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MECHANICAL PROPERTIES OF ADOBE MASONRY OF HISTORICAL BUILDINGS IN PERU

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Abstract. *Within the frame of the "Seismic Retrofitting Project" a joint research Project between the Getty Conservation Institute, University College London and Pontifical Catholic University of Peru, more than 250 primary tests for the characterization of heritage building materials have been performed in the laboratories of the Catholic University in Peru. Building materials from houses of the Historical Center of Lima, historical church in Cusco and historical church in the Peruvian coast have been collected and tested in order to obtain quantitative and qualitative data necessary to perform adequate studies of structural evaluation and diagnosis in order to prevent damage by seismic events. Even though the main attention of the project was given to earthen buildings, in all buildings studied, stone and brick masonry were found combined with the adobe masonry either in the foundations or in the walls. This paper presents a summary of the experimental results of compression test on adobe piles; diagonal compression test on adobe wallets; shear-compression test of adobe/adobe, adobe/fired brick and adobe/stone triplets and compression test on adobe units. Besides, tests of soil classification for adobe units and mortars were included. The experimental results show significant differences between the original heritage materials compared with those specified in the bibliography and in codes for new construction.*

1 INTRODUCTION

The objective of the Seismic Retrofitting Project is to study the seismic behavior and develop retrofitting strategies for earthen historical buildings in Peru. Four representative historical buildings were chosen to be studied analytical and experimentally [1, 2].The prototypes are built mainly with adobe masonry. Although there are information about mechanical properties of adobe masonry in the Peruvian code for new buildings [3], information about historical buildings in Peru is almost inexistent. This paper focuses the experimental analysis of the mechanical properties of the adobe masonry from these historical buildings.

2 OBJECTS AND AIMS

The aim of this article is to provide values for mechanical properties of the adobe masonry in Peruvian historical buildings. Original materials were collected from the cities of Lima, Ica and Cusco. The experimental program includes testing of piles, wallets, triplets and units to find compressive strength shear strength, angle of friction and cohesion. The last two properties, angle of friction and cohesion were found also for the interaction between the brickwork and stonework base course with the adobe wall. Besides this, adobe units were tested and properties of the soil and mortar were determined.

3 MASONRY IN PERUVIAN HISTORICAL BUILDINGS

3.1 Adobe Masonry

Adobe masonry is the most common material in the architectural heritage from the Viceroyalty era and the Republic era in Peru. All the first stories walls of the historical houses from the Historical Centre of Lima were built with adobe. In fact, adobe is the main material for colonial houses and religious buildings in the coastal cities in Peru. Besides, adobe masonry is also the main material in two story and three story houses of the Historical Centre of Cusco[1].

3.2 Brickwork

Brickwork composed by fired brick and lime mortar was used as a traditional reinforcement of adobe walls. Indeed, brickwork is surrounding the openings in the historical buildings; also was used as basement and base course of the adobe walls.

3.3 Stone masonry

Stone masonry with joints of lime mortar composes mostly the basements and base courses of historical buildings in Peru.

4 MATERIALS AND METHODS

4.1 Materials

With permission of the Minister of Culture of Peru, the materials used for testing were collected from the residuary material of the restoration work of historical buildings in Lima, Ica and Cusco. In the case of Lima, adobe blocks, stones and bricks as well as mortar samples were obtained from three houses from the Historical Centre of Lima: Hotel El Comercio, Casa

Jr. Ancash and Casa Welsch. In the case of Ica, adobe blocks and mortar was obtained from Ica Cathedral, an historical church located in South Lima to 300 Km. In the case of Cusco, an adobe block was obtained from Kuño Tambo church, which is located in a rural town in southeast of the Cusco city. In most of the cases, the testing specimens were built using historic adobe blocks; the mortar used was prepared with the original joint mortar and water. In the case of shear compression tests, part of the specimens was built with contemporary adobe blocks and mortar. Each sample were left to dry for 5 weeks before the testing.

Figure 1:Historical Center of Lima. Location of buildings. a.Hotel El Comercio. b. Casa Jr. Ancash. c. Casa Welsch.

