Consolidation and Upgrading of Historic Earth Block Masonry Constructions

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ABSTRACT

Earth structures constitute a great part of European Monumental Heritage and are closely related to the wider historic, socioeconomic and environmental aspects of each region. They have been constructed with various materials and techniques which depict the regional constructional traditions, with respect to economy of resources and energy consumption in building. Many techniques of building with earth have been developed, while in South Eastern Europe the mostly encountered type is buildings with earth-blocks.

Nowadays there is no policy for their retrofitting, maintenance and upgrading, since the tradition of manufacturing earth masonry has vanished and there is lack of relevant regulations. As a result, earth-block houses have been abandoned and destroyed due to damages from earthquakes, ageing or unsuitable interventions (use of concrete members, cement based mortars) and many historic centers with earth houses have been marginalized and demolished.

In this paper, a methodology is presented regarding the analysis of building materials and techniques of historic earth block houses situated in Northern Greece, as well as the design and testing of compatible repair materials for their rehabilitation. A series of laboratory tests have been performed to the historic materials, in order to define their microstructural characteristics and their physico-mechanical and chemical properties. Results have been evaluated and led to the design of compatible repair materials based on earth. A series of soil based grouts were manufactured and tested, while their properties were enhanced by the use of specific additives and admixtures.

Experimental results showed that the development of compatible repair materials for the stabilization and restoration of historic earth-block buildings should be based in scientific criteria. This means that proper mortar and grout compositions based on earth could sufficiently fill joints, cracks and lacunae and could therefore lead to the maintenance and upgrading of historic earth block buildings.

Keywords: *Earth-block buildings, restoration, compatibility, mortars, grouts*

INTRODUCTION

Earth structures have been continuously used in construction from prehistory until nowadays (33% of worldwide houses are built with earth), due to their low cost and easy production, without high energy embodied materials. They constitute a great part of European Monumental Heritage and are closely related to the wider historic, socioeconomic and environmental aspects of each region. They are constructed with local clayish materials by using techniques which depict the regional constructional traditions. Many techniques of building with earth have been developed, such as cob in UK and taipa in Portugal.

In SE Europe they are usually located in lowland villages and mountainous settlements. Some of them are still inhabited, others have been abandoned. They are considered as cultural heritage of vernacular architecture, since they are constructed with earth blocks and mud-mortars of local raw materials and by using traditional techniques (Figs.1-2).


Figures 1-2 Earth-block houses of N Greece (town of Goumenissa)

Up to date there is no policy for their retrofitting, maintenance and upgrading, since the tradition of manufacturing earth masonry has vanished and there is lack of relevant regulations. As a result, earth-block houses have been abandoned and destroyed due to damages from earthquakes, ageing or unsuitable interventions (use of concrete members, cement based mortars), while many settlements with earth houses have been marginalized and abandoned. Meanwhile, modern engineers are not accustomed to this type of buildings and there is lack of scientific knowledge and experience in repairing and upgrading them.

Under the light of sustainability in constructions, alternative ways of building are pursued, for low energy consumption and environment protection. According to literature [1] [2] [3] [4], about 50% of raw materials taken from nature are for buildings and modern cement based construction is responsible for the 40% of worldwide energy consumption and 50% of the total waste burden of the planet. To this direction, building with earth has been reconsidered and there is a revival of the interest all over the world and in many European countries such as France and Germany.

During the last decade, a research on the development of effective materials and techniques for repairing old earth block masonries has initiated at the Laboratory of Building materials of Aristotle University, aiming in using compatible and locally available raw materials. In this paper, the holistic study of analyzing the existing building materials of traditional earth-block houses and the proposals of compatible repair materials are presented.

RESEARCH ANALYSIS OF EARTH BLOCK STRUCTURES

Traditional earth-block houses can be of 1 or 2 storeys (Figs. 1-2). Masonries are usually 50-100cm thick and are constructed with earth-blocks and mud mortars (structural mortars, renders, plasters) based on locally available clay. Wooden beams and conjunctions reinforce the structure by connecting the structural members and increasing bearing capacity (Fig. 3). Foundations are usually of stone masonry in order to be stable and resistant to humidity.

