Adobe material of the Temple of the Sun, Pachamac, Peru: engineering geological classification and sustainability assessment as a chalenges

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Abstract: Only two small pieces of an ancient adobe from an important archeological site near Lima were available for a laboratory research, making the engineering geological soil classification challenging. An experienced engineering geologist is able to assess the most important physical properties of the soil if it is properly classified according to STN EN 72 1001: 2011. However, less than 100 g of the material are insufficient for standard classification tests common in Slovakia. How to carry out the engineering classification of such a small sample? The answer to this question is the main goal of this study. Searching for an alternative, a SEDIGRAPH was used instead of the Casagrande hydrometer method for the grain-size analysis, and water adsorption by the Enslin - Neff method gave input data for both the liquid limit and plasticity index calculations according to Dieng (2006). This allowed the engineering geological classification of the material as a clayey sand, class S4, symbol SC (STN 72 1001:2011). Additional mineralogical analyses confirmed the low content of clay minerals and explained the low plasticity also due to the low amount of the expandable vermiculite in the bulk sample. Consequently, several conclusions can be made about other physical properties of that adobe based on general experience with the soils from the class S4. To take advantage of the available test results, an approximate sustainability assessment of the adobe became the secondary goal of the case-study. The low content of cohesive particles makes the adobe quite brittle, load-sensitive, but minimizes destructive volume changes when saturated with water. The related higher hydraulic conductivity and erodibility, higher than in a typical adobe with high content of fines, are a matter of concerns due to the specific local climate with occasional heavy rains. The less known laboratory methods applied in this case-study are a good alternative if the size of the soil sample is too small for standard classification tests (objects protected by law etc.). This is the most important outcome, because a proper engineering geological classification can tell a lot about the physical properties of the soil, as illustrated in this case-study.

Key words: Pachacamac Temple of the Sun, adobe, engineering geological classification, grain size analysis, Enslin – Neff, mineralogical analysis, clayey sand

1. INTRODUCTION

A standard procedure for the engineering geological classification of fine-grained soils consists of the determination of the grain-size distribution and Atterberg consistency limits, i. e. liquid limit w_L (%), plastic limit w_P (%), and of the calculation of the plasticity index $I_P = w_L - w_P$ (%) (STN 72 1001:2011). Based on these results, the engineering-geological or geotechnical soil class can be attributed. In Slovak geotechnical laboratories, soil sieving combined with the sedimentation method using a Casagrande hydrometer is a standard procedure of the grain-size analysis. This requires at least 80 to 100 g of a clayey or silty sand sample (STN EN ISO 17892-4: 2016). Another 200 to 300 g are needed for the standard cone test of w_L and the plastic limit test (BS 1377: 1990). The minimum mass for an engineering-geological classification would be 300 g of soil. However, less than 100 g of the adobe material (Fig. 1) were available for analysis from the Temple of the Sun at the Pachacamac archeological site near Lima, Peru.

Fig. 1 The original size of the sample available for the engineering geological/geotechnical classification

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It is the largest and most impressive building at Pachacamac (Solar, 2011). Adobe, also known as mud bricks, is the building material consisting of raw earth or clay usually mixed with straw, dung or other additives, fashioned into sun-dried un-burnt bricks (the term adobe is often used for buildings constructed from such bricks, as well). The 2000 years old complex was on the Tentative World Heritage List of UNESCO since 1996 (http://whc.unesco.org, 2014-04-30). Any non-standard, sample-saving methods had to be adopted for the classification of the small sample. The proof of a concept of applying existing laboratory techniques to limited sample material was the primary goal of this study. Additional mineralogical analyses not only supported the results, but together with the engineering geological classification, they allowed a sustainability assessment for this adobe as a secondary goal. Considering all data, some conclusions could be done about its mechanical properties, followed by a suggestion to the adobe preservation. The paper shows the hidden informative potential of a small piece of material for engineering geologists.

2. PACHACAMAC ARCHEOLOGICAL SITE

The site is located at the central Peruvian coast, 25 km east of the Lima center (Fig. 2), at the Lurin River where it enters the Pacific Ocean.