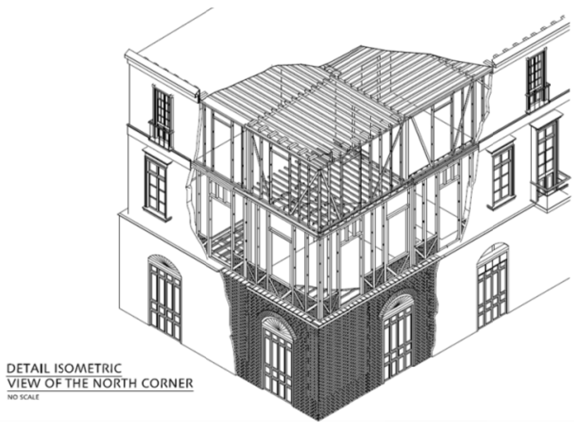

Figure 2: Isometric view of the structural configuration of Hotel Comercio. First floor has adobe walls [1].

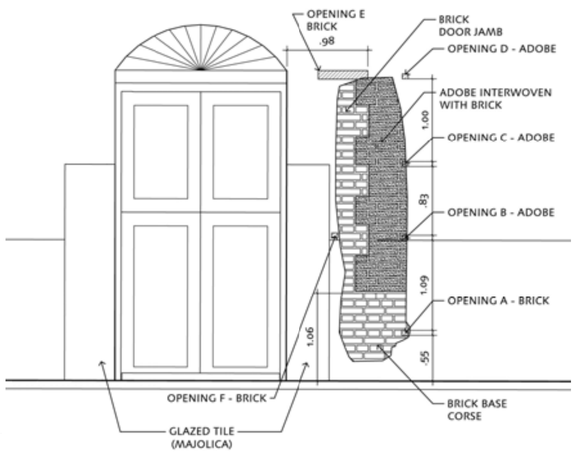

Figure 3: Prospection in Hotel El Comercio. Fired brick masonry surrounds the openings in first floor and also conforms the base course[1].

Figure 4: Casa Jr. Ancash (a) and Hotel El Comercio (b).

Figure 5: Kuño Tambo church.

Figure 6:.Ica cathedral.

4.2 Methods

4.2.1. Uniaxial compressive test in piles

The piles were tested in compression and the vertical deformations were measured in order to obtain the elasticity modulus. The latter has been calculated with the slope of the compressive stress - strain curve, taking account values until one third of the maximum stress achieved. The load velocity was 1.5 kN/min. The current Peruvian Adobe Code E.080 was used as reference to the testing. [3]

4.2.2. Diagonal compression test in wallets

Horizontal and vertical deformations were also measured to determine the shear modulus (G), which has been calculated with the slope of the stress – strain curve, between 20% and 40% of the maximum stress. The load velocity was 1 kN/min. The current Peruvian Adobe Code E.080 was used as reference to the testing.[3]

4.2.3. Shear compression test in piles

The test procedure has two phases, in the first one the vertical load was applied to the assembly and in the second one the horizontal force was applied to the central unit until failure. The testing procedure and levels of vertical stress were applied according to the British Standard BS EN 1052-1:1999[4]. According to Procedure A of the Standard, the compression loads were 0.1 N/mm^2, 0.3 N/mm^2, and 0.5 N/mm^{2}because the strength of the specimens are less than 10N/mm^2, the ratio of the shear stress was 0.4 N/(mm^2/min).

4.2.4. Compressive strength in units

The testing of compressive strength of the adobe units was carried out in adobe cubes. The arista of the cube was the lower dimension of the adobe unit. The current Peruvian Adobe Code E.080 was used as reference to the testing.[3]

4.2.5. Soil characteristics of adobe bricks and mortar

The soil of adobe blocks and mortar was tested using the following standards: Granulometric analysis ASTM D 422 [5];Soil classification, ASTM D2487[6]; moisture content (w), ASTM D2216 [7]; liquid limit (LL) and plastic limit (PL), ASTM D4318 [8]; shrinkage limit (SL), ASTM D427[9] and specific gravity of soil solids (SG),ASTM D854 [10].

