Engineering Structures 172 (2018) 869–876

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Mechanical properties of three-leaf masonry walls constructed with natural stones and mud mortar

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ARTICLE INFO

Keywords:
Three-leaf masonry
Mud mortar
Compressive strength
Modulus of elasticity

ABSTRACT

Although earth is the first masonry mortar material with continuous use throughout history, little experimental research on stone masonry with mud mortars has been carried out, particularly concerning its restoration. This paper presents the experimental investigation of the mechanical properties of three-leaf masonry constructed with natural stones and clay (mud) mortars under compression focusing on the production and properties of the mortars. Two different mortar mixes were designed for the external and internal leaves. Soil was collected and prepared (crushing of clods, sieving, drying and mixing with river sand). The water content was defined by flow table tests. Evaluation of the raw materials used for the production of the mortars was done by examining the particle size distribution by hydrometer and by sieves and by measuring the concentration of the total soluble salts and the organic material, while the hardened mortar evaluation was done by measuring the compressive strength, the flexural strength and the volumetric shrinkage. The compressive strength, flexural strength and splitting tensile strength of stones were also determined. Wallettes were subjected to monotonic compression after a six-month maturation period to determine the compressive strength, modulus of elasticity and deformation characteristics of the masonry. Adequate compressive strength, low modulus of elasticity and high transverse and longitudinal deformations were documented.

1. Introduction

The majority of buildings until the early 20th century were built with masonry walls of various types. One of them, often encountered in historic structures, is three-leaf stone masonry. Two external leaves made of stone or brick masonry are constructed at a distance, which is then filled with a loose, low strength material, made of stone fragments and/or bricks and mortar, constituting the internal leaf [1]. The stones of the external leaves can be uncoursed or semi-dressed, while the mortar used as laying mortar in the external leaves or as filling mortar in the core consists either of lime or mud [2]. The main structural problems of this masonry type are: (i) the weakness of the internal layer, which has significantly poorer mechanical properties than the external leaves (ii) the deterioration of the external joint mortar and (iii) the absence of connection between the leaves. As a consequence, they are very sensitive to brittle collapse mechanisms, which usually manifest, both under vertical and horizontal loads, as detachment of the leaves and out-of-plane deformation [3].

Mud has been extensively used as building material the world over. Depending on the availability, the type of the soil and local tradition, people have adopted several construction techniques, such as adobe and rammed earth, involving mud as the prime building material or as a mortar.

The structural system of load bearing stone masonry with mud mortar is used in construction before 8000 BCE, prior to the introduction of adobe masonry [4]. Even nowadays, using mud mortar is still a common practice in some countries, which have developed standards [5] and guidelines [6] for its appropriate preparation and application. It is a misconception that mud mortar in stone masonry was used only in lower status buildings and in less developed territories with scarcity of limestone. On the contrary, mud mortar has been applied in places such as England in high status gentry houses [7], Italy from the Roman times until the first decades of the 20th century in noble residences, churches, monasteries and institutional buildings [8] and Slovenia as the infill mortar in three leaf masonry [9]. Also in Greece, the extensive use of stone and mud masonry since 6000 BCE is well documented [10–13].

Despite the widespread use of earth in construction for millennia and the renewed interest in it as a sustainable material, it has not been the subject of significant research. In particular, the application of mud mortar in masonry other than adobe is overlooked. Thus, the main aim

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https://doi.org/10.1016/j.engstruct.2018.06.015
Received 3 July 2017; Received in revised form 30 March 2018; Accepted 5 June 2018

of this paper is to experimentally investigate the mechanical behaviour of three-leaf masonry built with semi-dressed stones and mud mortar. Understanding the behaviour of this type of masonry and proposing a procedure for the evaluation and application of mud mortars, since there are only few experimental results on the latter, will hopefully contribute to better design of interventions to such existing masonries.

2. Materials

For the preparation of the mortar, soil from Agios Stefanos in Attica, Greece, was collected, after removing the topsoil (about 40 cm) to avoid organic matter, from an area near a stream. River sand and gravel were also used. Stones used in construction were limestones quarried from Paramythia.

Soil is a complex material composed of gravel (2–60 mm), sand (0.06–2 mm), silt (0.002–0.06 mm) and clay (< 0.002 mm) [14] in various proportions. Clay acts as a binder for all larger particles while silt, sand and gravel constitute the fillers [15]. There are two overlapping uses of the term clay that must be distinguished. On the one hand, the term refers to the clay particle size class which includes those particles smaller than 2 μm, and on the other, to the micro-crystalline secondary minerals based on hydrous aluminum or magnesium silicate with a sheet-like structure [16].

