculate the soil cohesion due to suction. Both authors found that the shear strength of the soil is proportional to the suction, obtained from the soil-water characteristic curve (SWCC).

A second challenge for the analysis of earthen blocks is the broad range of soils used for their production, as has been previously pointed out in the literature [9]. Low consensus on the optimal soil type for this use has been achieved, as some authors propose an amount of clay for the blocks [4], [10], whilst others do not [9], [11]. This hinders the ability to create standards for earth block production, as the physicochemical properties of each employed soil might vary vastly. As an example, in their study, [11] showed that soils with identical classifications can produce contrasting physical and mechanical properties when used for adobe blocks matrices production.

Hence, the objectives of the present research are: (i) to characterise the type of soil used for Chilean adobe block vernacular buildings, and (ii) to observe if the standard shear box test without suction control can be used to measure unsaturated shear strength.

2 Materials and Methods

2.1 Soil Sample

The soil used in this research was collected from an adobe manufacturing pit located in Putaendo (Chile) and air shipped to London (United Kingdom) for its analysis. The particle size distribution of the soil was obtained using a mechanical sieve shaker following the procedures stated in the British standards [12] and can be seen in **Fig. 1**. Alongside this, using the same standards, the plastic and liquid limits were also obtained, which had a value of 35 and 40% respectively, and fall in the category of ML & OL in Casagrande's plasticity chart. Finally, the specific gravity of the soil was measured and resulted in a value of 2.54.

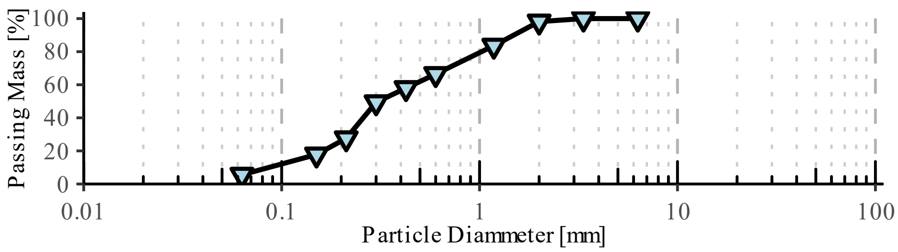

Fig. 1. Particle size distribution of the studied material

2.2 Organic Content

To obtain the organic content of the soil, a thermogravimetric analysis (TGA) was used. The soil was tested using a heating ramp of 20 °C/min, in three stages: (i) from 0 to 150 °C, (ii) from 150 to 550 °C, and (iii) from 550 to 950 °C as per the suggestions of [13]. After each stage was completed, the temperature was left constant for 30 minutes to ensure all the compounds were incinerated. The organic content of the soil was calculated as follows:

$$OC = \frac{(M_{150^\circ} - M_{550^\circ})}{M_{150^\circ}} \quad (1)$$

where OC is the organic content of the soil in percentage, M_{150° and M_{550° are the mass measurements at the end of the first and second stage respectively. Two samples of 30 µg each were used for this test.

2.3 Scanning Electron Microscope (SEM) – Energy Diffractometry Spectroscopy (EDS)

To observe the differences between coarse and fine soil particles, SEM coupled with an EDS was employed in this study to obtain both images and the chemical components of each part of the soil. Tests were performed on two specimens taken from the complete soil sample and two from the fractions that passed the 63 µm sieve; the weight of each sample was approximately 5 grams.

2.4 Soil-Water Characteristic Curve (SWCC)

For this study, the SWCC was obtained for the soil using the non-contact filter paper method (total suction), as stated in the ASTM D 5298 standard [14], and was calibrated as per the suggestions of [15]. The suction was then correlated to the calibration curve and the moisture content of the paper. Fig. 2 shows the SWCC, which starts at a suction value of 0.1 kPa, because the logarithmic scale diverges at 0. Initial voids ratios for unsaturated samples varied between 0.91 and 1.38, while their moisture content ranged between 5 to 23%. Values obtained using the filter paper technique are plotted in the figure, whereas the regression line using the model proposed by [16] is also represented. It is worth mentioning that two other points were obtained at saturations closely to 100%

and were used to calculate the regression curve but are not plotted due to their low suction (i.e., 10^{-7} kPa).

