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ASSESSMENT OF MECHANICAL PROPERTIES OF THE HISTORICAL BRICKS OF BURGOS GATE IN ALCALA DE HENARES IN MADRID

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Abstract. *The subject of the research is a comparative study of minor-destructive strength measurement method using micro-core specimens and standard testing of large size specimens from the Medieval structure of Puerta de Burgos (Burgos Gate), being a remain of the former town fortress now leading to the Monastery of St. Bernard and the Archbishop´s Palace in the city Alcala de Henares near Madrid. Standard size specimens were tested within the framework of the project of the Regional Government of Madrid "Durability and conservation of built heritage geomaterials" by Instituto de GeocienciasIGEO (CSIC-UCM), Spain. Micro-cores testing of sub-size specimens were done at Smart Technology Centre of Institute of Fundamental Technological Research Polish Academy of Sciences. Standard tests included measurement of longitudinal ultrasonic wave velocity, flexural strength and uniaxial compressive strength measurements. They form a set of the reference results for the other group of tests using minor-destructive Compact Diagnostic Test (CoDiT) procedure based on measurements and analysis of the mechanical properties of small samples of the materials drilled out in a form of micro-cores having the diameter of several millimeters. Minor-destructive CoDiT procedure allowed measuring of ultrasonic surface wave and longitudinal wave velocities, uniaxial compressive, flexural and indirect tensile strengths of original construction bricks. The results of standard tests and CoDiT tests of micro-cores having less than 8 mm diameter confirm that mechanical properties of historic materials can be assessed on the basis of micro-core testing if the tested material is homogeneous enough within the size of the micro-core being used.*

1 INTRODUCTION

The first stretch of the fortified wall in which the Burgos wall is enclosed dates back from the 13th century, as the main entry to the Archbishop´s Palace. At this stage a first cubic structure was built, a little bit higher than the wall in which it was embedded. The Gate was successively enlarged, both in surface and height, in the 14th and 15th centuries with superimposed bodies [1]. Some collapses of part of the structure occurred along the history of the Gate, the latest in 2005. This collapse probably happened because during a long period the structure was in a semi-ruined state caused by a complete lack of maintenance. The last restoration was carried out in 2011, mainly focused on its structural consolidation (Figs. 1, 2).

Besides bricks, which are the main building materials, due to the fact that Alcala de Henares surroundings have important clays deposits which have derived in a significant ceramic industry [2], the structure was also constructed with rammed-earth and stone (limestone).

The fortified wall complex was listed Cultural Interest Good in 1968, and the University and Walled Complex of Alcala de Henares is UNESCO´s World Heritage since 1998. The Burgos Gate is the oldest mediaeval structure of the city. It was the exit of the historical city towards the North.

Figure 1: The Gate of Burgos, from left to right: South façade: in 2003; after the 2005´s collapse; in 2012, after its restoration.

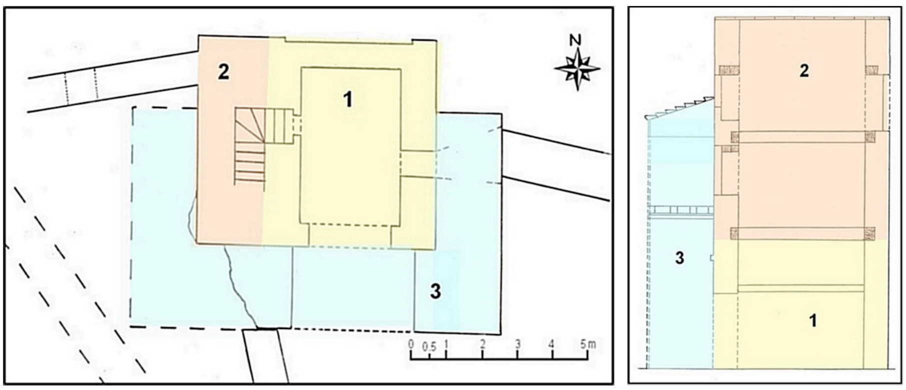

Figure 2: The 3 main construction stages of the structure, in ground plan, left, and elevation, right. 1: 13th century; 2: 14th century; 3: 15th century.

The bricks analyzed in this study were sampled from waste material available after the last structural collapse of 2005. The bricks were tested by standard and nonstandard methods to assess mechanical properties of Burgos Gate construction material.