A very brief overview of the cultural history and the present situation was published e. g. by Solar (2011). Construction at

Fig.2 Location of Pachacamac (with the blank map from mapsoft.net, 2020-11-09)

Fig.3 Ruins of the Temple of the Sun , Pachacamac archeological site, Peru

the site was begun at the Old Temple (200 BC – AD 500) by the Lima culture, later continued by the Huari culture with their monuments. The Inca contributed the massive Temple of the Sun (Fig. 3) and the House of Chosen Women before the arrival of the Spanish in 1533. With the volume of 300 000 m^3 of soil, the Temple of the Sun is the largest and most impressive building at Pachacamac, but also the biggest Inca construction on the Pacific coast (Solar, 2011; Pozzi-Escot et al., 2017).

Pachacamac became the most legendary home of powerful oracles who lived and prophesied in the temples. Then, within

Fig. 4 Shape and size of adobe bricks compared to a 0.5 l bottle

just a few years, one of the largest Inca sites in Peru was abandoned. It is comprised of pyramides (compacted earth within retaining walls), palaces, cemeteries, roads and other structures built from mud bricks (Fig. 4), i. e. adobe (Thompson, 2012; Canziani, 2016).

For such building material, climate is very important. Lima's climate is in transition between mild and warm, despite being located in the tropics and in a desert. Although classified as subtropical, Lima's proximity to the cool waters of the Pacific Ocean leads to temperatures much cooler than those expected for a subtropical desert, and can be classified as a mild desert climate (Capel Molina, 1999). The relative humidity is always very high, particularly in the mornings. In the winter, small water drops (*"garúa"*) are formed (air humidity 70 % – 100 %). Real rainfall is rare. Coastal districts like in Pachacamac receive only 1 to 3 cm of rainfall per year (mainly during the winter months) (World Meteorological Organization 2014; BBC 2014). But, sometimes in the summer irregular heavy rains occur, bringing floods into the subtropical desert (up to 16 mm/day) and destroying the adobe constructions. They are the result of the El Niño – Southern Oscillation (ENSO). Two mega events (1982/1983, 1997/1998) showed the high vulnerability of the adobe cultural heritage (Gamarra, 2014). Due to severe earthquakes (e. g. in 2007) together with weathering and erosion (by wind, insects and water), various destruction levels can be observed on the constructions and adobe (Fig. 5).

Fig. 5 Destruction of the adobe walls of the Temple of the Sun

Peru's National Museum began a program of reconstruction focused on the Temple of Sun already in the late 1930s. The Global Heritage Fond led three on-site workshops. In 2012 one of them was dealing with practical suggestions for the conservation of adobe sites to minimize earthquake damages (Thompson, 2012). Also the original material source for the adobe fabrication was searched in the Pachacamac surroundings. Samples from aeolian sediments of the sanctuary, from fluviatile sands of the Lurin River banks, from the lagoon, as well as from agricultural soils near the archeological site were studied and compared to samples of the Old Temple adobe by scanning electron microscope (SEM) technique (Torres & Chipana, 2014); but no outright source was identified. Pozzi-Escot & Torres (2016) studied the grain-size distribution of the adobe material, but no published data on the physical properties of the adobe material were available. Summarized knowledge about the Pachacamac site with all those different constructions was later presented also in a video available on internet and published with the same title, both by Pozzi-Escot et al. (2017). Most of the papers on Pachacamac are in Spanish language which makes a deeper archival study complicated for foreigners with language barrier.

3. METHODS

Before the grain-size analysis, the adobe material samples were dispersed with 10 % hydrogen peroxide. After the reaction had subsided and the extra H_2O_2 was removed, the water suspension was exposed to ultrasound for 15 minutes. The particle size analysis was carried out in combination with the clay mineral analysis. The coarse parts of the samples were fractionated using sieves with mesh-sizes ranging from 2 to 0.040 mm. The fine particles were analyzed by means of sedimentation analysis with a SEDIGRAPH III 5120 (Micromeritics, Georgia, USA). The fundamental physical phenomenon of this method is the absorption of low-energy X-ray by the solid phase in the suspension depending on the density that is continuously decreasing during the gravitational sedimentation (Andrenelli et al., 2013). The analysis was interpreted according to Stoke's law. Only 3 g of the sample are needed. Calgon was used for better disintegration of aggregates.