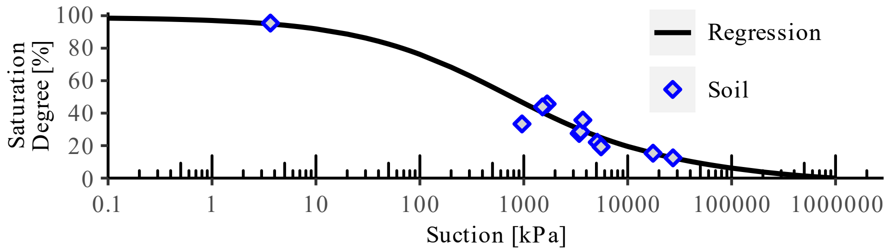

Fig. 2. Soil-water characteristic curve

2.5 Shear Box Test

To obtain the effective shear strength of the soil, the shear box test was used following the recommendations stated in the British Standard [17]. Normal stresses of 40, 177 and 354 kPa were used. Normal stresses of 40 and 177 kPa are common service conditions for walls in adobe houses, and the normal stress of 354 kPa was selected to evaluate high demand cases. Unsaturated tests were performed to evaluate the effect of suction on the soil with saturation degrees that ranged between 20 and 90%. All tests were performed using a displacement protocol of 0.5 mm/min, as the estimated permeability (with Hazen's formula [18]) of the soil is approximately 10^{-5} m/s.

The specimens were prepared inside the shear box, by pouring a controlled amount of soil and measuring the height of the sample. This allowed calculating the initial voids ratio of each sample individually. For all samples, the soil was cooled down for 3 hours under laboratory conditions after being oven-dried at 105 °C for 24 hours and mixed with water to reach different moisture contents ranging between 5 to 30%. This was then let to homogenize for a period of 24 hours under laboratory conditions in a sealed container to avoid any moisture loss. The soil was then put inside the shear box to obtain an initial voids ratio of about 1.28, which is the value measured for plastic adobe samples. To evaluate the moisture content, an initial sample was taken from the container and this value was measured. After the test was concluded, a sample from the middle of each specimen inside the shear box was taken and its moisture content was also measured to check consistency between initial and final determinations.

3 Results and Discussions

3.1 SEM-EDS

Fig. 3 shows the microscopy images of the soil sample. Coarse particles (between 2.31 mm and 75 µm) have the typical shape of sands, with angular edges (Fig. 3a). Fine particles (smaller than 75µm) can be seen over the surface of the sand grains. When observing the fine particles, it can be noted that their shape is similar to peat soils [19], with a configuration of small webbed clusters. These particles have an average diameter of 40 μm, with a rough surface and angular edges. The results obtained from the liquid and plastic limits, the particle size distribution, SEM, EDS and TGA test all indicate a lack of clay and some amount of organic matter, which is different from what many researchers have found previously in their tested soils [1]. Although the cohesion of the soil for the saturated and dry shear box tests resulted in a low value (5.7 kPa), it could also be counted as a possible indication of organic matter. This is consistent with the results obtained for peat soils, which showed values for cohesion between 6 to 17 kPa [21]. However, due to the low accuracy of the shear box test, further study using triaxial test is suggested to validate the latter.

Table 1 reports the mineralogical composition of the soil, which shows that the coarse particles are composed mainly of silica, aluminium, and ferrous oxides, which is consistent with the chemical compounds of silica sands [20]. On the other hand, fine particles are composed primarily of carbon and silica, which is consistent with organic soils.

