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The multi-scale approach of masonry, paradigm of clay brick.

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Abstract

Recent progress in nanoscience and engineering allows advanced characterization of materials. This type of characterization includes investigations revealing the scale dependent microstructure and mechanical as well physical properties of each component incorporated in the heterogeneous material. Its applicability and efficiency is confirmed in the field of cement based materials where the paradigm of these materials is solved, and universal buildings blocks and the multi-scale nature are well described. As a consequence, material researchers and engineers have knowledge about the impact of basic constituents and microstructure on macro behaviour of cement based materials. In the masonry field, a quite diverse situation is found. Although clay brick is among the oldest building materials, the main building blocks are still unknown. This knowledge gap is apparent in structural masonry, since the present homogenization and upscaling techniques consider only mortar joints, brick units and interface as a basic units. Here, the mechanical properties and elementary arrangement of these three components in the representative volume element (RVE) are assumed to govern the behaviour of masonry as a composite. But, it is understood that mortar may be broken down to lower scales, and its macro mechanical properties considered in the already developed approaches are governed by the lover scale components and its microstructure. Similarly, as it is shown by the authors in this contribution the brick unit may be broken down to lower scales, in which the basic material components and theirs properties are inherent. Therefore, the macro behaviour of composite masonry wall and its durability is considered to be ruled by the phenomena from the much lower scales present in the mortar, clay brick and the interface of these two.

1. Introduction

Masonry walls, pillars etc. are composite structures which consist of mortar joints and units of clay brick, concrete blocks, calcium-silicate blocks, etc.. Most of the masonry structural elements have one common characteristic: the units are stacked in a periodic way. Due to this special future, the homogenization technique of periodic media is very popular among researchers (Lourenço [6]) as a tool for structural analysis of large scale structures, rather than a detailed micro-modeling approach. Macro and micro-modeling approaches departs from the scale of $>10^{-2}m$, where the materials properties of mortar, brick and interface represent the macro properties of these components obtained in laboratory tests. However, it is known that the mechanical performance of materials depends on their morphology and phase constitution, in case of a composite. Therefore, it is correct to assume that the structural behaviour of masonry on engineering scale is ruled by the phenomena existing on scales much lower than $>10^{-2}m$, which are related with microstructure of mortar, clay brick and eventually theirs interface.

Recent studies in material science revealed the existence of microstructural features of mortar on lower scales. As a consequence, its macro-properties and macro-behaviour is governed by lower scales phenomena. Mortar, according to this multi-level representation is a material with four levels of microstructure, which obeys the principle of separation of scales (Ulm [7], Constantinides [3]). In this hierarchy Level "0" is associated with nanoscale and single colloidal particle of C-S-H solid. Changing the scale order leads to Level "I", of hundreds nanometers, where the single particles tend to agglomerate to form C-S-H gel matrix with gel porosity. Level "II" represents the structure of cement paste, which is formed from C-S-H matrix, large Portlandite crystals, unhydrated cement clinker and macroporosity. In the last level (Level “III”), the sand particles and interfacial transition zone (ITZ) are incorporated. This think model of mortar morphology, together with results of experimental characterization of mechanical properties of existing phases and advanced mathematical methods of micro-poromechanics allows bridging the existing scales and relating properly the material macro-properties with its microstructure and composition.

The research carried out here is directed towards understanding the microstructural paradigm of clay brick, combining it with a microstructural model of mortar, and bridging it with existing approaches in structural masonry, see Figure 1. This endeavour includes the definition of material scales for the clay brick and the classification of the morphological futures present at each level of observation. The chosen strategy closes the existing gap in the masonry science regarding multi-scale modeling. Moreover, it establishes the solid link between the lowest material levels and the scale of engineering applications for masonry. By doing so, the authors believe see new directions for the development of optimal and sustainable masonry constructions, where the influence of changes of the main building blocks on structural performance and durability of masonry may be easily captured.

Some attempts to explore the clay brick material characteristics were done in the past and recent years. However, they are focused mainly on separated sub-domains of this complex problem like: phase transformation during the firing process (Grim [5], Brindley [1]), influence of raw materials and brick processing on global physical and mechanical properties of brick (Cultrone [4], Freyburg [2]), or attempt the general characterization of construction materials.