Mud mortars have sufficient compressive strength compared with other types of historic mortars, such as air-lime mortars where compressive strength is typically between 0.5 and 3 MPa [17]. However, the mechanical and physical characteristics of building elements made of soil are affected by several factors:

- In direct contact with water they return to the plastic state and in the transition process to the hardened state their volumetric shrinkage is of different order of magnitude compared with other building materials, reaching up to 30% [18].
- The proportions of clay, silt and sand significantly influence soil structure, plasticity, cohesion and permeability [19]. Different percentages of clay can lead to different compressive strength and volume change. Too much sand and little clay can result in a weak bond between the unit and the mortar [20].
- In general, the compressive strength of soils where kaolinite is predominant can reach up to 1 MPa, of illitic soils up to 3 MPa and of soils with montmorillonite up to 5 MPa [21]. Montmorillonite clay also has larger specific surface area [22], leading to higher compressive strength and volumetric shrinkage.
- The compressive strength and the volume change are also affected by the grain size distribution of silt and sand [15].
- Organic matter in high levels decreases the maximum dry density and the compressive strength and increases swelling [23]. Thus, when soil is to be used for structural purposes, the organic content should not exceed 2–4% [24].
- Soluble salts maximum content must be 2%, due to their tendency to crystalize and make soil fragile [24].

Prior to collecting the quantity needed to produce the mortars, samples were taken and examined in order to determine the aforementioned characteristics.

- Sieve analysis was carried out according to EN 933-1 after removing the clay and silt fraction with a 0.063 mm sieve and distilled water and drying the remaining aggregates.
- The cohesive material was classified through sedimentation using the Bouyoucos hydrometer method [25].
- Organic content was determined according to the Walkley-Black method [26].
- Soluble salts were quantified by measuring electric conductivity in a saturated paste of soil and water (Saturated Paste Method).

Table 1
Agios Stefanos Soil (AGS) properties.

	Soluble salts (%)	Organic content (%)	Clay (%)	Silt (%)	Sand (%)
AGS	0.21	0.78	36.28	33.36	30.36

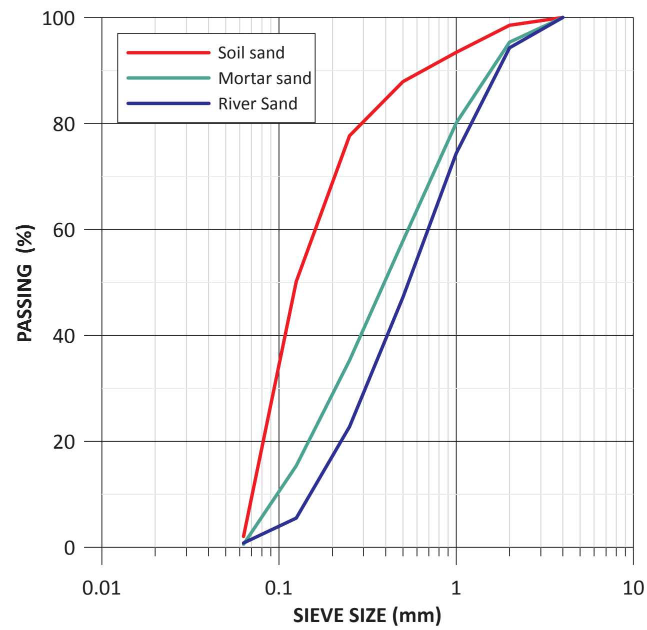

Fig. 1. Granulometric curves.

The obtained results for Agios Stefanos Soil (AGS) are presented in Table 1 and the results of the sieve analysis on the sand in Fig. 1, in which the sand already contained in the soil is mentioned as "soil sand", the added sand as "river sand" and "mortar sand" is the product of soil and river sand mix.

Soluble salts and organic content values were within limits but soil texture was unsuitable. As mentioned before, soil texture, and clay percentage in particular, is one of the most important soil properties. In general, higher clay content results in higher compressive strength, but also higher volume change, higher water/soil ratio and the appearance of shrinkage cracks of significant width that can cause structural issues. The balance between these contradictory attributes is very important when soil is to be used for structural purposes. Literature offers little information on the desirable texture for mud mortars. In general, it is proposed that mud mortars should have the same texture as adobe bricks for which clay percentage varies from 5% to 40% [27], but with a maximum grain size of 3 mm and without straw [14,28]. The IS 13077-1991 standard, which includes specific references to mud mortars, specifies that the clay fraction should be in a narrow range between 18% and 22% [5]. Consequently, sand was added in order to reduce the clay content according to the values proposed by the IS standard and also optimize grain size distribution.

In other mortar type there are two distinct main constituents: binder and aggregates. On the contrary, the soil used in mud mortars already contains both sand (aggregate) and clay (binder), so the granularity of the sand already contained in the soil is a decisive parameter for the selection of sand to be added as to obtain a desirable granular curve (Fig. 1). The final granulometric curve of the mortar is the product of the mix of the sand already contained in the soil and the added river sand. As it can also be seen in Fig. 1, 77.68% of the soil sand is fine (d < 0.25 mm). Since mortars with fine sand tend to have increased drying shrinkage, reduced compressive strength, modulus of elasticity and bond strength, and require more water to achieve a given consistency [29], a coarser river sand (Fig. 1), as well as river gravel