Instead of standard tests of Atterberg consistency limits, the water adsorption method by Enslin - Neff was used, where water sorbed by the sample due to capillary suction is measured in a special glass equipment (DIN 18132:1995; Petkovšek et al., 2010). This method requires only 1 g of the dry sample per measurement, tests with five samples were done. A blind test was used to measure the evaporation and to correct the measured water adsorption. Interpretation of w_L and I_P followed empirical relations published by Dieng (2006):

a) if $(w_A + 0.3w_{Ai}) \leq 210\,\%$, then $w_L = 0.61(w_A + 0.3w_{Ai})$ and $I_P = 0.51(w_A + 0.3w_{Ai}) - 13$;

b) if $(w_A + 0.3w_{Ai}) > 210\,\%$, then $w_L = 1{,}13(w_A + 0.3w_{Ai}) - 126$ and $I_P = 1.1(w_A + 0.3w_{Ai}) - 140$

where w_A is the water sorbed by the sample after 24 h testing duration, $w_{Ai} = w_{A100} - w_{A5}$ and w_{A100} is the water sorbed after 100 min, w_{A5} is water sorbed after 5 min (all in wt. %). Equations a) and b) are valid for $w_A > 40\,\%$.

For the bulk mineral analysis by X-ray diffraction (XRD), dried samples, ground in a rock mill to analytical size, were prepared according to the backloading method and X-rayed with a Panalytical XPert Pro MPD diffractometer with an automatic divergence slit, Cu LFF tube, 45 kV, 40 mA, and a X´Celerator detector. The samples were measured from 2° to 70° 2Θ. The recordings served as the basis for calculating the qualitative and semi-quantitative mineral content.

Before the analysis of clay minerals in the clay fraction, the samples were pre-treated as for the grain-size analysis, the <0.002 mm fraction was obtained by means of suspension centrifugation after last sieving. Cation exchange was the next step. 40 ml of the clay suspension were each mixed with 10 ml 4 N KCl solution and 4 N $MgCl_2$ solution, respectively, and shaken for 12 hours. The texture specimens were placed on ceramic platelets, onto which the clay suspension was sucked via low pressure. After the measurement by XRD, the platelets were put into ethylene glycol atmosphere (for the distinction of smectite and vermiculite) and the K-exchanged samples were put into the DMSO (dimethyl sulfoxide)-atmosphere (distinction chlorite / kaolinite). After the next measurement by XRD, the K-and Mg- exchanged specimens were heated for 2 hours at 550 °C (distinction of primary and secondary chlorite). After that the individual clay mineral phases were evaluated according to the same principle as the total mineral analysis. In general, the identification of the minerals and clay minerals was carried out according to Brindley & Brown (1980) and Moore & Reynolds (1997). For the simplification, the sum of clay minerals was considered to be 100 % in the semi-quantitative clay fraction analysis, other minerals of the clay fraction were not calculated.

In clay mineralogy, thermal analyses provide additional information about the clay minerals in a sample and are therefore used more and more in clay science. Clay minerals contain different amounts of hydroxyl groups which are liberated when energy is absorbed. Clay minerals also undergo considerable weight losses at moderate temperatures. Below 1000 °C, many lattice transformations in the clay minerals take place which are also reflected as energy changes (Mackenzie, 1964, Smykatz-Kloss 1974). Within the Simultaneous Thermal Analysis (STA), Thermogravimetric (TG) and Differential Scanning Calorimetry (DSC) measurements were done.

The STA analyses were carried out on Netzsch STA 409 PC Luxx®. Between 50 to 51 mg of the sample were weighed in a Pt-cup and then analysed in a controlled atmosphere with 50 ml/min air and 10 ml/min N2. The heating rate was 10° C/min, the samples were heated up to 1000°C.

The physical parameter measured in DSC is the difference in energy inputs into the sample and reference material, when both are subjected to a controlled temperature programme. Endothermal and exothermal reactions can be observed (Wilson, 1987). During TG measurements, changes of the sample mass were recorded.

Determination of total carbon C_{tot} was done by Leco TruSpec (sample ignition by 950°C, IR detection of CO_2) as mean of two measurements. Determination of total nitrogen N_{tot} was done in two steps: 1. reduction of NOx by Cu-catalysator, 2. determination of N_2 by thermal conductivity. Finally, mean of two measurements was calculated.

4. RESULTS

The sandy fraction is prevailing (75.5 %), the fine fractions represent only 24.5 % of the sample (silt 13.4 % and clay 11.1 %) (Fig. 6). A quite identical particle distribution was presented by Pozzi-Escot & Torres (2016a), where the content of fines < 0.063 mm was below 25 %, the rest was sand.