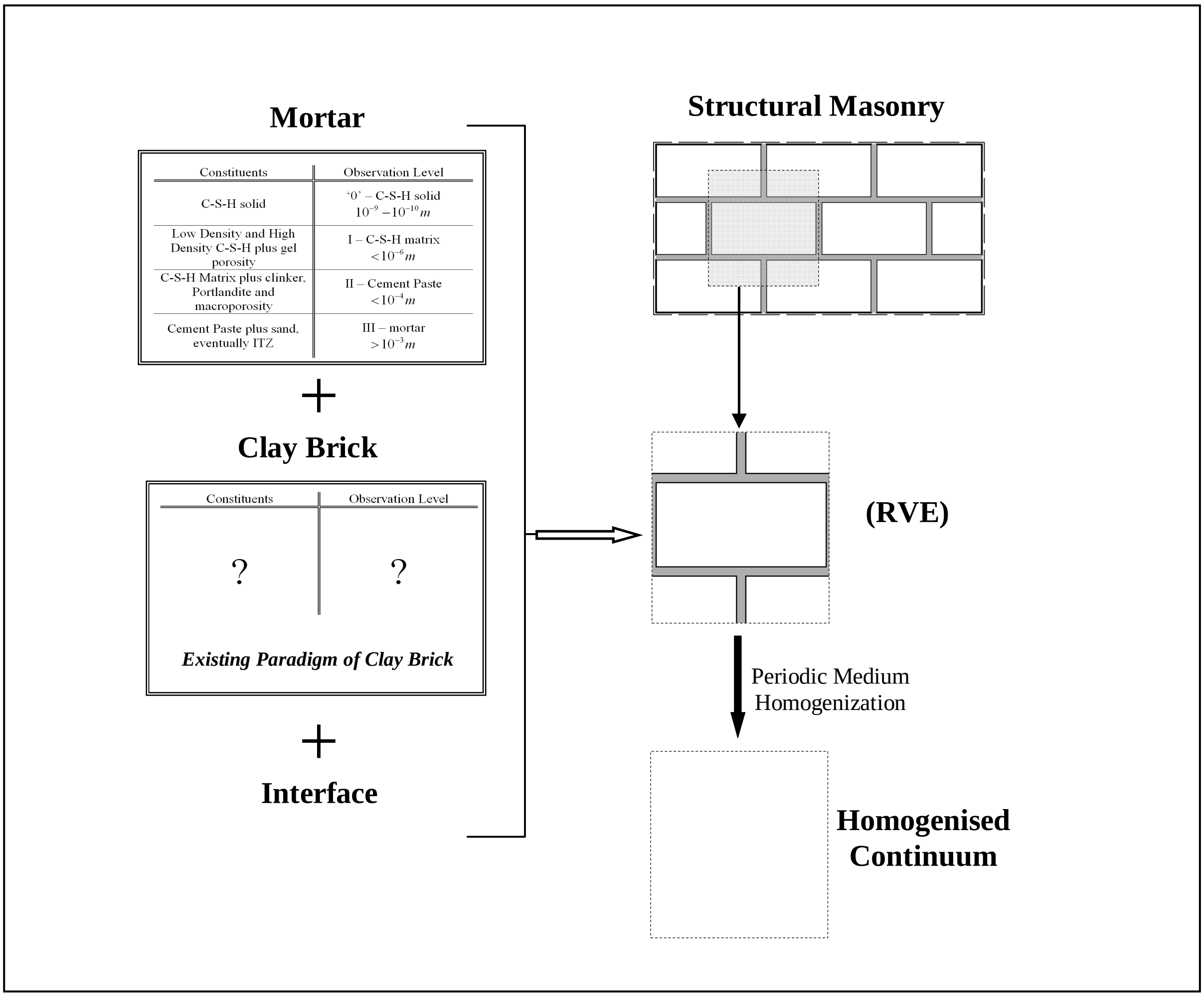


Figure 1: Assumed strategy to combine material scales within masonry

2. Experimental part

Characterization of the morphology of clay brick is carried on the samples obtained from the production lines of three Portuguese plants. The collected samples represent different classes of masonry bricks: facing brick, standard quality brick and low quality brick representing ancient masonry constructions. The characterization of bricks includes: classification of existing phases by X-Ray Diffraction, optical microscopy etc.; porous network description and microstructural arrangement are evaluated with use of SEM/AFM/TEM Microscopy, Mercury Intrusion Porosimetry, and traditional gravimetric methods; identification of mechanical properties of constituents at smallest scales by massive grid nanoindentation; macro strength and stiffness coefficients obtained by standard laboratory means and procedures.