5 RESULTS AND DISCUSSION

5.1 Adobe Masonry

5.1.1. Uniaxial compressive strength in piles

Eight piles were built using original adobe blocks from historical buildings walls. The soil used to the mortar was obtained from the original walls mortar. Three piles were built with Ica Cathedral materials and five piles with materials from three different historical houses from Historic Centre of Lima. The adobes and mortar from Lima don´t have straw, although in the case of Casa Welsch, a sort of organic material, like animal manure, was found. In the case of Ica, the materials doesn´t have straw. The results are shown in Table1.

Table 1:Compressive test of adobe piles.

Location	Name of the building	Compressive strength (MPa)	Young´s Modulus (MPa)
Historic Centre of Lima (houses)	Hotel Comercio	0.42	104.23
	Hotel Comercio	0.36	95.49
	Casa Welsch	0.39	93.71
	Casa Welsch	0.58	48.44
	Jr Ancash	0.76	48.89
Ica (church)	Ica cathedral	0.47	74.91
		0.48	60.32
		0.44	106.42

The type of failure in all specimens is the typical vertical crack running through the units and the mortar. The average compressive strength of piles constructed with material from the Historical Center of Lima is 0.44Mpa.The results from historical centre of Lima present a significant standard deviation, 0.17.The piles from Ica Cathedral have an average compressive strength of 0.463Mpa, and the standard deviation is 0.02; in this case, the variability is not significant. In existent adobe houses in Portugal compressive strength of the existent adobe masonry are between 0.66 and 2.15 MPa [11] [12]. The values of experimental analysis for

Peruvian new adobe masonry are higher; they are between 0.77 MPato3.72MPa [13,14,15]. The admissible value of compressive strength in the Adobe Peruvian Code is 0.2 MPa [3].

The results of Young´s modulus are varied. The values are between 48.89 and 106.42 MPa. The literature indicates also variation on their results, 33 - 448 MPa[11, 13, 16, 17, 18, 14, 19, 20].

5.1.2. Diagonal compression strength in wallets

Six wallets were constructed using original adobe blocks; the soil for the mortar was obtained from the original walls. Three wallets were from Ica Cathedral and three from the Center of Lima, they were tested in diagonal compression to obtain the shear resistance of the adobe masonry. The results are shown in Table 2.

Table 2: Diagonal compression testing of adobe wallets.

Location	Name of the building	Shear Strenght (Mpa)	Modulus of elasticity in shear (Mpa)
Historic Centre of Lima (houses)	Hotel Comercio	0.014	26.24
	Casa Welsch	0.033	8.01
	Casa Welsch	0.050	2.90
Ica city (church)	Ica cathedral	0.010	49.16
		0.043	6.73
		0.030	12.84

A greater dispersion is observed in the ultimate load capacity in comparison with the axial compression tests of piles with the same material, the values are between 0.010 – 0.05 MPa. In both cases, Lima and Ica samples, the standard deviation are 0.02. Literature shows values between 0.026 - 0.109 MPa [14, 24, 21, 18, 16, 13, 25].The ultimate shear strength in the Peruvian Code is 0.025 MPa [3].

On the other hand, the dispersion is even bigger when is related to the Shear Modulus (G), they are between 2.90 MPa and 49.16 MPa. Regarding literature, the values are between 30.2 MPa – 39.8 MPa. [16, 18, 21]. The dispersion can be understood because of the crack pattern; in the wallets, the crack is not uniform in all the specimens, the ideal crack pattern would be a vertical one from the upper to the lower corner but other patterns run by the joints with a lower load capacity.

5.1.3. Shear compression strength in triplets

5.1.3.1.Shear compression strength in triplets adobe-adobe

Fifteen specimens were constructed assembling three units of adobe (triplets) to be tested in shear/compression to obtain the angle of friction and the cohesion for the masonry. Twelve triplets were constructed with new material adobe and mortar and three triplets were constructed using original units and historical material from Ica Cathedral. There is not much difference between the new material and the historical one. The cohesion and the friction angle for the new masonry have values of 37.71Kpa and 0.60rad respectively. The specimens with historical material from Ica Cathedral have a cohesion value of 44.46Kpa and a friction angle of 0.50rad. The results are shown in Figure 7 and Table 3.

