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Earth Masonries in the Medieval Grange of Cuna – Siena (Italy)

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Abstract
The Grange of Cuna was the administrative and storage centre of the bigger farm of Santa Maria della Scala Hospital in Siena. Built from the early 14th century, the Grange is characterized by continuous development of the building until the second half of the 18th century. For his extraordinary state of preservation, its size and the internal organization of individual buildings, it is notable for being one of the finest and rare examples of fortified farm in the context of Italian and European Middle Ages. At present a plan of restoration is under preparation, for whose completion many studies have been performed. The architectural survey, thanks to the accuracy of laser scanner technology added to a critical interpretation and data processing, represented the first knowledge of spatial and geometrical information and also gave a model useful to identify structural instabilities and deformations in order to direct the diagnostic phase. The stratigraphic investigations extended over the entire architectural complex made it possible to distinguish the historical constructive phases of the farm. Among the different masonries, fired brick masonries with earthen bedding mortars have been found in the original medieval nucleus, while rammed earth masonries plastered with lime mortar are present in some late medieval or post-medieval additions. Specific “in situ” investigations such as sonic and double flat jack tests were carried out on each masonry typology. Samples from the masonries with earthen bedding mortar and rammed earth were characterized in their mineralogical and petrographic features. This paper represents a first indication and reports a thorough investigation of walls built with earthy materials in this important medieval complex in Tuscany.

Keywords: Earth masonry, Medieval building, Grange, Stratigraphic investigation, Mineralogical petrographic characterization, Mechanical test.

1. Introduction: historical note
Between the end of the 13th and early 14th century, the hospital of Santa Maria della Scala in Siena initiated the organization of its landed property, which extended over vast areas of southern Tuscany, on farms called granges. For almost five centuries, until the end of the 18th century, they represented the very foundations of the hospital’s economic activities (Epstein, 1986).
The term granges also indicates the administrative headquarters of these farms, that is, the fortified building complexes where grangers resided, and where agricultural commodities were stored before being transported to the urban cities. The Grange of Cuna, located south of Siena, on Via Francigena, near the village of Monteroni d’Arbia, was the largest and most productive grange of Santa Maria della Scala.
The brick complex consists of a small village surrounded by walls with gates and towers; the current farm develops within the village, with the imposing structure of the granaries accessed by a partly covered ramp (Figure 1). For its extraordinary state of preservation, its size and the internal organization of several buildings,

the Grange of Cuna is one of the finest examples of architectural productive structures in the context of Italian and European Middle Ages.
Starting from some acquisitions in Val d'Arbia during the 12th and the 13th centuries, the origin of the Grange dates back to the donation to the Santa Maria della Scala hospital by the rector Ristoro di Giunta Menghi of all his possessions in the area, occurred in 1304 (ASS, Ospedale, ms. B 41). Cuna is recorded among the possessions of Santa Maria della Scala in the Statute of the Hospita,l dated 1318 (Banchi, 1877, p. 40), and a not documented historical tradition attests the building of the "palace" of the Grange in the year 1314 (Merlotti, 1995, pp. 174-175). The written sources and the material evidences testify a continuous and significant building development during the 14th and 15th centuries, which led to the construction of many blocks, a monumental granary and three fortified walls. The last major building project concerns the construction of the access ramp to the different levels of the granary built between 1709 and 1712 (Coscarella and Franchi, 1982; Dandria et al., 2015). From the beginning of its construction the complex was one of the poles of radiating towards the countryside of Siena Hospital, which drew its wealth from the exploitation of the land administered by the structures of Granges scattered throughout the territory.
The Grange of Cuna had such economic importance that it was not included in the disposal of the Hospital arranged by Granduca Leopoldo di Lorena in 1775, while it was entrusted to a special committee, and only in the XIXth century the dismemberment of the complex began with the sale or rental of some of its portions.
Since the early 1990's, the farming activities have been permanently discontinued and many of its areas completely abandoned. Recently, the municipality of Monteroni d'Arbia acquired a portion of the building complex in order to locate the resources necessary for addressing its research and restoration.

Figure 1: Aerial view of the Grange of Cuna. The big building on the right is the granary (after D'Andria et al., 2015, modified).

2. **Earth-based masonry types in the Grange of Cuna**

During the diagnostic phases aimed at collecting information useful to the restoration project of the Grange (funded by Monteroni d'Arbia Municipality and by Tuscan Region), several types of masonries were found. The main type is a brickwork masonry with lime mortar. Two types of earth-based masonries were also identified. In this paper we focus on these earth-based structures, giving a mineralogical-petrographic characterization and a determination of their mechanical properties (Fratini et al., 2011), also trying to contextualize them from the historical point of view.
The identification of the earthen walls was not immediate because covered by lime plasters and their presence was disclosed after sampling and/or performing mechanical tests. After the first findings, the research and

analyses aimed at identifying the extension of such structures continued, taking into account the results of the study of the building phases and carrying out specific thermographic investigations.
The first type of earth-based masonry is constituted by fired bricks connected by earthen bedding mortars. The outer parts of the joints are constituted by smoothed lime mortars (Figure 3a, b, c). Walls of this type were found both indoors and outdoors (Figure 2; walls A, B, C).
The second type of earth-based structures is represented by rammed earth masonries covered by plasters. This kind of masonry was found only indoor (Figure 2; walls D and E), usually adjoining brickwork masonries with lime mortars. Their direct observation was possible only after the removal of the covering plasters. Analyses on this type of masonry were carried out in two zones, chosen for their position and the possibility to perform tests easily.
Regarding the rammed earth wall D, the assay performed in the southern side brought to light the presence of two horizontal levels, whose thickness is about 4 cm, constituted by aligned bricks. The upper one is discontinuous, while the lower one shows the presence of a wooden element (Figure 3c). The distance between the two levels is about 40 cm. On the northern side of the same wall, a single horizontal level about 6 cm thick constituted by wood is visible, which corresponds to the lower level of the opposite side (Figure 3d). In both sides many types of materials added to earth are present. They are mainly represented by plaster, mortar and brick fragments, and subordinately by wooden pieces. The thickness of this wall is 75 cm at the bottom and 60 cm at the top.
Rammed earth wall E, found at a lower floor with respect to the wall D and parallel to the first one (Figure 2), is made almost exclusively of earthy material (Figure 3f), with rare presence of small mortar fragments and pebbles with a random distribution. Its thickness is between 70 cm at the top, and 83 cm at the bottom.