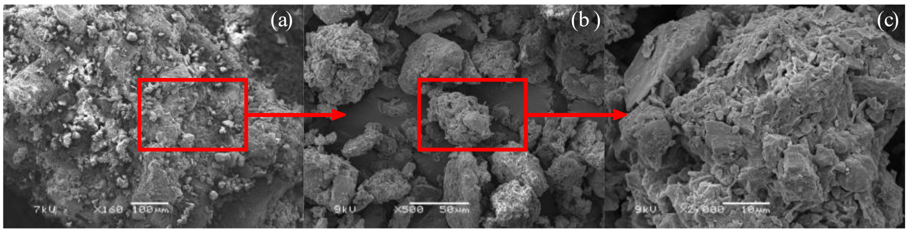

Fig. 3. SEM images of: (a) coarse grain, (b) fine particles and (c) close-up view of fine particles

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Table 1. Soil chemical composition

Particles	Na_2O	MgO	Al_2O_2	SiO_2	K_2O	CaO	TiO_2	C	Fe_2O_3
Coarse	3.71	2.05	22.94	53.06	1.85	2.02	0.7	-	9.08
Fine	0.88	1.7	7.08	18.97	0.94	1.5	0.35	64.93	3.44

3.2 Unsaturated Shear Strength

The unsaturated shear strength of the soil and suction are plotted in Fig. 4 for each normal stress (i.e., (a) for 40 kPa, (b) for 177 kPa and (c) for 354 kPa). Red triangles show the shear strength obtained at a failure state, whereas blue points represent the shear strength at a 20% shear strain state. Samples that had an initial voids ratio higher than 1.28 are plotted in grey. It is worth mentioning that the suction values were estimated using the SWCC, showed in **Fig. 2**. For the normal stress of 40 kPa, the shear stress varied between 35.7 and 42.1 for suction values of 360 and 7900 kPa respectively. Samples at vertical stress of 177 kPa had a peak shear strength between 119 and 144, for suctions between 33 and 8950 kPa respectively. Finally, samples at a normal stress of 354 kPa showed shear strength values between 229 and 263 kPa for suctions between 3 and 5750 kPa respectively. It is worth reminding that these values only consider the samples with an initial voids ratio approximately of 1.28.

As suction increases, shear strength increases for almost all samples tested. The rate of increment is higher for suctions below the air entry value, of around 500 kPa, and continues to increase but at a lower rate, for suctions higher than 1000 kPa. The latter is consistent with the observations of [22], [23].

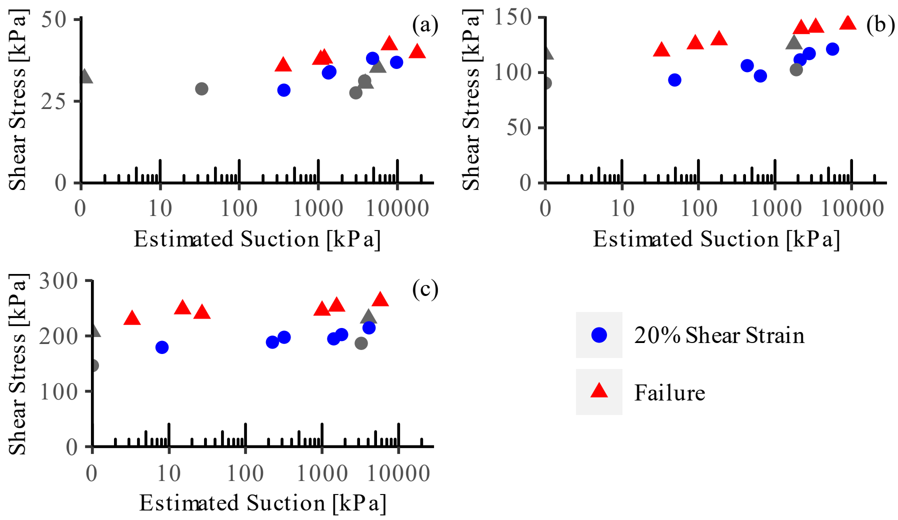

Fig. 4. Unsaturated shear strength at a normal stress of: (a) 40, (b) 177 and (c) 354 kPa