The values of angle of friction of adobe masonry are scarce in the literature. There are some values, but the testing is not detailed or the samples and testing are pieces of adobe blocks [22, 23] references values are 0.35 rad, 0.56rad and 1rad; and cohesion values, 37 KPa - 65 KPa [22].

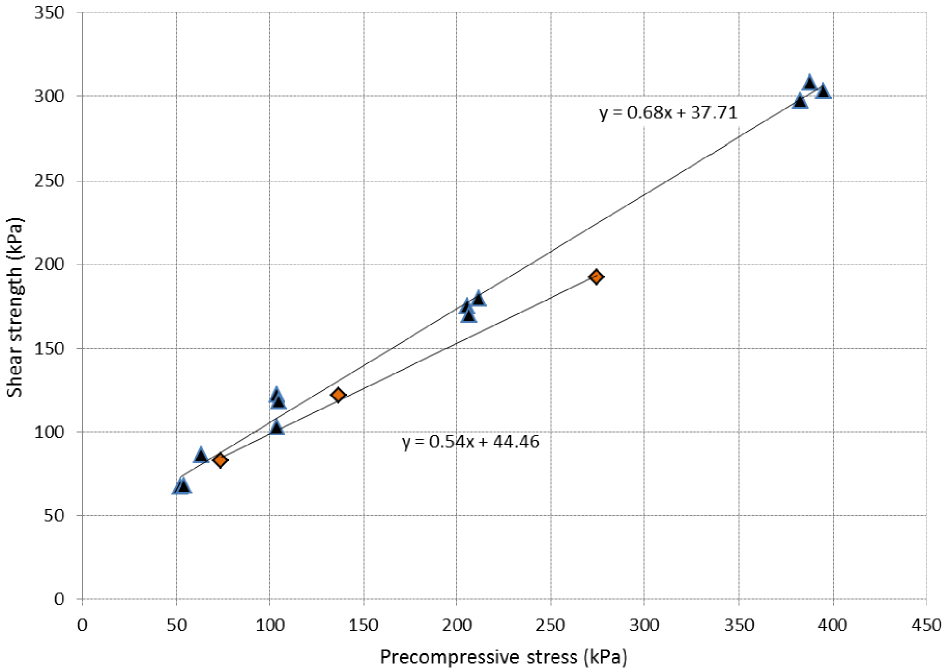

Figure 7: Shear vs Compression curve for adobe-adobe triplets.

Table 3: Cohesion and Internal friction angle of adobe masonry

	Cohesion (kPa)	Internal friction angle ϕ (rad)
adobe/adobe contemporary	37.71	0.60
adobe/adobe Ica cathedral	44.46	0.50

5.1.3.2.Shear compression strength in triplets adobe-fired brick

Twelve triplets were constructed with two adobe blocks and one intermediate fired brick block, the mortar used for the joint was mud. The units, fired bricks and adobes blocks are original material from Hotel El Comercio and new soil was used for the mud mortar joint. Cohesion and friction angle for adobe-fired brick has values of 33.36Kpa and 0.59rad respectively.

5.1.3.3.Shear compression strength in triplets adobe-stone

Eleven specimens were built with two stone blocks and one intermediate adobe block, the mortar used for the joint was mud. The stone blocks are original material from Hotel ElComercio and the adobe blocks and mud mortar are contemporary. Cohesion and friction angle for adobe-stone masonry has values of 36.45Kpa and 0.61 rad respectively.

The comparison between the values of shear compression testing of adobe/adobe, adobe/fired brick and adobe/stones are shown in the Figure 8 and Table 4.

Figure 8: Comparison of curves for triplets.