2 STANDARD TESTING METHODS

The average size of the bricks employed in the Gate is 273 mm long, 168 wide and 39 mm thick. Bricks from corresponding to the 3rd construction stage (15th century) available after the last collapse were sampled (Figure 3). From previous studies [3], these bricks show a real density of 2460 $Kg{\cdot}m^{-3}$, a bulk density of 1670 $Kg{\cdot}m^{-3}$, a porosity accessible to water or open porosity (n0) of 32%, a capillarity coefficient of 6.2 $Kg{\cdot}m^{-2}{\cdot}h^{0.5}$, and a coefficient of water absorption after 48 hours of 18%.

Ultrasound velocity measurements were performed with 3 different equipments:

- Pundit Plus CNS Farnell with 54 KHz transducers (at Alcala University);
- Ultrasonic Testing 309 ultras 55 with 54 KHz transducers (at Alcala University;
- Pundit CNS Electronics with 1 MHz transducers (at Petrophysics Laboratorio of Geosciences Institute).

The dimensions of the prismatic specimens, obtained from representative bricks, were 160 mm long and 40 mm side, in average.

Figure 3: Stockpile of bricks from the 2005´s collapse of the structure, left, and bricks sampled (right).

Mechanical tests were performed at the University of Alcala de Henares - uniaxial compression strength (UCS) and flexural strength - by means of a RMU testing equipment, Multitester, with a capacity of 20 Ton, with a breaking load rate of 1kN/s (UCS and FS) and a distance between supports of 100 mm (FS).

The specimens dimension was the same as referred for ultrasound velocity measurements. Results of the ultrasonic and strength measurements are presented in Section 4.

3 CODIT MEASUREMENTS

Compact Diagnostic Test method (CoDiT) was developed for testing properties of heritage construction materials with minimal possible destruction to the monument [4]. It uses small samples of the material called micro-cores and whenever it is possible micro-cores should be over-cored as a by-product during drilling holes for technical purposes. In this case on gets specimens for testing instead of pulverizing historic material. The common example is fixing of scaffolding to a monument when possibly drilled micro-cores would have a diameter of 10—12 mm and no additional destruction to the monument would be introduced.

In experiments performed at Institute of Fundamental Technological Research Polish Academy of Sciences smaller specimens with diameter around 8 mm were used to show that in some cases even such a small material samples can provide valuable material characteristics.

CoDiT procedure is a sequence of experimental steps, which allows us to measure many physical and mechanical properties of historic materials [5, 6, 7]. Testing a single micro-core in accordance with CoDiT procedure enables to measure material flexural strength (FS), indirect tensile strength (ITS) uniaxial compressive strength (UCS), Young modulus of elasticity (E) and ultrasonic longitudinal (VP) and surface Rayleigh waves (VR) velocities.

Brick sample from Burgos Gate is shown in Fig. 4. The sample and assigned local coordinate system is shown on the left. The right image shows drilled sample surface and micro-cores. On the brick surface several lines parallel to Z-direction were drawn prior to drilling to allow further orientation of micro-core specimens with respect to the coordinate system. The orientation is necessary during FS and ITS measurements to ensure identical loading direction of each specimen.

Figure 4: Sample of the brick from Puerta de Burgos with sample coordinate system (left) and drilled micro-core specimens (right).

At first Rayleigh surface wave VR velocity was measured on the flat surface of the brick sample parallel and perpendicular to the lines drawn on that surface. The measurements were done with edge probes [8, 9, 10, 11] at five surface points for each of both directions before micro-cores drilling. Figure 5 shows edge probes placed on the brick surface and one of the registered surface wave profiles. Upper wave profile is a measured signal and lower one is the reference wave. Propagation time was measured using signal correlation method.