Figure 3 Wooden beams and conjunctions of earth-block structure

The common damages confronted in earth-block structures can be divided in two main categories. The ones concerning the facades of the masonry and those referring to the bearing capacity of the structural elements. They can be synopsized as following [5]:

- detachments of plasters and renders due to moisture
- scratching or loss of materials due to abrasion
- pulverization of the surface due to the action of frost or salts crystallization
- presence of insects
- growth of plants the roots of which destroy some times deeply the unbaked brick masonry
- diagonal cracks in the plane of masonry walls created by earthquakes' vibration
- cracks vertical due to superposition of extra loads because of other uses of the building
- bulge of earthen walls, due to the pushes created by a different reasons: such as movements of wooden beams or wooden floors
- decay of the wooden beams and floors as well as of the wooden roof.

According to the analysis of the building materials from earth-block structures in Greece (Kolligospita, Zografou settlement, Chalkidiki), performed in the Laboratory of Building Materials, the following remarks arose [6]:

Earth blocks (Fig. 4) were compact, with dimensions 30x15x10cm, manufactured with clay of local origin. Inert material, such as fine aggregates, wooden fibers, straw, was added in order to increase their stability and flexural strength. Their compressive strength was low, around 0.5MPa, while their porosity was around 10% and Apparent specific gravity 1,7. As expected, their water absorption and capillary sanction was high and led to material detachments.

Figure 4 In situ, macroscopic and microscopic figures of a traditional earth block

Structural mortars (Fig. 5) were also based in clay of local origin, while hydrated lime was added in a ratio of clay:lime around 3:1. Aggregates were of natural origin and granulometry 0-8mm, while wooden fibers in a percentage of 2% w.w. of binders were added.

Binder/Aggregates (B/A) ratio was around 1/1,5. Compressive strength was around 0.6MPa, porosity 23% and apparent specific gravity 1.6

Figure 5 In situ, macroscopic and microscopic figures of structural mortars

Plasters and renders (Fig. 6) were manufactured in 2 or 3 well compacted layers of total width 3cm. The internal layer was based in clay and hydrated lime in a proportion of 1:1. Low percentage of aggregates (granulometry 0-4mm) and wooden fibers were added. Binder/Aggregates (B/A) ratio was around 1/1. Compressive strength was around 1MPa, porosity 24% and apparent specific gravity 1.6. Subsequently, 1 or 2 thin layers (2-5mm thick) of lime were externally placed.

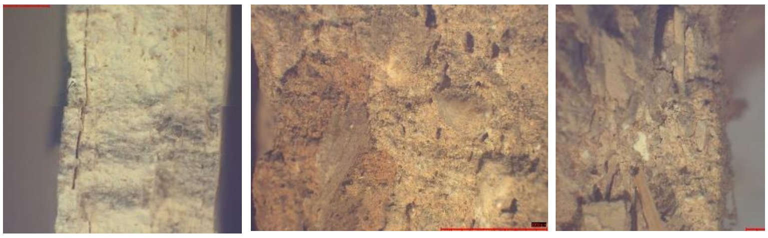

Figure 5 Microscopic figures of plaster. a. External layer, b. intermediate layer, c. internal layer

REPAIR MATERIALS AND TECHNIQUES

Grouting is an old and widely used irreversible technique for consolidating historic masonries. Most of the grouts used in the past for historic masonries consolidation were based on cement, by which their strengthening was achieved. However, the introduced strong cement changed significantly the behaviour of the masonries' grouted parts, regarding deformability and response to hydrothermal loading, as well as the porosity properties and the moisture movement.

According to former experience [5] [6], in the case of earth-block structures, high performance grouts based on clay can be applied, aiming at maintaining the compatibility between the old and the repair materials and consequently avoid the heterogeneous behavior of repaired masonry.

In order to proceed to the proposals and testing of compatible clay based grouts for earth-block masonries consolidation, local soils taken from the areas around the studied earth structures were tested so as to be classified. The characteristics of the soils are presented in Table 1.