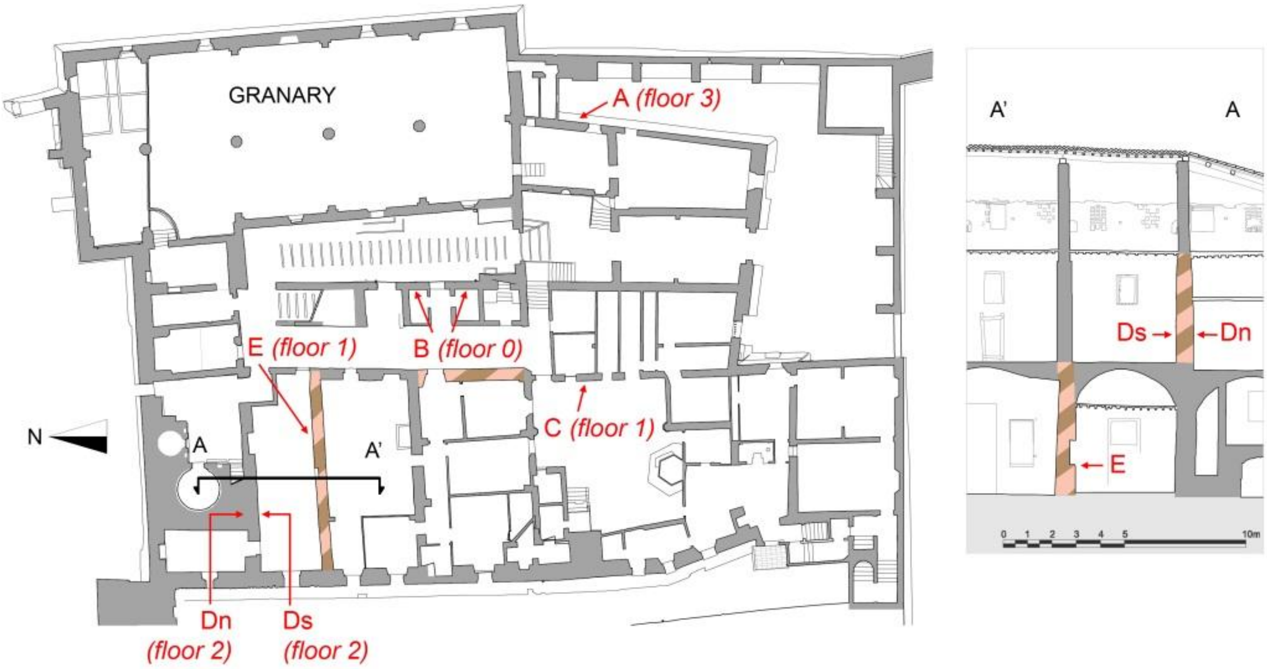


Figure 2: Grange of Cuna **-** plant of the first floor and A-A'section, with indication of the sampling points. A, B, C: brick masonries with earthen bedding mortar; D, E: rammed earth masonries (Ds: wall D, southern side; Dn: wall D, northern side). Pink and brown masonries: rammed earth masonries alternating with brick masonries with lime bedding mortar.

3. Stratigraphic investigations, chronological attribution of the earth masonries and sampling

1. Brick masonries with earthen bedding mortar. This kind of masonries has been found in several structures in the Grange belonging to three distinct building bodies.
1.1. Original building (samples PI 207, 208) (wall A). Stratigraphic investigations allowed identifying the original nucleus of the Grange (or, at least, the older structure whose relics are still visible) in the building body near the eastern perimeter wall of the complex. This body probably dates to the first years of the 14^{th} century (Dandria et al., 2015, pp. 227-236).