4 Summary and Conclusions

In this study, the partially saturated shear strength of a Chilean soil used in the production of adobe blocks is evaluated. A geotechnical characterization, the SWCC and the determination of the shear strength through the shear box apparatus were conducted. The major findings of this study are listed as follows:

1. The soil used in this study is a sand with low fines content. Its composition is different from most studied soils for earth brick manufacturing purposes, as those usually have clay. It is suggested that the organic content of the soil might

be helping in achieving the cohesive strength that allows the block to maintain its shape, but further research to confirm this assumption is needed.

2. The standard shear box test can be used to obtain the shear strength of unsaturated soils. However, it is suggested that another type of equipment, such as the triaxial, should be used, as the measurement of volumetric changes in the shear box apparatus might not be accurate enough.
3. The control of the initial conditions of the sample, mainly the voids ratio, has to be precise if accurate results are to be obtained. In general, it was observed that higher initial voids ratios resulted in lower shear strength values, even though suction was higher for those samples.

5 Acknowledgements

The authors would like to thank Dr F.C. Antico, Dr B. Baudet and Dr P. Ferreira for their suggestions, which greatly improved this research. The authors would also like to thank Mr. Boorman and Mr. Wilkinson for their help with the testing equipment, and Mr. Arnaldo Puebla, for showing and teaching the traditional process of adobe manufacturing. Finally, the authors thank the Chilean National Agency for Research and Development (ANID) / Scholarship Program / DOCTORADO BECAS CHILE / 2020 – 72210077 for the founding of this research.

6 References

[1] Laborel-Preneron, A., Aubert, J. E., Magniont, C., Tribout, C., and Bertron, A., “Plant aggregates and fibers in earth construction materials: A review,” Constr. Build. Mater., vol. 111, pp. 719–734, 2016, doi: 10.1016/j.conbuildmat.2016.02.119.

[2] Concha-Riedel, J., Antico, F. C., and Araya-Letelier, G., “Mechanical and damage similarities of adobe blocks reinforced with natural and industrial fibres,” Rev. Mater., vol. 25, no. 4, pp. 1–11, 2020, doi: 10.1590/S1517-707620200004.1206.

[3] Araya-Letelier, G., Concha-Riedel, J., Antico, F. C., Valdés, C., and Cáceres, G., “Influence of natural fiber dosage and length on adobe mixes damage-mechanical behavior,” Constr. Build. Mater., vol. 174, pp. 645–655, 2018, doi: 10.1016/j.conbuildmat.2018.04.151.

[4] Danso, H., Martinson, B., Ali, M., and Mant, C., “Performance characteristics of enhanced soil blocks: A quantitative review,” Build. Res. Inf., vol. 43, no. 2, pp. 253–262, 2015, doi: 10.1080/09613218.2014.933293.

[5] Pedergnana, M. and Elias-Ozkan, S. T., “Impact of various sands and fibres on the physical and mechanical properties of earth mortars for plasters and renders,” Constr. Build. Mater., vol. 308, no. 37, p. 125013, 2021, doi: 10.1016/j.conbuildmat.2021.125013.

[6] Bui, Q. B., Morel, J. C., Hans, S., and Walker, P., “Effect of moisture content

on the mechanical characteristics of rammed earth," Constr. Build. Mater., vol. 54, pp. 163–169, 2014, doi: 10.1016/j.conbuildmat.2013.12.067.

[7] Heath, A., Walker, P., Fourie, C., and Lawrence, M., "Compressive strength of extruded unfired clay masonry units," Proc. Inst. Civ. Eng. Constr. Mater., vol. 162, no. 3, pp. 105–112, 2009, doi: 10.1680/coma.2009.162.3.105.