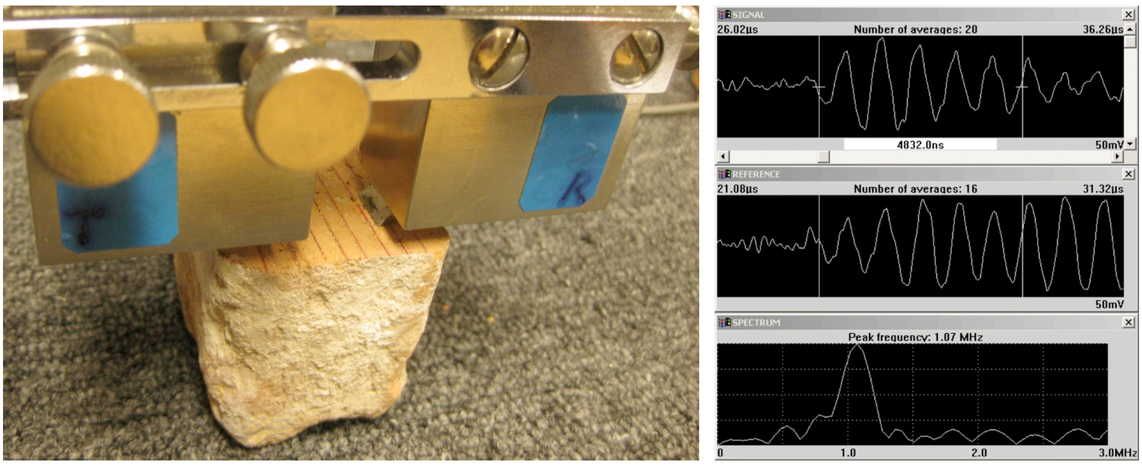

Figure 5: Surface Rayleigh wave VR propagating in X-direction measured with edge probes (left) by signal correlation method.

The next step was over-coring of the specimens and selecting the ones suitable for three point bending tests. The selection was done on the basis of specimens' length and morphology (visible pores, voids, cracks and inclusions). Figure 6 presents specimen L11 under three CoDiT strength tests. Three-point bending (left picture) provides FS strength and two shorter "half-specimens" of different length. Both 'half-specimens' had their ends cut to produce cylinders with flat parallel bases. The longer cylinder of slenderness approx. 2:1 was used for UCS testing (central picture). The shorter one with slenderness approx. 1:1 was used for ITS measurement (right picture)

Figure 6: Micro-core L11 after testing using CoDiT method: three-point bending (left), uniaxial compression (center) and diametral compression (right).

Longitudinal VP wave velocity was measured on cylinders resulting from bending test. The cylinders and 1 MHz ultrasonic probes were placed in vertical position as shown in Fig. 7 and measurements in transmission mode were done. To assure proper contact of the specimen and the probes additional dead load was used. In this test wave propagation time was measured on the basis of wave falling edge zero-crossing point as it is shown in the right picture.

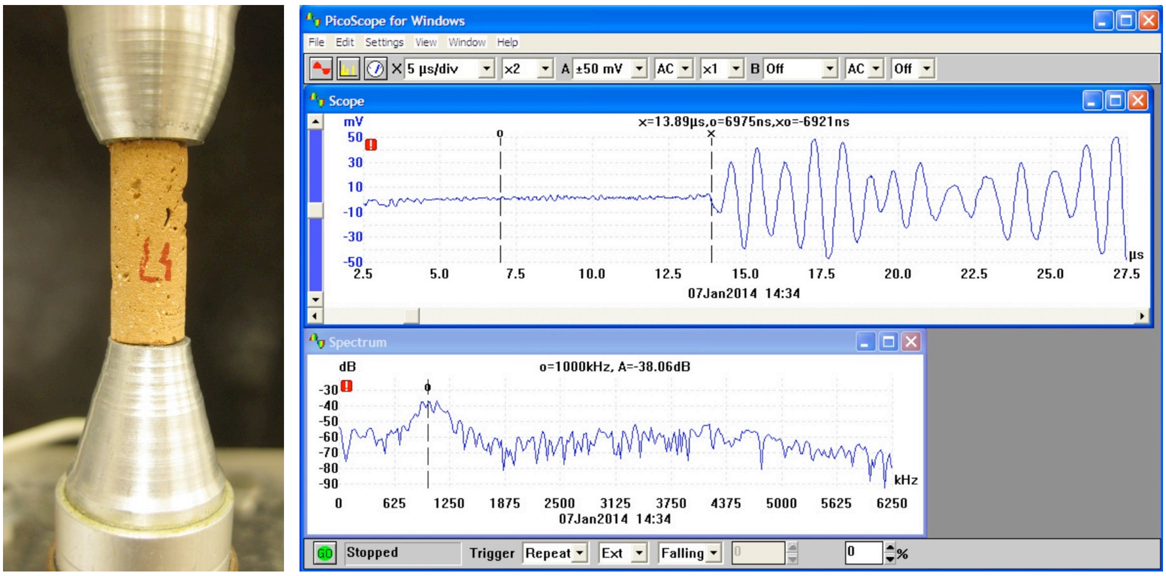

Figure 7: Recording of longitudinal V_P wave in a brick specimen from Puerta de Burgos.