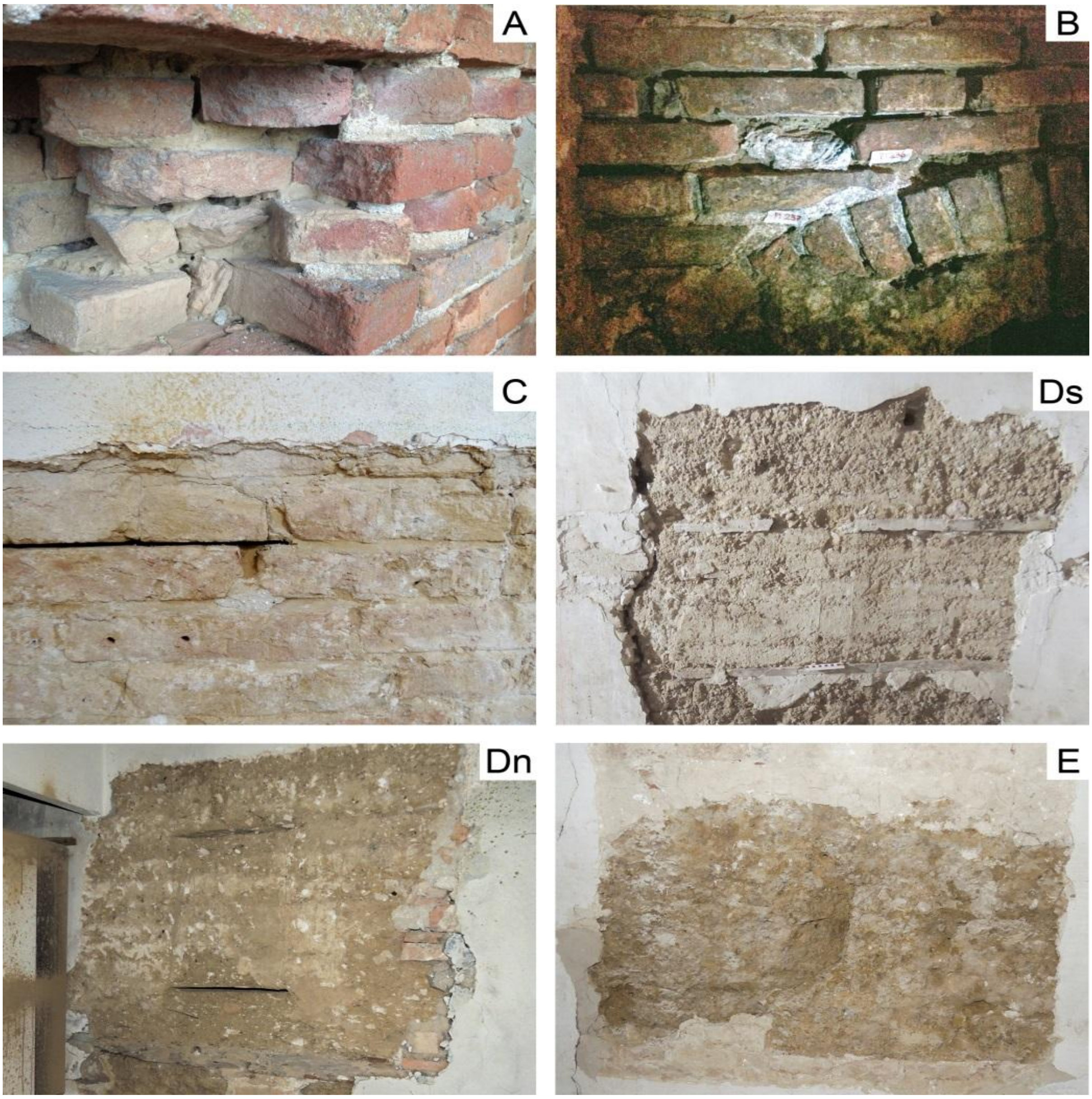


Figure 3: Macroscopic aspect of the walls under study. A, B and C - brick masonries with earthen bedding mortar and lime mortar in the outer part of the joints; Ds, Dn, and E - rammed earth masonries (see text for details) The lacunas in the plaster of the rammed earth masonries have a width of about 1 meter. **A** – the top of the oldest building of the Grange (wall A, samples PI207, 208); **B** – masonry on the 0 floor (wall B, samples PI234, 235, 236, 237); **C** - masonry on the 1st floor (wall C, samples PI503, 504); **Ds** – the southern side of the masonry on the 2nd floor (wall D, samples PI495, 496, 498, 499); **Dn** – the northern side of the masonry on the 2nd floor (wall D, sample PI500); **E** - masonry on the 1st floor (wall E, sample PI502).

1.2. Eastern perimeter wall of the cellars (samples PI 234-237) (wall B). From a stratigraphic point of view, this wall is later than the original nucleus, but the masonry above the wall shows technical and stylistic features still attributable to the 14th century.
1.3. Eastern perimeter wall of the courtyard with the well (samples PI 503, 504) (wall C). This wall is contemporary or prior to an open gallery showing architectural features typical of the 14th-15th centuries.
2. Rammed earth masonries (samples PI 495, 496, 498, 499, 500, 502) (walls D and E). The presence of plaster coverings prevented effective stratigraphic analysis. Walls D and E are sited in the north-western corner of the Grange, delimited by the first town wall, probably dated to 1367-1370 (ASS, Ospedale 516, cc. 231v, 248v, 262v). A third wall, not investigated, is located in the central part of the complex (Figure 2), and it is certainly previous to the building of the ramps at the beginning of the 18th century (Dandria et al., 2015).

Table 1 reports the collected samples together with a sample of sediment collected from the bank of the Arbia Stream, few hundred meters north-east, of the Grange, analysed for comparison purposes (PI231).

Table 1: Synthesis of the samples collected, with indications of provenance, sample type and colour (based on Munsell Soil Colour Chart)

Sample	*Type of masonry*	*Wall*	*Sample type*	*Colour*
PI207	Brick masonry with earthen bedding mortars	A	Earthen bedding mortar	10YR 6/4
PI208	Brick masonry with earthen bedding mortars	A	Mortar covering earthen bedding mortar in the outer part of the joint	
PI234	Brick masonry with earthen bedding mortars	B	Earthen bedding mortar	10YR 6/4
PI235	Brick masonry with earthen bedding mortars	B	Mortar covering earthen bedding mortar in the outer part of the joint	
PI236	Brick masonry with earthen bedding mortars	B	Earthen bedding mortar	10YR 6/4
PI237	Brick masonry with earthen bedding mortars	B	Mortar covering earthen bedding mortar in the outer part of the joint	
PI503	Brick masonry with earthen bedding mortars	C	Earthen bedding mortar	10YR 7/4
PI504	Brick masonry with earthen bedding mortars	C	Mortar covering earthen bedding mortar in the outer part of the joint	
PI495	Rammed earth masonry	D, southern side	Plaster covering the masonry	
PI496	Rammed earth masonry	D, southern side	Plaster and mortar fragments inside the rammed earth	
PI498	Rammed earth masonry	D, southern side	Plaster and mortar fragments inside the rammed earth	
PI499	Rammed earth masonry	D, southern side	Earthy material with occasional small pebbles and fragments of mortar and terracotta	10YR 7/3
PI500	Rammed earth masonry	D, northern side	Earthy material with frequent coarse pebbles and fragments of mortar, terracotta and wood	
PI502	Rammed earth masonry	E	Earthy material with occasional pebbles	10YR 6.5/3.5
PI231	Arbia Stream bank		Earthy material	

4. Mineralogical and petrographic characterization of the earthy materials and the mortars

The determination of the colour of the earthy materials was carried out by means of a visual comparison with Munsell Soil Colour Chart (USDA, Soil Conservation Service).

The powders obtained from the samples were analysed with a PANalytical diffractometer X'Pert PRO (XRD) with radiation CuKα1 = 1.545 Å, operating at 40 KV and 30 mA, investigating the range (2θ) 3-70°, equipped with X' Celerator multirevelator and High Score data acquisition and interpretation software, to determine the principal mineralogical composition. Analyses were carried out on the bulk samples. In particular the semi-quantitative determination of the mineral components as quartz, feldspar and calcite, was carried out, and the content of clay minerals + accessory minerals was obtained as a difference. The semi-quantitative determination of the reported minerals was done by measuring the elongation of selected diffraction peaks for each mineral, and multiplying it by coefficients determined on the diffraction spectra of samples of known composition.

The clay minerals composition of the earthy materials was determined on the fraction <4 µm extracted through sedimentation according to the Stokes' law (Cipriani, 1958; Cipriani and Malesani, 1972), investigating the range (2θ) 2-32° with the above mentioned diffractometer.

The grain size distribution of the earthy materials (samples PI499, 500, 502, 503) was carried out through sieving in order to separate the following fractions: sand (Ø > 63 μm), silt (4 μm< Ø < 63 μm) and clay (Ø < 4 μm).
From one to three thin sections (about 35 μm thick) were prepared for each sample, and analyzed by means of a polarizing microscope under transmitted and reflected light (OM).