[8] Beckett, C. T. S., Augarde, C. E., Easton, D., and Easton, T., "Strength characterisation of soil-based construction materials," Geotechnique, vol. 68, no. 5, pp. 400–409, 2018, doi: 10.1680/jgeot.16.P.288.

[9] Duarte, I., Pedro, E., Varum, H., Mirão, J., and Pinho, A., "Soil mineralogical composition effects on the durability of adobe blocks from the Huambo region, Angola," Bull. Eng. Geol. Environ., vol. 76, no. 1, pp. 125–132, 2017, doi: 10.1007/s10064-015-0800-3.

[10] Bouhicha, M., Aouissi, F., and Kenai, S., "Performance of composite soil reinforced with barley straw," Cem. Concr. Compos., vol. 27, no. 5, pp. 617–621, 2005, doi: 10.1016/j.cemconcomp.2004.09.013.

[11] Concha-Riedel, J., Antico, F. C., and López-Querol, S., "Mechanical strength, mass loss and volumetric changes of drying adobe matrices combined with kaolin and fine soil particles," Constr. Build. Mater., vol. 312, p. 125246, Dec. 2021, doi: 10.1016/j.conbuildmat.2021.125246.

[12] British Standards Institution, "Methods of test for soils for civil engineering purposes — Part 2: Classification tests," Br. Stand., no. 1, p. 40, 1990.

[13] Bensharada, M., Telford, R., Stern, B., and Gaffney, V., "Loss on ignition vs. thermogravimetric analysis: a comparative study to determine organic matter and carbonate content in sediments," J. Paleolimnol., vol. 67, no. 2, pp. 191–197, 2021, doi: 10.1007/s10933-021-00209-6.

[14] ASTM International, "ASTM D 5298 - 16 Standard test method for measurement of soil potential (suction) using filter paper," 2016 [Online]. Available: https://compass.astm.org/EDIT/html_annot.cgi?D5298+16

[15] Likos, W. J. and Lu, N., "Filter Paper Technique for Measuring Total Soil Suction," Transp. Res. Rec. J. Transp. Res. Board, vol. 1786, no. 1, pp. 120–128, 2002, doi: 10.3141/1786-14.

[16] Fredlund, D., and Xing, A., "Equations for the soil-water characteristic curve," Can. Geotech. J., vol. 31, no. 4, pp. 521–532, 1994, doi: 10.1139/t94-061.

[17] British Standard Institution, "Soils for civil engineering purposes: Part 7 : Shear strength tests (total stress)," London, BS 1377, no. 1, 1990.

[18] Hazen, A., "XXIII. Some physical properties of sands and gravels, with special reference to their use in filtration," in State Sanitation: A Review of the Work of the Massachusetts State Board of Health, Volume II, Harvard University Press, 2013, pp. 232–248.

[19] Aminur, M. R., Kolay, P. K., Linda, S. N., Taib, D., Ibrahim, M., and Ahmad Kamal, A. A., "Physical, geotechnical and morphological characteristics of peat soils from Sarawak," Inst. Eng. Malaysia, vol. 72, no. 4, p. 5, 2011.

[20] Mckeague, J. A. and Cline, M. G., "A. McKeague and M. G. Cline," Adv. Agron., vol. 15, no. 802, pp. 339–396, 1963.

[21] Kim Huat, B., "Deformation and Shear Strength Characteristics of Some

Tropical Peat and Organic Soils," Pertanika J. Sci. Technol., vol. 14, no. 1 & 2, pp. 61–74, 2006.

[22] Gan, J. K. M., Fredlund, D. G., and Rahardjo, H., "Determination of the shear strength parameters of an unsaturated soil using the direct shear test," Can. Geotech. J., vol. 25, no. 3, pp. 500–510, 1988, doi: 10.1139/t88-055.

[23] Vanapalli, S. K., Fredlund, D. G., Pufahl, D. E., and Clifton, A. W., "Model for the prediction of shear strength with respect to soil suction," Can. Geotech. J., vol. 33, no. 3, pp. 379–392, 1996.