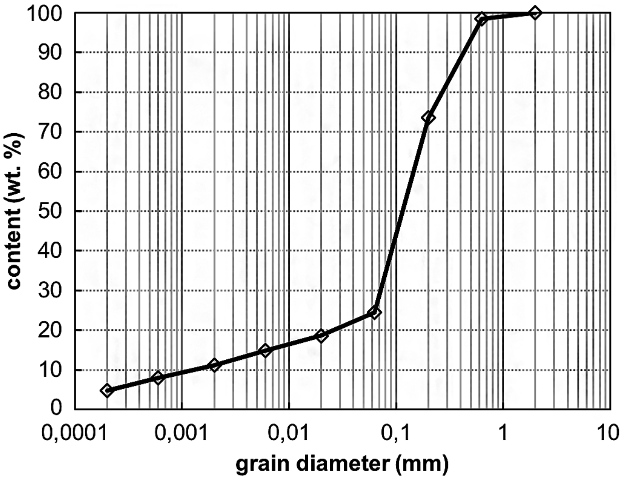

Fig. 6 Grain-size distribution curve of the adobe material

Figures 7 to 9 show volumes of sorbed water measured by Enslin-Neff in ml, which were later recalculated to w_A in wt. % and other parameters (Tab. 1). The mean value of w_L is 33 % and mean I_P is 14 %. As the water adsorption is low, the calculated plasticity of the adobe material is low, as well (Tab. 1), but above the A-line in the "silt-or-clay" classification plot (STN 72 1001: 2011).

Based on mean values, the tested adobe material can be classified as a clayey sand, class S4, symbol SC. This complies well with the findings of Pozzi-Escot & Torres (2016b) who stated that "the type of soil used in the confection of selected adobes of different buildings within the Pachacamac Sanctuary is lime sand, mix of sand and lime, with fine materials being non-plastic and of low plasticity", i. e. sand is the major fraction. However, no lime was identified in our samples.

Table 1 Results of the water adsorption w_A, liquid limit w_L and plasticity index I_P (other symbol explained in Chapter 3).

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
wA (%)	44	64	48	57	53
wA5 (%)	34	33	33	33	33
wA100 (%)	34	37	35	36	36
wAi (%)	0	4	2	3	3
wA+ 0.3wAi (%)	44	65.2	48.6	57.9	53.9
wL (%)	27	40	30	35	34
IP (%)	9	20	12	16.5	14

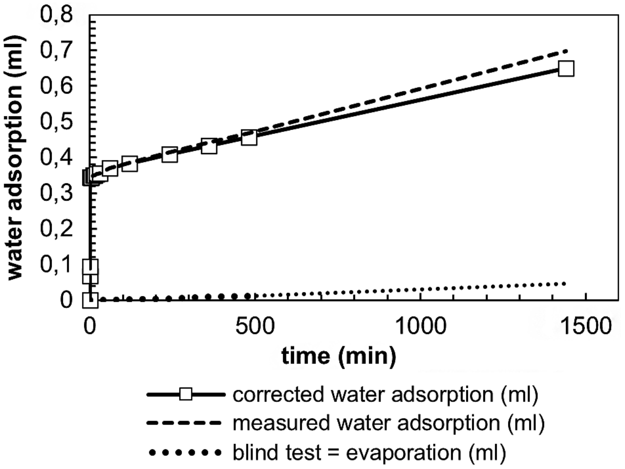

Fig. 7 Water adsorption by the Enslin-Neff method, an example of one measurement and its correction using a blind test of evaporation

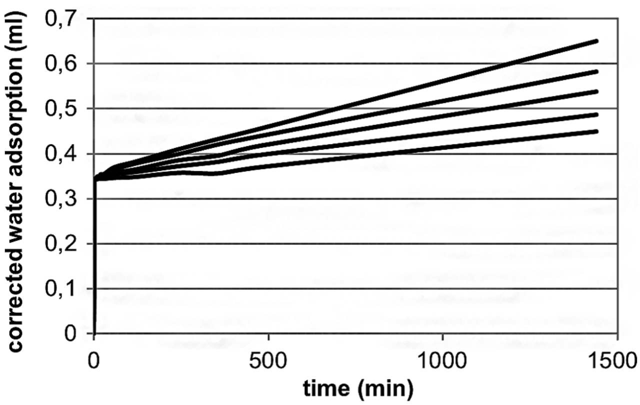

Fig. 8 Corrected water adsorption by the Enslin-Neff method, complete plots after 24 hours