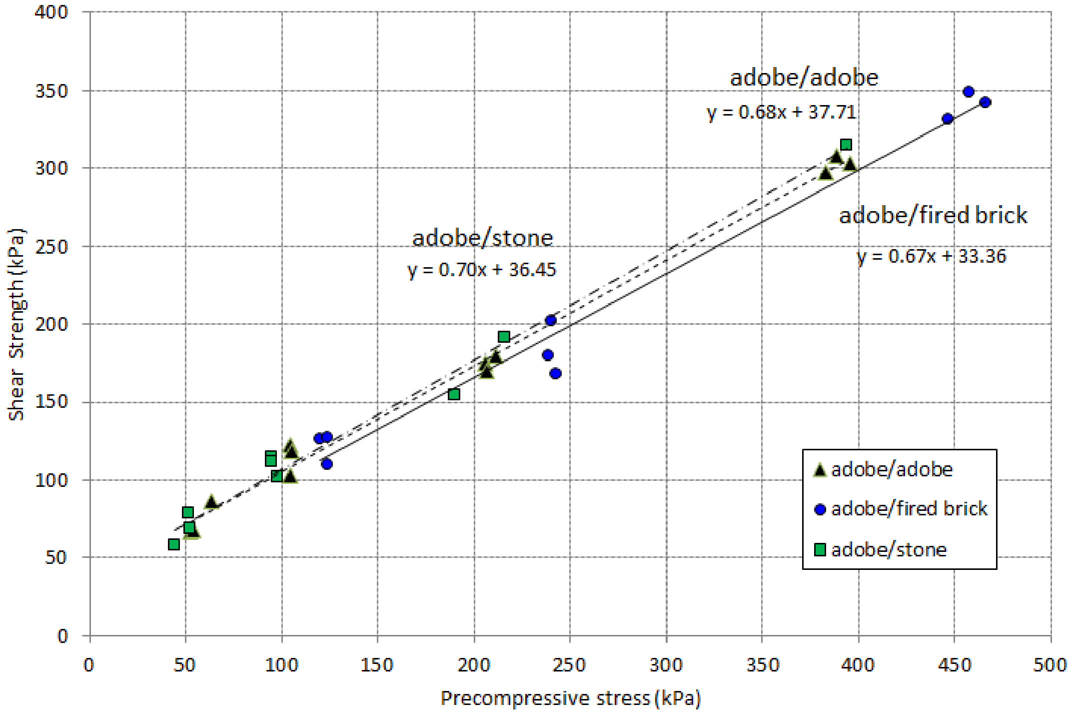

Table 4: Cohesion and Internal friction angle

	Cohesion (kPa)	Internal friction angle ϕ (rad)
adobe/adobe	37.71	0.60
adobe/fired brick	33.36	0.59
adobe/stone	36.45	0.61

The values about cohesion and internal friction angle are quite similar between the triples of the adobe/adobe, adobe/fired brick and adobe/stone. Due to the fact that the failures, in all the cases, were produced in the mud mortar joint between the blocks, the shear strength is governed by the resistance of the mortar and the cohesion and internal friction are almost constant.

5.1.4. Compressive strength in adobe bricks

Adobe blocks from El Hotel Comercio, Casa Welsh, Ica Cathedral and Kuño Tambo church were collected and carved in cubes of 10cm by side approximately to be tested in compression. Table 5 represents the summary of the results.

Table 5: Results from compression test of adobe units.

	Hotel Comercio	Casa Welsch	Ica cathedral	Kuño Tambo
Compression Strength (Mpa)	1.65	1.45	0.65	0.84
	1.53	1.27	0.59	0.65
	1.59	1.43	0.65	0.48
	1.84	1.28	0.62	0.87
	1.74	1.33	0.43	

Compressive strength of adobes from Ica Cathedral presents the lowest values from all. The adobes from the historical center of Lima have the highest values being similar the adobes from Casa Welsch and Hotel El Comercio. The Adobe Peruvian Code [3] considers 1.2 Mpa as the minimum value for new adobe blocks.

5.1.5. Soil characteristics of adobe bricks and mortar

Granulometric analysis

Soil classification by granulometric analysis was performed for 5 different adobes bricks and 5 different mortars coming from historical constructions. Figures 9 and 10 show the granulometric curves of adobe block and soil mortars used on this work.

