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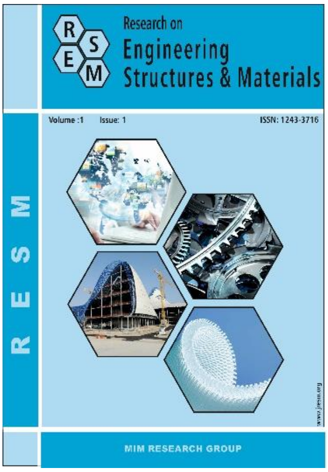

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Research Article

Constructional characteristics and restoration aspects of historic earth block structures

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Abstract

Earth structures constitute a great part of European Monumental Heritage and are closely related to the wider historic, socio-economic and environmental aspects of each region. In this paper, a methodology is presented regarding the analysis of the constructional materials and techniques of historic earth block structures situated in Northern Greece, as well as the design and testing of compatible repair materials for their restoration. A series of laboratory tests were performed, in order to define the physico-mechanical and chemical characteristics of the historic materials (earth blocks, structural mortars, renders-plasters). After the evaluation of the results compatible repair materials based on earth were designed, manufactured and tested.

1. 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 they are closely related to the wider historic, socio-economic and environmental aspects of each region. They are constructed with local clayish materials by using techniques which depict the regional constructional traditions [1-4]. 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 constitute characteristic examples of regional vernacular architecture, since they were constructed with local raw materials by using traditional constructional techniques (Figs.1-2).

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

The common damages confronted in earth-block structures could 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 [4]:

- 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

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- biological and higher plants growth
- diagonal cracks in the plane of the masonry created by earthquakes' vibration
- vertical cracks due to superposition of extra loads (secondary uses)
- bulge of earthen walls, due to the pushes created by different reasons (i.e. movements of wooden beams or wooden floors)
- decay of the wooden beams and floors as well as of the wooden roof.

(1)

(2)

Figs. 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 constructing 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.

Fig. 3. Wooden beams and conjunctions of earth-block structure

On the other hand, under the light of sustainability in constructions, alternative ways of building are pursued, for low energy consumption and environmental protection. According to literature [5-8], about 50% of the raw materials taken from nature refer to the constructional sector, while the contemporary cement and concrete industry is responsible for the 40% of the worldwide energy consumption and the 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 research interest on developing durable and cost-effective earth structures with low environmental footprint [5, 8-11].

During the last decade, a research on the development of effective materials and techniques for repairing historic earth block structures has initiated at the Laboratory of Building materials of the Aristotle University of Thessaloniki, 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.

2. Materials and Methods

Research focused on the analysis of the building materials from a settlement of historic earth-block structures (Kolligospita, Zografou settlement), located in Chalkidiki peninsula, N. Greece and dated in 1845(Fig.4). The settlement is nowadays abandoned, while earth-block structures confront severe damages [6].

Fig. 4. In situ, macroscopic and microscopic figures of a traditional earth blocks

A total number of 12 samples (earth blocks, structural mortars, plasters) were analyzed, according to the holistic methodology developed during the last 25 years in the Laboratory of Building Materials of the Aristotle University of Thessaloniki [6].

For mortars and plasters the tests realized were: microstructure observation (stereoscope Leica Wild M10), aggregates gradation (EN1015-1:1998), wet chemical analysis assisted by Atomic Absorption and HPLC, determination of porosity and apparent specific gravity (RILEM CPC 11.3), while compressive strength was tested in shaped cubic samples of 4x4x4cm.

For earth blocks the tests realized were: microstructure observation (stereoscope Leica Wild M10), determination of porosity and apparent specific gravity (RILEM CPC 11.3) and compressive strength (EN1926:2006).

3. Results and Discussion

3.2 Analysis results of historic building materials

The analysis results of the building materials from Kolligospita were comparatively studied, concluding to the following remarks [12]:

Earth blocks (Fig. 5) 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, probably due to their extreme deterioration (cracking and material detachments). Porosity was around 10% and apparent specific gravity 1.7. As expected, their water absorption and capillary sanction were high and led to material detachments.