4.1. Results earthy materials
Information on the colours of the earthy materials is reported in Table 1. They range from light yellowish brown to very pale brown to pale brown, denoting an overall high degree of similarity in terms of colour.
The results of XRD and grain size analyses are reported in Tables 2, 3 and 4.

Table 2: Principal mineralogical composition of a selection of the samples of earthy materials collected (semiquantitative data). acc. = accessory minerals: hematite in PI499, PI502, PI503; gypsum in PI499, PI500, PI502. (Ds, wall D, southern side; Dn, wall D, northern side)

Sample (wall)	*Quartz*	*Calcite*	*Feldspars*	*Phyllosilicates+ acc.*
PI499 (Ds)	32	12	17	39
PI500 (Dn)	33	12	24	31
PI502 (E)	35	8	8	49
PI503 (C)	40	13	25	22

Table 3: Composition of the clay minerals of a selection of the samples of earthy materials collected (semiquantitative data). (Ds, wall D, southern side; Dn, wall D, northern side)

Sample (wall)	*Kaolinite*	*Illite*	*Clorite-vermiculite*	*Illite-smectite*	*Vermiculite*
PI499 (Ds)	15	30	15	30	10
PI500 (Dn)	20	25	20	20	15
PI502 (E)	15	30	15	30	10
PI503 (C)	20	20	20	20	20

Table 4: Grain size distribution of a selection of the samples of earthy materials collected. (Ds, wall D, southern side; Dn, wall D, northern side)

Sample (wall)	*Sand %* *Ø > 63 μm*	*Silt %* *4 μm< Ø < 63 μm*	*Clay %* *Ø < 4 μm*
PI 499 (Ds)	65.8	14.2	20.0
PI 500(Dn)	63.7	15.0	21.3
PI 502(E)	59.2	16.8	23.9
PI 503(C)	77.5	16.0	6.5

Concerning the rammed earth samples collected from the wall D, the mixtures are quite lean, due to the strong amount of sand + silt. The mineralogical data are in agreement with the granulometric data as showed by the high amount of quartz and feldspars (to be referred to the sandy fraction).
As pointed out above, in the coarser fraction, a considerable amount of reemployed material like bricks and mortar fragments (see further) is also present (Figure 4). It is worth noting that the rammed earth wall E, found at the ground floor very near to the D wall, contains far less mortar additions. The fraction <4 μm shows the presence of illite, kaolinite, chlorite-vermiculite, illite-smectite and vermiculite in all the samples.

The comparison with the "optimal granulometric composition" reported by CRATerre for rammed earth (Houben and Guillaud, 1989) points out that the grain size of three rammed earth samples (PI499, PI500, PI502) falls within the zone of acceptability for this type of earthen architectural product (Figure 5).

Figure 4: Pebbles and fragments of mortar, terracotta and wood in the rammed earth masonry of the wall D (PI500)

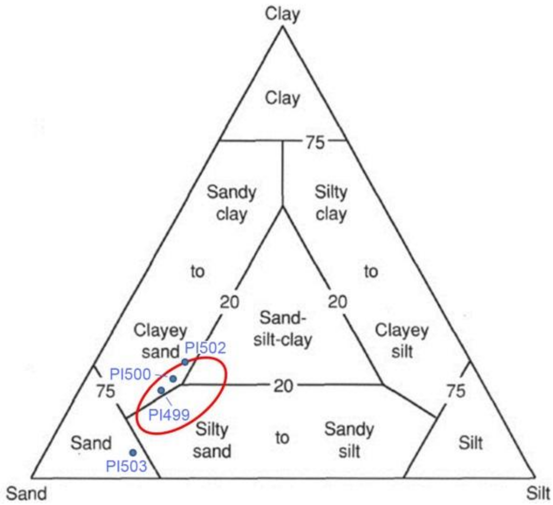


Figure 5: Shepard diagram with the points of the rammed earth masonries of wall D (PI499, PI500) and wall E (PI502). In red the optimal granulometric composition" reported by CRATerre for rammed earth

Concerning the earthen bedding mortar of the brick masonry type, the grain size analysis of a sample collected from the wall C (PI503) shows a mainly sandy composition. In a first instance, such a mixture does not guarantee a sufficient binding action among the fired bricks of the masonry.

The observation in thin section (Figure 6) of earthen bedding mortars and earthy materials from the rammed earth masonries, disclosed the presence of the following components in all the samples:

- monocrystals: quartz, plagioclase (with oligoclase and albite-oligoclase composition), potassium feldspar (orthoclase and rare microcline), sparry calcite, muscovite, biotite and chlorite lamellae;
- rock fragments: polycrystalline aggregates of quartz, fragments constituted by microcrystalline calcite (micrite and/or microsparite), polycrystalline aggregates of sparry calcite, argillite, siltite, chert, quartz-feldspars grains derived from intrusive magmatic rocks, micaschist;
- other components: carbonate bioclasts (mainly represented by foraminifera and mollusk shells), micro-nanocrystalline aggregates of iron oxides.

In all the cases, quartz fragments (both as monocrystals and polycrystalline aggregates) are prevailing, while the relative abundances of the other components can be slightly variable among different walls and also in different parts of the same wall.

Charred vegetal fibers and wood pieces, as well as fragments of mortars, are visible in thin sections of the rammed earth materials collected from the wall D, while the wall E contains charred vegetal additions but fragments of mortars were not observed at the microscopic observation. Both these two peculiar components were not observed in the earthy materials derived from the brickwork masonries.

Regarding the supply sites for the earthy materials, one can expect that a preferential source could be the Pliocene sands and clays widely cropping out in the eastern part of the Siena territory (Fabiani et al., 2001), which could be easily found all around the Grange complex. The mineralogical-petrographic features of the earthy material collected from the bank of the Arbia Stream near the Grange, reflecting the composition of such Pliocene substratum, are not dissimilar, in outline, from a compositional point of view, from the samples of the three walls, although the carbonate component appears to be more important. Unlike the earthy materials from the walls of the Grange, in which the silty-clayey component is always present, this stream sediment is essentially sandy and unbundled.