Table 2 Characteristics of soils used for grout mixtures

Soil nr	Composition			Color	U=D60/D10	WL Liquid Limit
	Sand	Silt	Clay			
1	73%	25%	2%	HUE 1.5 Y/R brown	<20	29,5
2	50,9	32,75	16,3	HUE 1.5 Y/R Strong brown	>55	47,5
3	72,7	23,8	3,45	HUE 1.5 Y/R Light olive brown	20	25,61

A number of grout mixtures were manufactured and their properties were measured (Tables 2-3). In order to evaluate their performance, grout mixtures were tested at fresh and hardened state. In fresh state, three properties were measured:

- Flow time, following ASTM C939-02 Marsh cone. The quantity of water was adjusted to keep flow time 9-11 sec, which according to previous experimental work [], maintains both fresh and hardened state properties in acceptable limits.
- Volume stability was tested 24 hours after mixing, according to ASTM C 940-98A. The grout was placed in a graduated glass cylinder (1000ml) and was covered. Volume stability was calculated according to the expression: [(V0 – V24) / V0] * 100%, where Vo (ml) is the volume of the specimen at the beginning of the test and V24 (ml) is the volume of the specimen after 24 hours. The upper limit of 5% was kept, as defined by the literature [] [].

At hardened state (28 days after their manufacture) determination of Compressive strength (ASTM C191-81) was performed.

Table 2 Soil based grout mixtures with the sandy soil Nr1. Proportions and properties

Constituents	Proportion of weight / Compositions					
	1	2	3	4	5	6
Soil 1	1	1	1	1	2000	1
Hydrated Lime	-	0.5	-	-	-	0.5
Pozzolan	-	0.5	-	-	-	-
Cement	-	-	0.2	0.3	0.4	0.5
Water/Binder ratio	1.27	1.05	0.95	0.84	0.98	0.92
Superplasticizer	1% w.w of binders					
Volume Stability Change in volume %	2.4	15.1	13.2	14.3	13.8	10.8
Fluidity Time of Efflux (sec)	10.1	9.8	9.6	9.5	9.4	10.1
28-d Compressive strength, (MPa)	0.05	0.18	0.55	0.89	1.98	1.02

Table 3 Soil based grout mixtures with the soils Nr and 3. Proportions and properties

Constituents	Proportion of weight / Compositions							
	1	2	3	4	5	6	7	8
Soil 2 +Soil 3	1	1	0.5	1	1	1	1	1
Hydrated Lime	-	-	0.5	0.5	0.5	0.5	0.2	-

Pozzolan	-	-	-	-	0.5	-	0.5	0.5
Cement	0.2	0.3	-	-	-	0.5	0.35	0.35
Water/Binder ratio	1.57	1.60	1.14	1.53	1.79	1.6	0.75	1.54
Superplasticizer	20.4	15.6	14.0	15.0	14.0	14.0	20.0	20.0
Volume Stability Change in volume %	5.16	13.6	27.2	27.2	28.7	17.8	8.4	12.1
Fluidity Time of Efflux (sec)	10.68	9.96	10.06	10.85	9.63	10.4	10.6	10.5
28-d Compressive strength, (MPa)	0.13	0.18	0.27	0.30	0.38	0.25	0.64	0.35

The effectiveness of the grout mixtures was checked by grouting models of mud-brick masonry which were previously crushed by applying loads at the Laboratory. The grout mixtures that have exhibited the higher mechanical strength, fluidity and volume stability were used for grouting earth block masonry walls previously loaded and crushed.

Before the grout penetrations, the walls have been subjected to pulse waves' velocity measurements made on the wall with sonometer in order to estimate the cracks or discontinuities of the crushed masonry walls. After one month period of curing at room conditions the consolidated masonry models were crushed again (Table 4). Measurements of the pulse waves' velocity were also made before the appliance of compressive loads. An adequate number of earth block masonry walls were crushed.

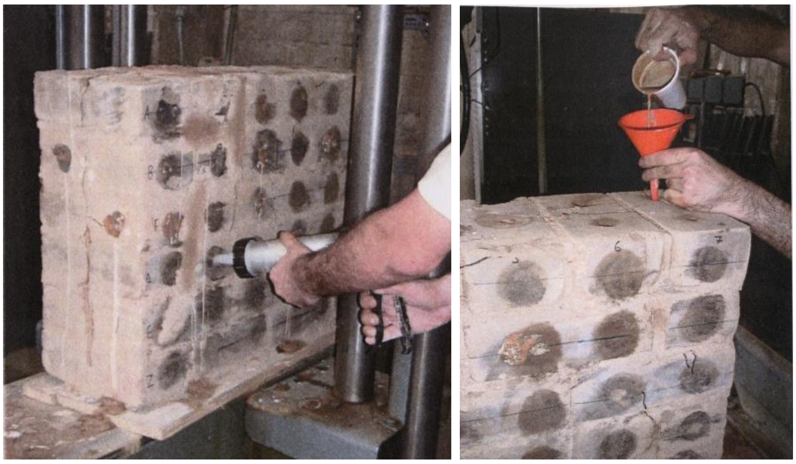

Figure 6 Grouting earth block masonry with soil based grouts

Table 4 Comparison of strength of earth block masonry models before and after grouting