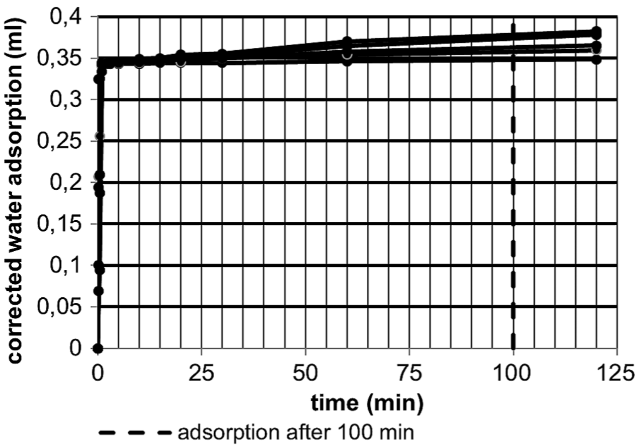

Fig. 9 Enslin-Neff in detail: curve segments used for the calculation of w_{Ai}

The XRD analysis of the bulk sample showed the following mineral assemblage (Fig. 10): plagioclase (48 %) and quartz (21 %) are major minerals, while orthoclase (13 %), mica (7 %) and amphibole (ca. 5 %) are minor minerals, the rest are clay minerals, mostly chlorite (ca. 2 %) and vermiculite (ca. 4 %). The semi-quantitative XRD analysis of the clay

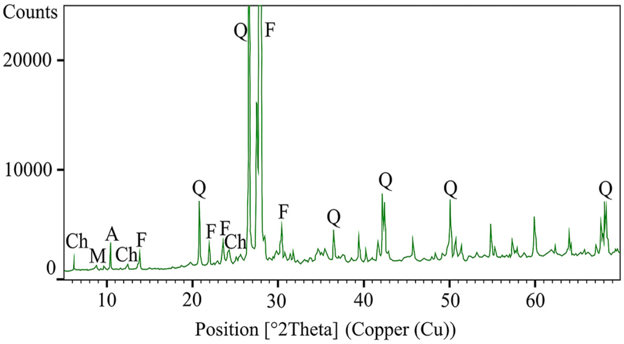

Fig. 10 XRD plot of the bulk sample. A – amphibole, Ch – chlorite, M – mica, F – feldspars, Q – quartz

fraction (Fig. 11) showed also illite (39 % of the clay fraction <0.002 mm) and the already mentioned vermiculite (40 % ditto) and chlorite (21 % ditto).

The low content of clay minerals is also reflected in the low mass of dehydroxilation water in the thermal analysis of the bulk sample (Fig. 12). The content of the organic matter represented by carbon (C_{tot} 0.256 %) and nitrogen (N_{tot} 0.024 %) is very low. It means that no organic additives are present which are currently used in modern adobe for better thermal insulation properties and higher tensile strength of less cohesive mud bricks.

The extraordinary features of this adobe, i. e. the extremely low content of fine grains and the missing organic material were found also by Martín & López de Azcona (1982) in the most eroded levels of the walls. The latter can be explained by the lack