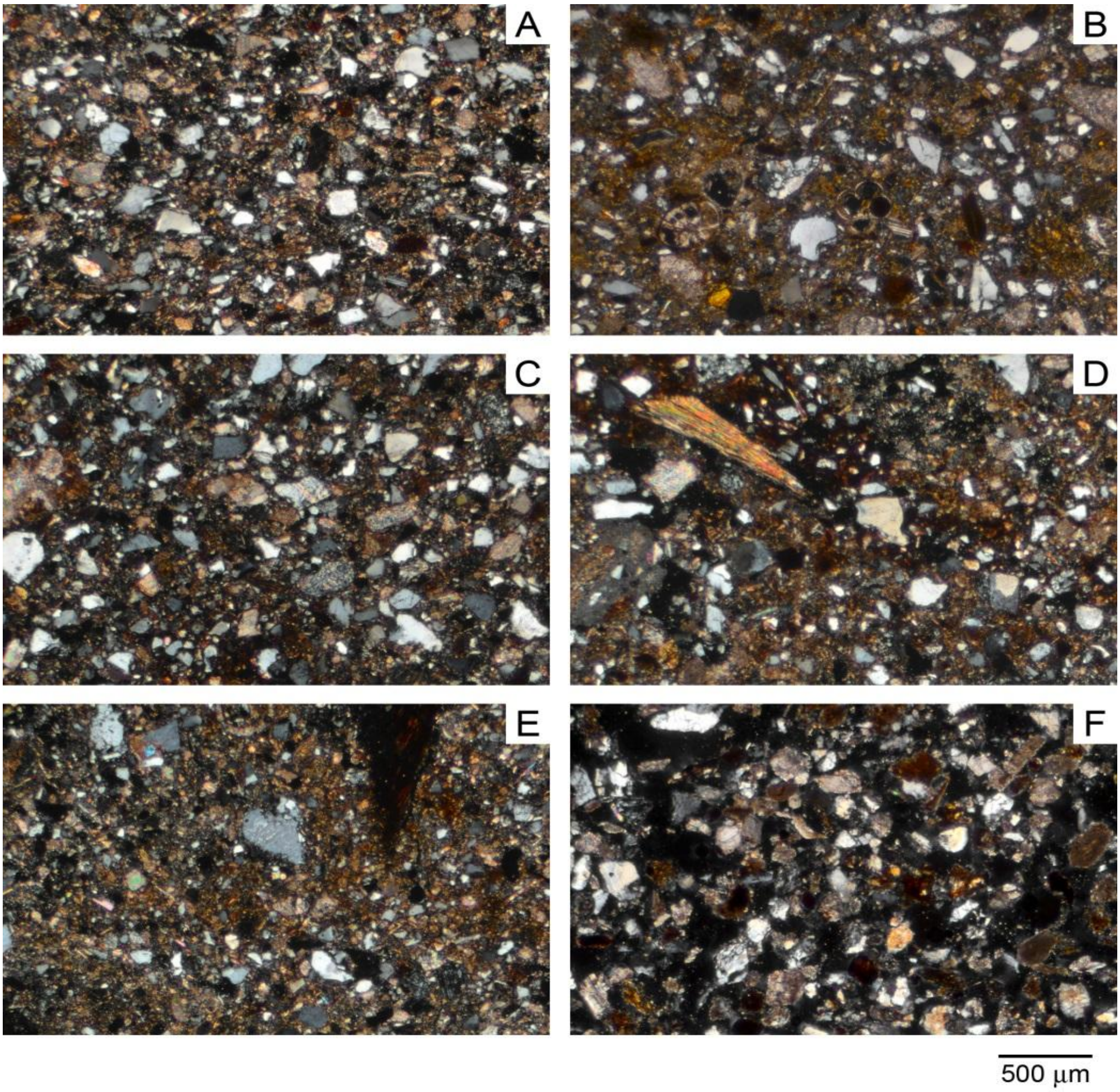


Figure 6: Polarized light microscopy images in thin section of a selection of the samples of earthy materials analysed (all obtained under crossed polarizers). Earthen bedding mortar samples: **A** - PI207 (wall A); **B** - PI236 (wall B); **C** - PI503 (wall C). Samples from the rammed earth masonries: **D** - PI499 (wall D, southern side); **E** - PI502 (wall E). **F** - Sandy material collected from the Arbia Stream bank (sample PI231).

On the whole, the differences observed among the earthy materials from different walls could indicate different supply localities, also taking into account the different age of the structures examined, but probably remaining in the context of the local Pliocene sediments and/or their recent reworking by streams.

4.2. Results mortars and plaster

The mortars covering the earthy materials in the outer part of the joints between the bricks in the walls A, B and C are lime mortars with a silty-sandy aggregate, with clots of microcrystalline calcite (Figure 7). The binder/aggregate ratio is about 1/1.5-1/2. In the mortars from the wall A, the maximum dimension of aggregate grains can reach about 3 mm, with a maximum frequency in the grain size distribution the interval 120-480 µm. In the walls B and C the grain size is slightly finer, on average (maximum grain size about 500 µm), and the binder content is a little higher. Among the grains of the aggregate, the same components described for the earthy materials were observed, to be attributed to Pliocene sands (Fabiani et al., 2001).
A minor content of ground terracotta grains was observed in the mortars from both the walls, but its scarce presence does not allow to discriminate between a purpose addition or rather an accidental component.

The analysis of mortar fragments found in the wall D showed the presence of two types of mortars:
- a lime mortar with a sandy aggregate, whose general features are reminiscent of those of bedding mortars of the granary (a more detailed study on these mortars should be performed in order to confirm a *post quem* dating of the masonry);
- a gypsum mortar without an aggregate but containing a large amount of dolomite crystals and dolomitic microsparite aggregates, to be considered as relics of burning of the original rock used for the production of the gypsum binder. Such precursor rock could be hypothetically attributed to a Triassic evaporitic-dolomitic succession (Burano Anhydrite Formation) cropping out few kilometers south of Siena (Fontazzi, Casciano di Murlo), not so far from the Grange complex.

These gypsum-based mortars were not found in the various structures of the complex of the Grange, and therefore do not constitute a useful chronological reference to the dating of the wall under study.
Finally, the plaster which covers the southern side of the wall D is a lime mortar with a mainly sandy aggregate (maximum grain size around 1.2 mm, maximum frequency in the interval 40-320 μm), with a binder/aggregate ratio around 1:2.5 and aggregate grains still constituted by components typical of the Siena Pliocene sands. The outer layer is constituted by a *secco* applied lime layer about 300-400 μm thick.