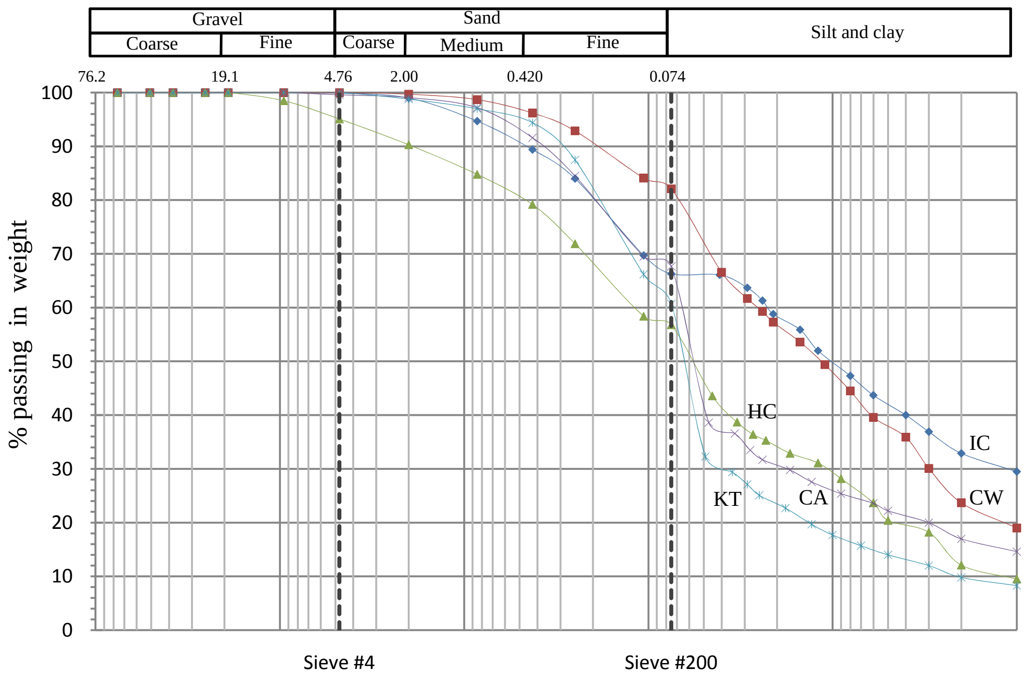

Figure 9: Granulometric curve for historical adobe bricks. Abbreviations: IC, Ica cathedral; CW, Casa Welsch; HC, Hotel El Comercio; CA, Casa Jr. Ancash; KT, Kuño Tambo church.

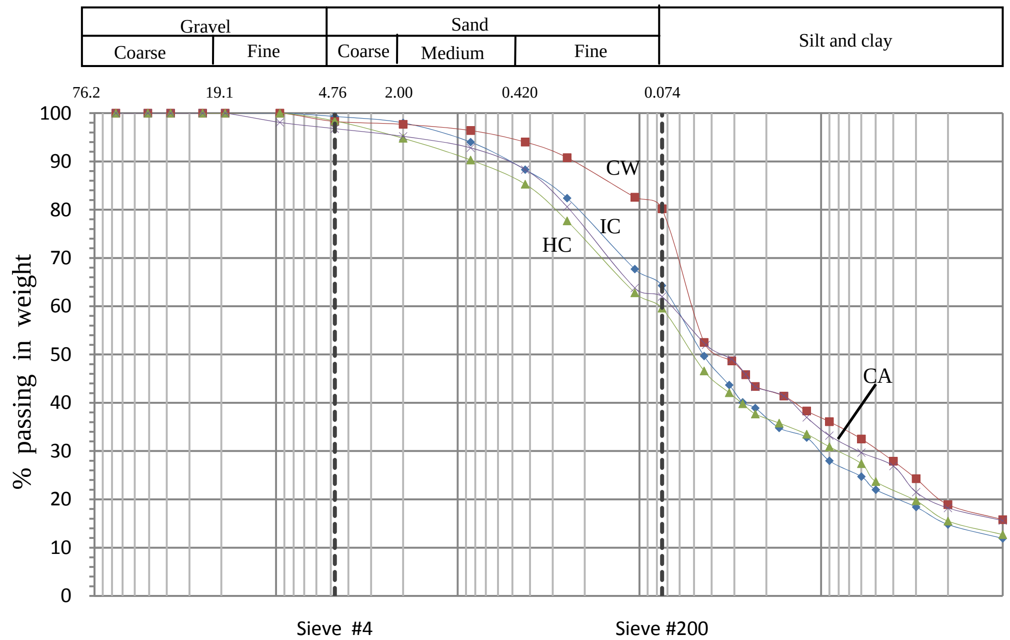

Figure 10: Granulometric curve for historical mortars. Abbreviations: IC, Ica cathedral; CW, Casa Welsch; HC, Hotel El Comercio; CA, Casa Jr. Ancash; KT,Kuño Tambo church.