(a) (b) (c)

Fig. 5. In situ, macroscopic and microscopic figures of a traditional earth blocks

Structural mortars (Fig. 6) 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

(a) (b) (c)

Fig. 6. In situ, macroscopic and microscopic figures of structural mortars

Plasters and renders (Fig. 7) 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.

(a) (b) (c) (d)

Fig. 7. In situ and microscopic figures of plaster layers b. External, c. intermediate, d. internal

3.2 Repair materials and techniques

Grouting is an old and widely used irreversible technique for consolidating historic masonries. Most of the grouts used during the last decades for historic masonries' consolidation were based on cement, by which their strengthening was achieved.

However, the introduced cement changed significantly the behavior of the masonries' grouted parts, regarding deformability and response to hydrothermal loading, as well as the porosity properties and the moisture movement [4, 13-14].

According to former research experience [4,12], 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 1. Characteristics of the soils used for grout mixtures

	Composition			Color	Uniformity Coefficient* $U=D_{60}/D_{10}$	WL Liquid Limit
Soil nr	**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

* classification of soils by sieve analysis

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, two 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 [13] [14], 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 [13] [14].

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

From the evaluation of the results it is concluded that the two types of soil (Nr1 and N2+Nr3) have different performance when stabilizers such as lime, pozzolan and white cement were added in the mixtures. It seems that the sandy soil (Nr 1) cooperated better with a short proportion of white cement (20% and 30% of the quantity of soil) than with other stabilizers, since the compressive strength is increased (Table 1). On the other hand, the combination of soil Nr2 and Nr3 was positively influenced when lime and pozzolan was added (Table 2).

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

Constituents / Composition	1	2	3	4	5	6
	Parts of weight					
Soil 1	1	1	1	1	1	1
Hydrated Lime	-	0.5	-	-	-	0.5
Natural Pozzolan	-	0.5	-	-	-	-
White cement CEM II/A-LL42.5N	-	-	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 reduction (%)	2.4	15.1	13.2	14.3	13.8	10.8
Fluidity (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 2 and 3. Proportions and properties

Constituents / Composition	1	2	3	4	5	6	7	8
	Parts of weight							
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	-
Natural Pozzolan	-	-	-	-	0.5	-	0.5	0.5
White cement CEM II/A-LL42.5N	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	1% w.w. of binders							
Volume reduction (%)	5.16	13.6	27.2	27.2	28.7	17.8	8.4	12.1
Fluidity (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

(a) (b)

Fig. 8 Grouting earth block masonry models with soil based grouts, through syringe and gravity

The effectiveness of the grout mixtures was further studied. The grout mixtures that have exhibited the maximum mechanical strength, fluidity and volume stability were used for grouting earth block masonry walls that were previously loaded and crushed (Fig.8).

Before the grout penetration, the walls were subjected to pulse waves' velocity measurements made 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.

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 crushed masonry models after grouting at 28d age (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 a great number of stabilizers make possible the significant improvement of the strength capacity and of other properties of the soil when this 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 the consolidated by grouting masonry models reached the 98.5% of the sound earth block masonry strength.

4. 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 is therefore a challenge in order to protect this significant part of the Monumental Heritage. This could lead to the revitalization and upgrading of abandoned historic centers and unprivileged settlements which are nowadays discriminated.

A holistic methodology on the analysis of the building materials and techniques of the existing masonries is a necessary stage for the design and testing of compatible repair materials based on locally available soil. The abundance of soil and its cooperation with a great number of stabilizers (lime, pozzolan, cement) may improve significantly the strength capacity and the other properties of the mixtures. Clay or silty soils can be mixed with a sandy one in order to have a more appropriate material for consolidation purposes.

The addition of cement in a proportion of 20-30% by mass in soil based grouts, increased considerably the strength development even at the age of 28 days, while the strength recovery of consolidated by grouting crushed masonry models reached 98.5% of the sound earth block masonry strength. Based on the results it could be said that historic earth block masonries can be consolidated with compatible soil based grouts and attain their original strength by applying a simple technique of grouting.

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