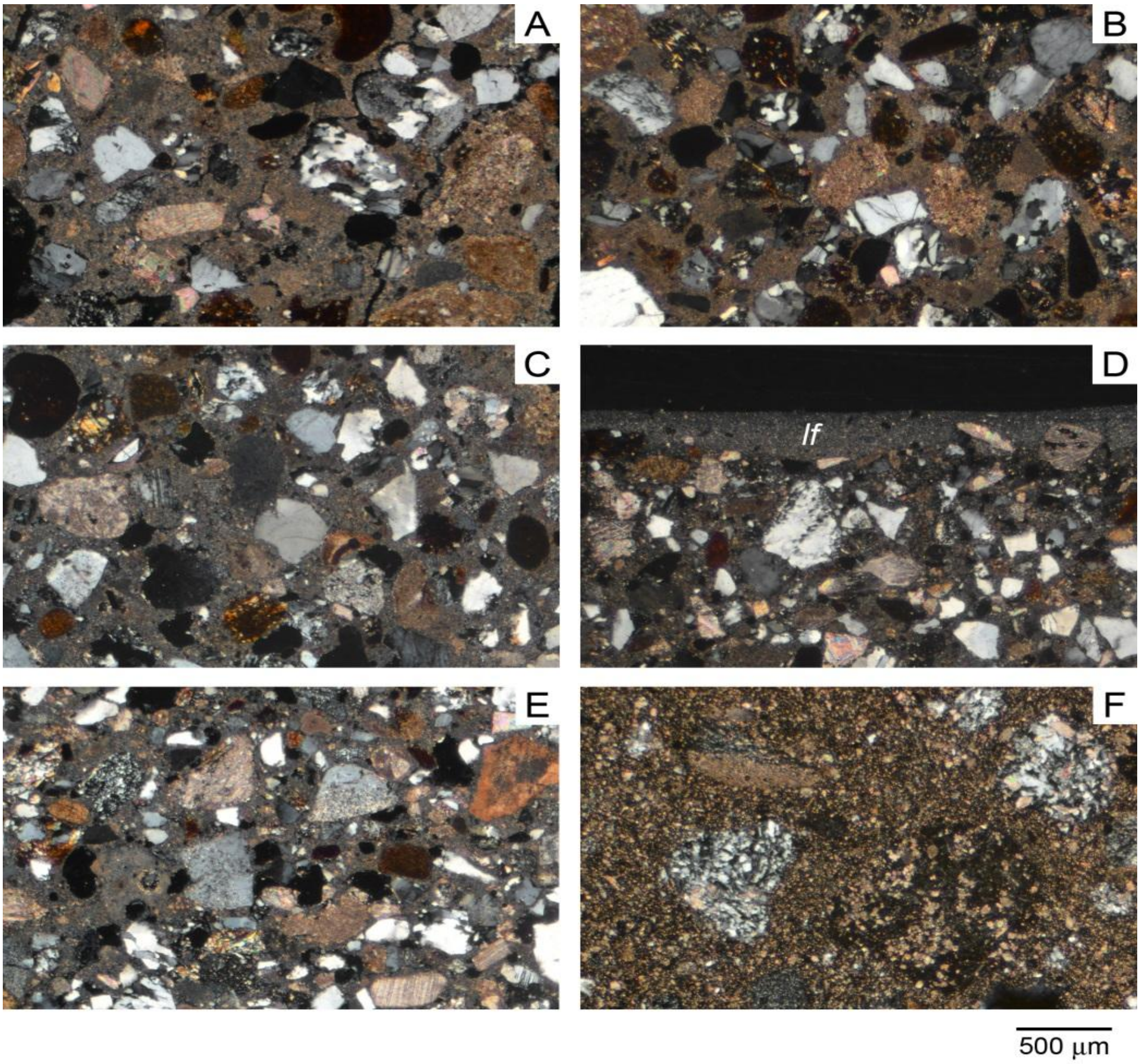


Figure 7: Polarized light microscopy images in thin section of a selection of the mortars covering the earthy materials (all obtained under crossed polarizers). Lime mortars samples from the joints, covering the earthen bedding mortars in the brick masonries: **A** - PI208 (wall A); **B** - PI237 (wall B); **C** - PI504 (wall C). **D** - Plaster covering the southern side of the rammed earth masonry (wall D), with the overlying lime finishing (*lf*) (PI495). **E** - fragment of lime mortar with sandy aggregate found inside the wall D, (PI500). **F** - fragment of gypsum mortar found inside the wall D (sample PI496)

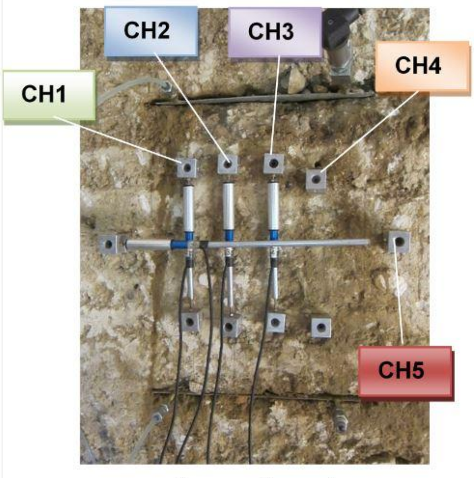
5. Mechanical tests

Double flat jack and sonic tests were extensively applied on the different masonry typologies of the Grange, in order to achieve consistent information on their composition and mechanical characteristics, with the aim of defining the structural response of the building. The Italian Technical Standards for Constructions (Technical Standard for Constructions - NTC 2008, Ministerial Decree 14/01/2008), suggest indeed the application of

diagnostic methodologies in order to minimize the uncertainties related to the definition of the structural and seismic response of any existing building.
The Italian standard includes, as a reference for the engineers/architects involved in the structural verification (Technical Standard for Constructions - §C8A.2.1, NTC 2008 explanatory circular nr. 617, 02/02/2009), a table containing the mechanical and physical parameters of the most common masonry typologies in Italy. However, due to the reduced presence of rammed earth structures in Italy, no information in the Standards is given on this masonry typology.
In the following paragraphs, the most relevant outcomes of the investigation campaign on the rammed earth masonry typology, and on a brick masonry with earthen bedding mortars are presented.