The tables 6 and 7 show the characteristics of SUCS classification, Atterberg limits and specific gravity were found of the adobe bricks and mortars.

Table 6:SUCS classification, Atterberg limits and specific gravity of soil from historical adobe bricks.

Origin	Building	SUCS	w	LL	PL	PI	SL	SG
Lima	Hotel El Comercio	CL	0.06	0.32	0.20	0.12	0.15	2.65
	Casa Jr. Ancash	CL	0.04	0.27	0.16	0.11	0.13	2.64
	Casa Welsch	CL	0.10	0.30	0.17	0.13	-	2.66
Ica	Ica Cathedral	CL-ML	0.04	0.26	0.19	0.07	0.15	2.66
Cuzco	Kuño Tambo	CL	0.04	0.30	0.19	0.11	0.14	2.58

Abbreviations: w, % moisture content of the sample; LL, liquid limit; PL, plastic limit; PI, plasticity index; SL, shrinkage limit; SG, specific gravity.

Table 7:SUCS classification, Atterberg limits and specific gravity of soil from historical mortar.

Origin	Building	SUCS	w	LL	PL	PI	SL	SG
Lima	Hotel El Comercio	CL	0.06	0.30	0.19	0.11	0.14	2.66
	Casa Jr. Ancash	CL	0.05	0.30	0.18	0.12	0.15	2.65
	Casa Welsch	CL	0.12	0.32	0.18	0.14	0.12	2.64
Ica	Ica Cathedral	CL	0.04	0.27	0.18	0.09	0.15	2.67

Abbreviations: w, % moisture content of the sample; LL, liquid limit; PL, plastic limit; PI, plasticity index; SL, shrinkage limit; SG, specific gravity.

Laboratory tests show that soil composition for adobe units and mortar is the same which may implies that it was a usual practice to use the same material source for both functions. Coarse and fine material content is similar in all cases: between 30 and 40% coarse material and between 60 to 70% for fine material content. In the Casa Welsch, the fine content is greater than the rest of the sites (80%). In general the soil composition of units and mortars present low plasticity clays with a greater presence of silt is in the soils from Ica Cathedral. The LL are between27% - 32%, the PL between 17%- 20%, and the SL are between 12% - 15%. The specific gravities are between 2.64 - 2.67.

It was evident that there are a correlation between the LL - LP and the compression strength of the units. Higher values of LL are related with higher compression resistance. However, it is known that there is a limit, for very high value of LL and LP, the resistance decrease. Also, the high content of sand is related with a better resistance of adobe units, but also is known that there is a limit [26].

6 CONCLUSIONS

According to the experimental results, the adobe masonry mechanical properties in historical buildings in Peru vary regarding the locations and buildings. Compared with the literature related to new adobe constructions, the mechanical properties from historical buildings are lower.

Reliable data for adobe masonry compressive strength can be achieved, but in the case of shear strength, the results show dispersion. In the cases of Young Modulus and Modulus of elasticity in shear, the values were also dispersed; this is due to the brittle nature of the material, in which a short deformation produces instantaneous collapse.

Numerous shear compression tests presented reliable information about the angle of friction and cohesion in adobe masonry. The results show clearly that resistance is governed by the joint material which was composed by soil mortar in all the cases. The type of the blocks used was irrelevant, because the results don´t depend on them.

The compressive strength of adobe units are different comparing Lima blocks with Ica and Cusco blocks. The Lima adobe blocks achieve similar values to the recommended values for new construction in the Peruvian Code. In the case of Ica and Cusco the values were much lower.

The soil properties of the adobe blocks and mortar were also presented and some trends can be observed, such as the relation between soil properties and resistance. Further studies are needed to better understand this important issue.

In overall, the present work contributes to the knowledge of mechanical properties of adobe masonry from Peruvian historical buildings. This knowledge is primordial to support the numerical models and future studies.

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