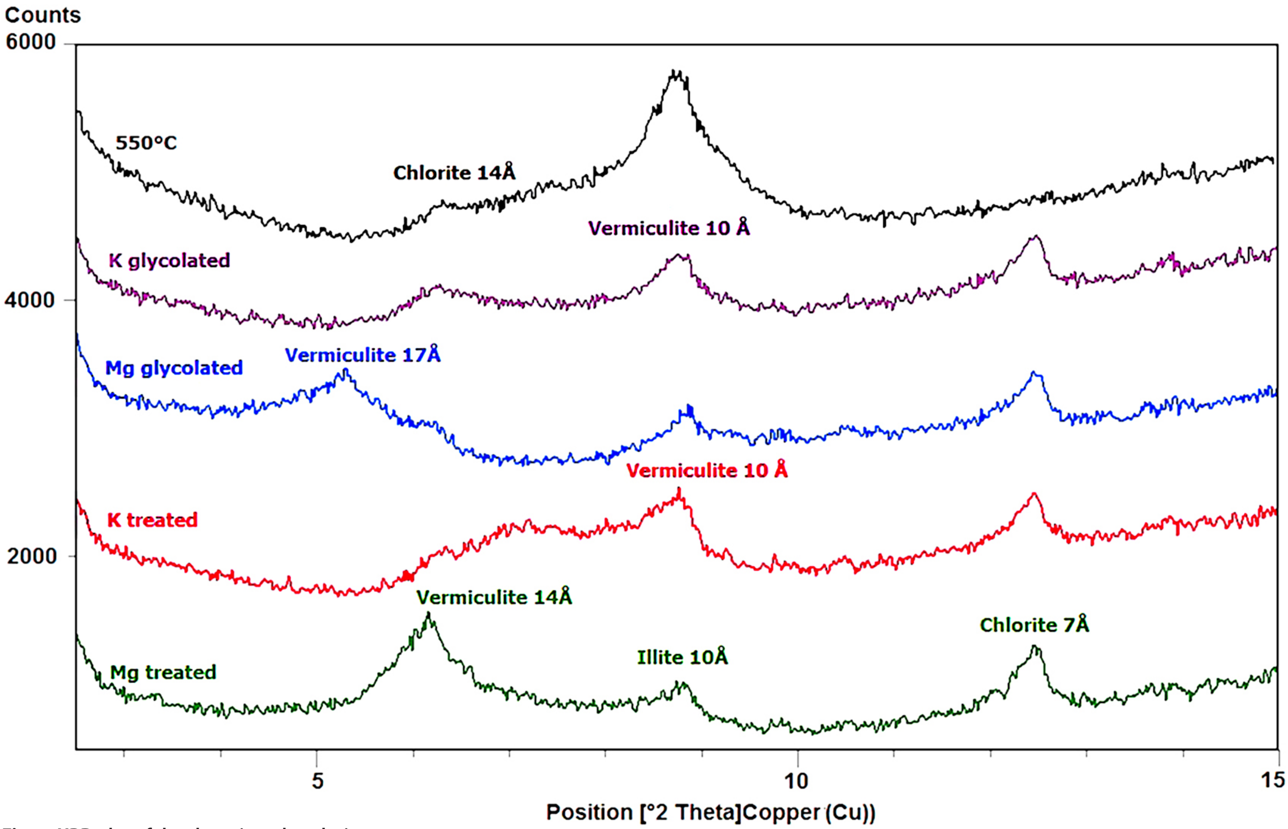

Fig. 11 XRD plot of the clay mineral analysis

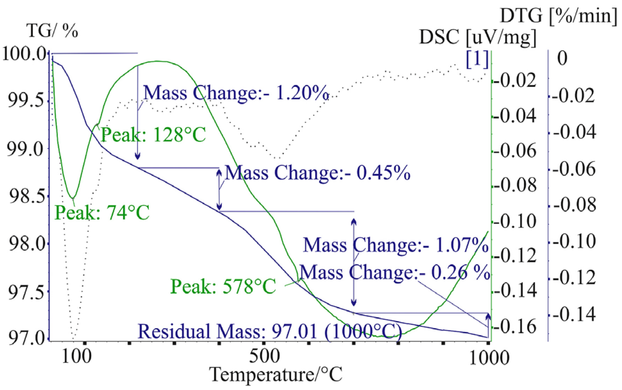

Fig. 12 Thermal analysis of the bulk sample. TG = thermogravimetry chart, i. e. relative mass change due to heating, DSC = differential scanning calorimetry, DTG = differential thermogravimetry

of the organic material in the surrounding desert. The absence of straw or similar plant-derived parts is a positive factor regarding the uniaxial compressive strength of the adobe (Chybík, 2009), because those substances would more weaken the already weak adobe bricks. Their vulnerability by a static and/or dynamic load is expected due to the low amount of the fine cohesive fraction (Kouakou & Morel 2009; Fratini et al. 2011) that was shown by the grain-size analysis. Especially, the content of clay grain-size fraction and clay minerals is surprisingly low, far from what would traditionally be considered as a good building material. This is the reason for the low plasticity, neither the identified swelling clay mineral vermiculite and the partly swelling illite can significantly control the cohesion due to their low amount. So, the reliability of the low liquid limit w_L and plasticity index I_P calculated from the water adsorption w_A by Enslin-Neff, was supported by the grain-size analysis and mineralogical analyses.