5.1. Flat jack tests

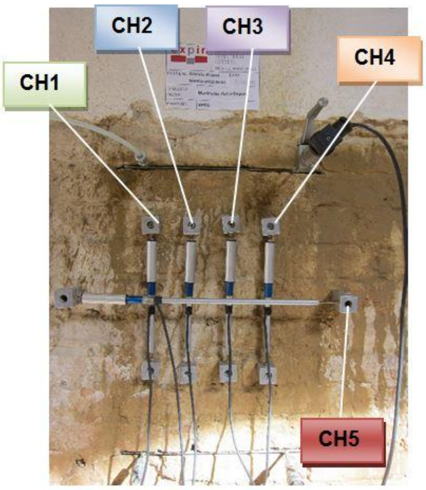
The flat jack test (RILEM Recommendation MDT.D.4 - MDT.D.5 ASTM C 1196-14a - ASTM C 1197-14a) has become a standard procedure as a relatively simple, minor destructive and reliable technique for the definition of the mechanical characteristics of the investigated masonry. By means of flat jack tests it is in fact possible to detect both the local state of stress and the deformability characteristics of masonry. The double flat jack test allows the experimental determination of the mechanical characteristics of a masonry, besides estimating the strength of a masonry at its “elastic limit”. The test consists in applying to the masonry a uniform compressive state of stress, by using two flat jacks.
The test MPD6C was carried out on the rammed earth masonry in the wall D, in the northern side. The tested masonry area corresponded to 0.5 (height) by 0.35 m (width). Results indicate reduced mechanical characteristics (Figure 8), with low elastic modulus (high deformability) and material plasticization at the value of 0.6 N/mm^2 (6 kg/cm^2).
The results of the test MPD5, carried out on the brick masonry with earthen bedding mortars in the wall C, indicate mechanical characteristics below the values proposed by the Italian standard related to "brickwork masonry with lime mortar", most likely for the presence of poor quality (earthen) mortar (Figure 9). A relevant stiffness decay at the value of approximately 1.0 N/mm^2 has been evidenced.



Sensors' layout

σ max stress applied [N/mm^2]	0,60
Load step [N/mm^2]	0,20
Young's modulus E_{tan} [N/mm^2]	**Δ (σ) [N/mm^2]**
202	0,00-0,20
183	0,20-0,40
89	0,40-0,60

Figure 8: Flat jack test on the rammed earth of the wall D, in the northern side.



Sensors' layout

σ max applied [N/mm^2]	1,20
Load step [N/mm^2]	0,30
Young's modulus E_{tan} [N/mm^2]	**Δ (σ) [N/mm^2]**
754	0,00-0,30
968	0,30-0,60
477	0,60-0,90
191	0,90-1,20

Figure 9: Flat jack test on the brick masonry with earthen bedding mortars (wall C).

5.2. Sonic tests

Through the execution of sonic tests (ASTM C597 - 09), it is possible to determine the velocity of propagation of mechanical (sonic) waves through masonry elements (walls, pillars, vaults…), obtaining indications of a qualitative/quantitative nature on the masonry consistency and soundness. Sonic tests may indicate the presence of cavities, cracks or heterogeneity of material intercepted along the transmission path of the wave. The sonic wave is generated on the masonry element by hitting with an instrumented hammer, and it is then received by a sensor (accelerometer) located on a different point of the structure. Both devices are connected to an acquisition unit for the data recording. The data processing consists in the calculation of the velocity in the masonry element once measured the flight time - time lapse between the impulse generation and the resulting vibration in the accelerometer - and the distance between transmitter and receiver.

The test executed in the rammed earth masonry (wall D) indicates homogeneous however very reduced velocity values, with an average value on 36 sonic paths equal to 542 m/s (Figure 10).

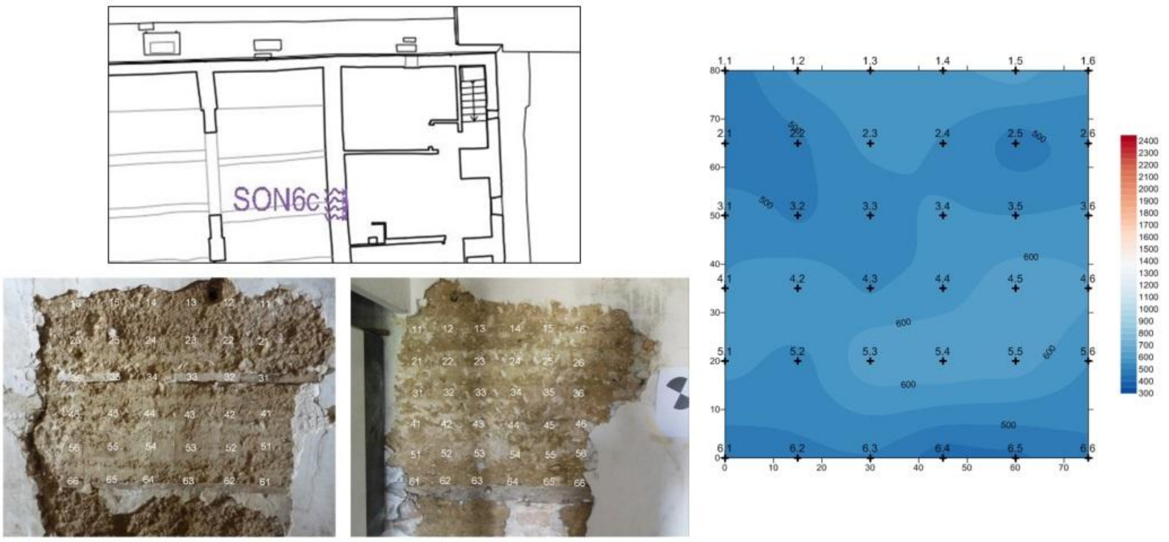


Figure 10: Sonic test on the rammed earth of the masonry D with the graphical representation of the velocity values (m/s).

Concluding remarks

This paper focused on the use of walls built with earthen materials in an important medieval complex in Tuscany, the Grance of Cuna. It is worth noting that the examined structures have different chronological collocation, testifying that this type of materials had a prolonged use in this area, although with different features.