The results obtained during the first period of research clearly indicate the existence of the 'glassy' matrix, aggregates of different size and porous domain Figure 2. The constituents are common for all types of samples. However, investigation of firing processes and raw materials composition indicates varying concentration of each phase with respect to the origin of sample, its firing history and raw material composition. The brick fired briefly at 1030ºC and cooled relatively fast has lower 'glass' matrix concentration. On the other hand, samples prepared in the traditional fashion with long maturing in 980ºC and relatively slow cooling rate are characterized by higher concentrations of 'glassy' matrix.

The investigated 'glassy' matrix is an amorphous, brittle material. Its volume fraction, together with the fraction of embedded crystal aggregates, strongly influences the mechanical properties of fired clay. Higher concentration of amorphous phase decreases the body strength and increases material brittleness. These observations are consistent with experimental results carried on macro scale.

The aggregates exist in three different forms: crystals embedded in the glass (order of nanometers), silt ($10^{-6} - 10^{-3} m$) and sand grains ($> 10^{-3} m$). The first type is the result of the viscous phase crystallization during cooling of brick in the firing cycle. Its concentration and concentration of glass phase are interrelated. Their volume fraction depends on the volume of the finest fraction grains in the raw materials, see Figure 3, as well as the maturing and cooling rate of the green body. The two other types of aggregates are the grains of silt and sand. The first fraction of raw material is partially affected by high temperature, and large percentage of it remains in the form of embedded grains. The sand fraction remains unaffected in the firing process. They are composed of mineral quartz. With respect to its hardness they form the back bone of fired brick and reinforce the material in similar way like in gravel aggregate in concrete.

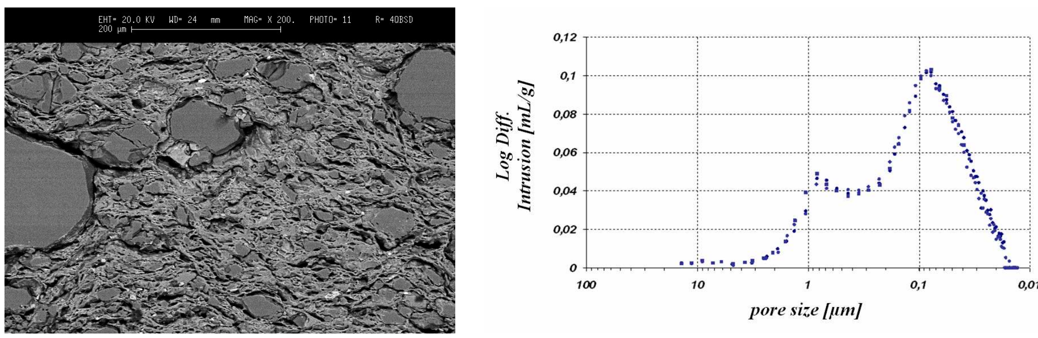
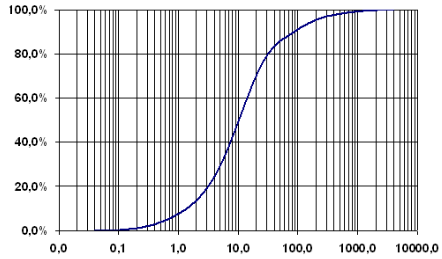


Figure 2: SEM image of clay brick microstructure; strings of 'glassy' matrix, fine and coarse aggregates and porous domain (left). Pore size distribution in engineering brick dominated by nano and micro pores (right)



fraction	*[%]**
$\geq 62\ \mu m$	***12,3 ± 0,45***
$62 - 2\ \mu m$	***73,9 ± 1,79***
$\leq 2\ \mu m$	***13,8 ± 0,43***

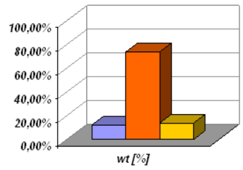


Figure 3: Grain size distribution of raw material: fine fraction (< 2 µm, yellow) is incorporated completely in the 'glassy' matrix; a part of the silt (62-2 µm, orange) is partially incorporated in matrix; sand (> 62 µm, blue) remains untouched in the form of large aggregates

The porous domain is in all cases oriented in the direction of the green body extrusion. It is the result of alignment of clay particles with respect to the flow lines of extruded mass. This feature is well visible in the SEM images of microstructure, see Figure 2. In this image the pores, represented by black colour, are obviously elongated along horizontal direction. Another important feature noted during this research is the brick lamination, which is the result of shaping technology (soft extrusion).

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