Our results indicate a successful application of the method by Dieng (2006) that can be recommended if the sample is too small for a standard determination of the plasticity. Together with the grain-size analysis by SEDIGRAPH, these analyses represent a sample-saving alternative to the standard/common engineering-geological classification tests.

Additionally, the available results of the mineralogical analyses lead to an attempt to identify the material source by a comparison to results published by Torres & Chipana (2014). They reported significant amounts of feldspars in the aeolian sand from the sanctuary, as well as in the fine alluvial sand of the Lurin River. Amphibole was not mentioned, but it was found in our sample. It could be a part of the „fragments of intrusive rocks" mentioned for the aeolian sand in that study. Their analyses were based only on the scanning electron microscope, some of the minerals might have been misinterpreted. For example, the only reported clay mineral was montmorillonite. This could be in fact the vermiculite recognized by a complete XRD analysis of the clay fraction in our sample. But, clay minerals were mentioned only in the lagoon sand. Rivero (2014) suggested that the adobe was prepared from the aeolian sand with some additives from the other sources. This explanation is best compatible with our results indicating a mixture of aeolian and alluvial sand. A detailed study of the local mineral assemblages including more laboratory methods would be necessary to identify the raw material source (Pagliolico et al., 2010).

The final notes address the expected physical properties of the adobe important for the site preservation, based on test results mentioned higher, as well as on common/general experience with soils of the S4 class. Duarte et al. (2017) reported a strong relation between the mineral composition and the durability of the adobe blocks in Angola. At Pachacamac, certain volume changes of the vermiculite (and partly of the illite) can be expected during the whole year due to the specific climate in this part of South America as mentioned above. But, the adobe of the Sun Temple does not suffer from dramatic volume changes, because the swelling clay mineral content is very low. Due to the unusually low content of the cohesive clay fraction in the adobe of the Sun Temple, a higher hydraulic conductivity and erodibility by water can be assumed than in a typical adobe with high clay content. Therefore, these adobe constructions should be preserved from heavy rains. The erodibility by wind will be also influenced by the low content of the cohesive fraction (Qu et al., 2007). The wind is up to 35 $km.h^{-1}$ at the site, coming from NW and from the ocean. Rivero (2014) reported destruction seen also on already restored adobe blocks. He found that the high sand fraction content explains the bad compaction, thus high porosity, low cohesion and low sustainability of the ancient adobe. He recommends to use a significant amount of clay mixed with the river sand (coarse and fine) and water for the preparation of new adobe for the restoration; the usage of the aeolian sand should be avoided.

5. CONCLUSIONS

Because of the high cultural, historical and touristic importance of the archeological locality Pachacamac (Peru), only two small pieces of adobe material were available from the weathering wall of the Temple of Sun built by Inca nation in the 15th century. Less than 100 g of the sample were sufficient for the basic engineering geological/ geotechnical classification by alternative „sample-saving" methods. SEDIGRAPH was used for the grain-size analysis and water adsorption by the Enslin-Neff method for the determination of plasticity according to Dieng (2006). The adobe material was classified as clayey sand, class S4, symbol SC (STN 72 1001:2011). The mineral composition and contents of carbon and nitrogen could also be determined, and 45 g of the original sample are still available for further research. These sample-saving methods can be recommended as an alternative to standard classification tests if samples of standard mass cannot be taken for any reasons, e. g. from objects protected by law. It was proven that a small soil sample can give a lot of information even to an engineering geologist (used to big samples) if the engineering geological classification can be done. How representative such a sample is can be a matter of a longer discussion. A higher number of small samples would be a good compromise.

The high content of sand and low content of the fine cohesive „binder" weaken the ancient adobe bricks. Any organic additives (common in modern Peruvian adobe) are surprisingly missing which means that they have no negative influence on the compressive strength. The „binder" contains the expandable clay mineral vermiculite, but its content in the bulk sample is too low to control the cohesion, swelling and hydraulic conductivity of the adobe reasonably. The present illite may exert only limited swelling on edges, the chlorite does not swell at all. Those adobe bricks will not suffer under critical volume changes. But, due to assumed enhanced hydraulic conductivity and erodibility, preventive measures against accidental heavy rainfalls should be considered.

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