Rammed earth masonries, adobe masonries and wattle and daub masonries are attested from antiquity to modern times (Francovich et al. 1980, Montevecchi 2004, 2010; Coccoluto & Cavari 2008). In the Alica Castle also earthen masonry mortar have been recognised (Montevecchi 2010). In Siena, earthen masonries have been reported near Porta dei Pispini, one of the gates of the city walls, and in a building close to the church of San Sebastiano (personal communication of Nadia Montevecchi).

Two examples of rammed earth masonries in the territory of Siena were reported by Parenti (2002): the Palace Bandinelli Corboli in Asciano (in the second building phase, dating to the 13th century) and Castelverdelli (San Giovanni d'Asso), where the earthen walls, made with different techniques, are largely used in the large complex, related to the 13th-14th centuries.

This research stimulates a prosecution of the study, both in the Grange of Cuna and in other Tuscan buildings, in order to verify the effective spread in the use of these kinds of structures, from a geographical and chronological point of view.

It would be appropriate to plan and carry out a more extensive research on earthen masonries and, in general, on the different types of walls based on earthy materials. Starting from a cataloguing of such structures, comparisons with other Italian and foreign earthen masonries could be possible, as well as a check of their spread in the territory of Siena and a differentiation from the chronological point of view. Thorough scientific investigations could also allow reaching correct evaluations regarding seismic safety. Cataloguing requires the contribution of all those working in the fields of building and civil engineering, who can accurately indicate new findings of earth masonries during past or current restructuring works.

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Author Contributions

All the authors contributed in the same way.

References

1. ASS (Archivio di Stato di Siena), Ospedale, ms. B 41.
2. ASS (Archivio di Stato di Siena), Ospedale 516, cc 231v, 248v, 262v.
3. ASTM C597-09, Standard Test Method for Pulse Velocity Through Concrete, *ASTM International*, West Conshohocken, PA, 2009.
4. ASTM C1196-14a, Standard Test Method for In Situ Compressive Stress Within Solid Unit Masonry Estimated Using Flat jack Measurements, *ASTM International*, West Conshohocken, PA, 2014.
5. ASTM C1197-14a, Standard Test Method for In Situ Measurement of Masonry Deformability Properties Using the Flat jack Method, *ASTM International*, West Conshohocken, PA, 2014.
6. Banchi L., Statuti senesi scritti in volgare ne' secoli XIII e XIV, vol. III, *Statuto dello Spedale di Siena*, (1877) Bologna, presso Gaetano Romagnoli.
7. Cipriani C., Ricerche sui minerali costituenti le arenarie: I. Sulla composizione mineralogica della frazione argillosa di alcune arenarie Macigno, *Atti della Società Toscana di Scienze Naturali 65*, (1958), 86–106.
8. Cipriani C., Malesani P.G., Composizione mineralogica delle frazioni pelitiche delle Formazioni del Macigno e Marnoso-arenacea (Appennino settentrionale), *Mem. Ist. Geol. Min.*, 29, (1972), 1-25.
9. Coccoluto M., Cavari F., Tecniche edilizie in terra cruda, in *Materiali per Populonia 7*, eds. Acconcia V., Rizzitelli C., *Edizioni ETS*, Pisa, (2008), 129-153.
10. Coscarella G., Franchi F.C., La grancia di Cuna in Val d' Arbia: un esempio di fattoria fortificata medievale, Firenze (1982).
11. Dandria S., Gabbrielli F., Giamello M., Giorgi E., Magrini A., Manzoni E., Randazzo F., Grancia of Cuna: From the Complexity of the Historical Building to a Composed Knowledge for the Project, in *Built Heritage:*

Monitoring Conservation Management, eds. Toniolo L., Boriani M., Guidi G., *Springer International*, (2015), 227-236.
12. Epstein S., Alle origini della fattoria toscana. L'Ospedale della Scala di Siena e le sue terre (metà '200-metà '400), (1986), Firenze.
13. Fabiani F., Giamello M., Guasparri G., Sabatini G., Scala A., I materiali lapidei dell'architettura senese: l'Arenaria Pliocenica ("tufo impietrito"). Il supporto scientifico all'intervento di restauro di Palazzo Spannocchi, *Nuova Immagine*, Siena (2001).
14. Francovich R., Gelichi S., Parenti R., Aspetti e problemi di forme abitative minori attraverso la documentazione materiale nella Toscana medievale, *Archeologia medievale*, VII, (1980), 173-246.
15. Fratini F., Pecchioni E., Rovero L., Tonietti U., The earth in the architecture of the historical centre of Lamezia Terme (Italy): Characterization for restoration, *Applied Clay Science 53*, (2001), 519-516
16. Houben H., Guillaud H., Traité de construction en terre de CRATerre, Marseille: *Editions Parenthèse* (1989)
17. Merlotti G. 1995, Memorie storiche delle parrocchie suburbane della diocesi di Siena, *ed. Marchetti M.*, Siena, riedizione Cantagalli.
18. Montevecchi N., San Gimignano, torre di Casaglia, in *Medioevo a Volterra. L'architettura nell'antica Diocesi tra Duecento e Trecento*, ed. Furiesi A., *Pacini* Pisa (2004), 152-153
19. Montevecchi N., Alica da castello a villa: i materiali archeologici, in *Peccioli e la Valdera dal Medievo all'Ottocento: itinerari archeologici fra Pisa e Volterra*: atti della giornata di studi del 18 aprile 2009, ed. Ciampoltrini G., *Fondazione Peccioli per l'arte*, Pisa (2010), 28-58
20. Parenti R., Il "chasamento" dei Bandinelli ad Asciano e Castelverdelli nella Val d'Asso, in *Le dimore di Siena, l'arte dell'abitare nei territori dell'antica Repubblica dal Medioevo all'Unità d'Italia*, ed. Morolli G., Firenze, Alinea (2002), 107-112.
21. RILEM Recommendation MDT.D.4: in-situ stress tests based on the flat-jack – RILEM TC 177-MDT: Masonry durability and on-site testing, *Materials and Structures*, Volume 37, Number 7 / August, 2004.
22. RILEM recommendation MDT. D.5: in-situ stress-strain behaviour tests based on the flat jack - RILEM TC 177-MDT: Masonry durability and on-site testing, *Materials and Structures*, Volume 37, Number 7 / August, 2004.
23. Technical Standard for Constructions – NTC 2008 – Ministerial Decree Jan.14 2008 Explanatory circular nr. 617, Feb. 02 2009 – Instructions for the application of the new Technical Standard for Constructions related to the Ministerial Decree Jan.14 2008.

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