Uniaxial compressive strength measurements were done with loading-unloading-reloading sequence. Unloading part of the load-displacement characteristic was used to calculate the brick elasticity E modulus. One of the recorded characteristics is shown in Fig. 8.

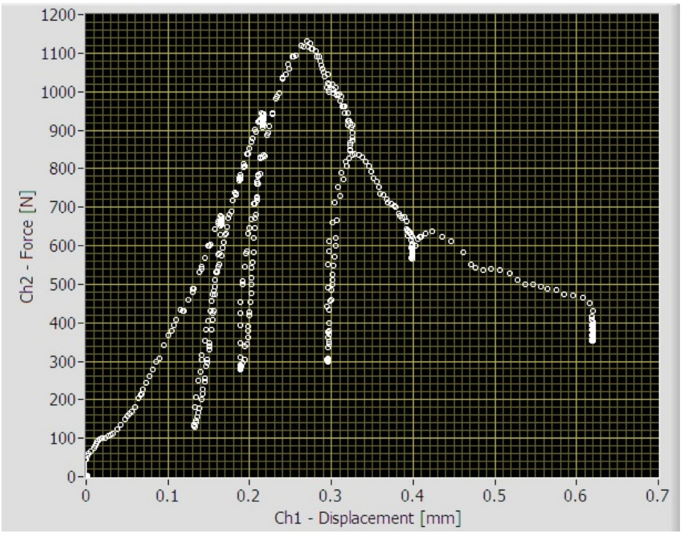

Figure 8: Micro-core uniaxial compression curve with unloading used for E-modulus calculation..

4 RESULTS AND BRICK PROPERTIES ASSESSMENT

Standard tests allowed measurement of longitudinal wave velocity, FS and UCS characteristics. CoDiT experiments provided VR and VP velocities and FS, UCS and ITS data. The results are grouped in two tables below. Both groups of tests allowed assessment of mechanical properties of medieval bricks from Puerta de Burgos of Alcala de Henares in Madrid.

Table 1includes sound wave velocity data measured with various methods at three laboratories. In CoDiT method the same 1 MHz nominal frequency was used during surface wave and longitudinal wave measurements. Longitudinal wave velocities are all in a very good agreement within a fraction of the standard deviation independent of the measurement method.

Table 1: Sound wave velocities.

Equipment	Nominal freq. [kHz]	VP mean [m/s]	VP StDev.	VR z-direction [m/s]	VR_z StDev.	VR x-direction [m/s]	VR_x StDev.
CoDiT	1000	2500	114	886	295	939	117
Pundit	1000	2495	43	-	-	-	-
Pundit Plus	54	2509	232	-	-	-	-
Ultras 55	54	2360	250	-	-	-	-

Strength data are collected in Tab 2. Standard compressive strength measurements were done on three different bricks. CoDiT measurements used a piece of one brick only and all the micro-cores were drilled out from that single material sample. This surely was a non-optimal sampling procedure. Normally in CoDiT method micro-cores should be drilled out from several various places of a historic structure element to provide more representative non-local values.

Table 2: Brick elasticity and strength.

Method	E [GPa]	E StDev.	UCS [MPa]	UCS StDev.	FS [MPa]	FS StDev.	ITS [MPa]	ITS StDev
CoDiT	5.9	3.9	24.6	3.8	6.3	0.6	2.4	0.7
Standard			12.33	5.5	4.8	single specimen	-	-

It can be observed that CoDiT results overestimate the strength values of UCS and FS measurements. This can be attributed to above mentioned different specimen sets used in both tests, which could make the data statistically incomparable. Calculated standard deviation of standard and CoDiT strength data confirm that hand made medieval bricks have very inhomogeneous mechanical properties. Thus whenever possible a greater number of specimens should be used to get more statistically representative results..

5 CONCLUSIONS

- Standard tests allowed measurement of VP wave velocity, FS and UCS characteristics of several bricks. CoDiT experiments provided VR and VP velocities and FS, UCS, ITS data measured on specimens over-cored from a small sample of one brick only.
- Brick strength properties assessed by standard and CoDiT method could not be this time statistically compared due to above mentioned various and limited sets of original materials used in the tests.
- Longitudinal wave velocities measured by standard methods and on micro-cores are in the very good agreement.
- Both methods show that historic hand made brick materials have a great variation of their strength properties confirmed by the large standard deviations of the measurement results.

6 ACKNOWLEDGEMENT

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