Grout Compositions	Strength of masonry models before grouting (MPa)	Strength of masonry models after grouting at age 28 days (MPa)	Percentage of Strength Recovery
soil 1 + 30% cement	2.40	2.36	98.5
soil 2 + Soil 3 + 30% cement	2.64	2.47	93.4
soil 1 + 50% hyd. lime + 50% pozzolan	2.33	1.71	73.4
soil 2 + soil 3 + 50% hyd. lime + 50% pozzolan	2.42	1.78	73.5
soil 1 + 20% cement	2.04	1.84	90.0

soil 2 + Soil 3 + 20% cement	2.61	2.35	90.3

The conclusions deriving from the experimental results can be synopsized as following:

- The abundance of soil and the cooperation of the soil with great number of stabilizers makes possible the great improve of the strength capacity and other properties of soil when it is considered as building material.
- Clay or silty soils can be mixed with a sandy one to have a more appropriate soil for use in stabilization.
- The addition of cement 20-30% by mass in soil based grout increases considerably the strength development even at the age of 28 days.
- The strength recovery of consolidated by grouting masonry models reached 98.5% of the sound earth block masonry strength.

UPGRADING AND EXPLOITATION OF EARTH BLOCK STRUCTURES

During the 20th century concrete prevailed in construction and building with earth was abandoned and almost vanished in SE Europe. Nowadays there is great demand of using non energy consuming building materials that will minimize the negative consequences to environment, during the whole life cycle of them. By adopting earth housing, natural recourses and natural environment are preserved, wasteful use of energy consuming materials is avoided and a harmonized to landscape and traditional house architecture is promoted.

The advantages of constructing with earth are multiple and can be synopsized as following [1] [4]:

- Low cost
- Easy workability
- Fire resistance
- High thermal capacity, low thermal conductivity
- Low porosity
- Subduing extreme outdoor temperature and maintaining a satisfactory moisture balance
- Low energy input in processing and handling
- Unlimited reusability
- Environmental appropriateness

The revival of earth housing, according to the regional traditional techniques, at suburban and rural areas is a very realistic challenge and can have a great impact to the life of citizens. There are many ways to reinforce these structures and improve the strength and impermeability of earth blocks so as the modern earth block buildings to be safe and durable [3] [7] [8]. Earth may be stabilized mechanically or with the addition of special stabilizers that make the weak points of earth block masonry to be strengthened. Therefore these constructions are safe cost effective, completely harmonized in the regional environment, with high ecological profile.

Regarding the upgrading and exploitation of earth houses two types of actions could be foreseen, as following:

- Restoration of historic earth-block structures, leading to the revitalization of unprivileged and abandoned settlements of SE Europe
- Construction of modern earth-block houses in accordance to the regional architectural and environmental aspects and the traditional constructional techniques

In both cases the following, long-term benefits could be achieved:

- Promotion of an alternative, environmental friendly type of housing, with low energy consumption
- Revival of traditional constructional techniques that are now vanished

- Preservation of the historic, architectural, environmental physiognomy of regions
- Development of a new regional market and enhancement of employment on building with earth (constructors, manufacturers, suppliers, technicians etc)

CONCLUSIONS

Traditional earth-block structures have been abandoned since there is no policy for their retrofitting, maintenance and upgrading. In addition, the tradition of manufacturing earth masonry has vanished and there is lack of relevant regulations. However, the benefits gained from the use of earth in construction, such as complete recycling, low energy consumption for the production and during service life, high health and comfort performance especially in hot Mediterranean climates, constitute earth structures an alternative and well-promising type of housing.

The restoration and strengthening of these structures could be achieved by using compatible and locally available raw materials. This could lead to the upgrading and revitalization of unprivileged settlements of SE Europe which are nowadays abandoned. To this direction, the construction of modern earth houses could also result to retaining the architectural and environmental characteristics of these regions, revitalizing traditional constructional techniques that are now vanished and developing a new regional market on building with earth.

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