Construction and Building Materials 112 (2016) 112–127

Contents lists available at ScienceDirect

Construction and Building Materials

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

Combining Brazilian tests on masonry cores and double punch tests for the mechanical characterization of historical mortars

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HIGHLIGHTS

- Novel MDT for mechanical characterization of mortar in existing masonry structures.
- Core-drilling of brick and lime mortar masonry walls using dry (no water) procedure.
- Brazilian tests on cores varying the inclination of the diametral mortar joint.
- Novel micromechanical model for joint interpretation of DPT and Brazilian tests.
- The model provides reliable estimation of mortar's mechanical parameters.

ARTICLE INFO

Article history:
Received 9 September 2015
Received in revised form 3 February 2016
Accepted 23 February 2016

Keywords:
Historical masonry
Lime mortar
Coring
In-situ sampling
Minor Destructive Testing (MDT)
Brazilian test
Double punch test (DPT)
Mohr-Coulomb theory
Shear strength
Failure envelope

ABSTRACT

This research presents a novel integrated methodology for the experimental characterization of historical mortars, including different types of laboratory tests. Different experimental tests on lime mortar brickwork were carried out, including Brazilian tests on core drilled masonry samples with one diametral mortar joint and double punch tests on extracted mortar joints. By representing the mortar's state of failure on the Mohr's plane for the different tests, it is possible to estimate the material's strength envelope through a least square minimization method. The proposed approach can be useful to evaluate the compressive, tensile and shear behaviour of mortar in existing structures.

1. Introduction

The experimental characterization of existing masonry is still a challenging task due to the large possible combinations of material components, their complex mechanical behaviour and the difficulties related to testing and sampling techniques. The evaluation of the mechanical properties of masonry in historical buildings is often made difficult by the need to minimize the damage caused during the inspection. Samples extracted from the buildings should be sufficiently small so as to cause a minimum disturbance, preserve the original material and avoid risks and difficulties linked to the alteration of structural members.

Clay bricks and lime mortar are normally the most common components in historical buildings of the built heritage. In Italy, for instance, this has been confirmed by several studies based on chemical analysis conducted on a large portion of the Italian territory [1] and more recently on the areas struck by the 2012 Emilia-Romagna earthquake [2].

As for the experimental characterization of the material components (mortar and units), the current standards only consider tests made on standard specimens that are mainly intended for new structures, like whole units or prismatic specimens of mortar [3,4].

Binda and co-workers [5,6] conducted experimental campaigns on new masonry components to evaluate their main mechanical

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http://dx.doi.org/10.1016/j.conbuildmat.2016.02.168
0950-0618/

properties, working on standard prismatic specimens of clay brick and either hydraulic or aerial lime mortar. The studies showed the intrinsic difficulties related to the experimental estimation by laboratory testing of important parameters like Young's modulus, Poisson's ratio, compressive and tensile strengths. Standard tests were carried out, like compression on bricks and three-point bending and compression tests on mortar, following the available technical standards [7–9].

Standard tests considered by technical regulations are hardly applicable to existing masonry structures. They are in fact only applicable to bricks, since entire units or sufficiently large brick samples may be extracted without deteriorating excessively the masonry member. On the other hand, the difficulties related to the analysis of historical mortars even arise from the extraction of undisturbed and appropriate specimens. The standard tests on prismatic mortar specimens are practically impossible, since only thin mortar joints can be extracted from the existing masonry. Recent studies showed the issues related to non-standard testing of irregular samples of historical mortars [10,11]. Besides the mechanical characterization of elastic and strength properties, it is usually necessary to evaluate also the shear behaviour of existing masonry, especially in seismic prone countries. In-situ diagonal compression tests [12] are rather expensive and usually inappropriate for historical constructions, since the structure normally cannot be excessively damaged during the testing activities.

In most cases, a preferable alternative seems the adoption of Minor Destructive Testing (MDT), also in possible combination with Non-Destructive Testing (NDT). Among the MDT procedures, an interesting possibility is the extraction of small specimens to be tested in laboratory. This methodology is appropriate for historical constructions, since samples can be extracted from hidden structural members reducing to the minimum the amount of induced damage. Recent studies showed the possibility of in-situ core drilling, perpendicular to the face of the structural member, to extract masonry cylindrical samples to be tested in the laboratory [13–15]. This sampling technique does not induce excessive damage to the historical structure and it allows a direct estimation of the mechanical properties by testing the core specimens in the laboratory. The cores include two circular segments of brick and a diametral mortar joint, with a total diameter of the sample from 70 to 110 mm. The cylindrical samples are tested according to a new layout for the Brazilian test, with the diametral mortar joint inclined with respect to its original horizontal position in the wall. Such special testing setup induces to the mortar in the joint a stress state of simultaneous normal compression and tangential shear. Different combinations of shear-compression stresses can be applied to the mortar joint by varying the diametral joint inclination.

This last improvement of the experimental technique led to the derivation of more information from the tests than in previous studies [16,17], where the Brazilian tests were carried out with a fixed inclination of the mortar joint of 45°. In these studies from the nineties, the authors were mostly interested in obtaining a relationship between the shear strength of the joint and those of medium (triplets) and big (walls) assemblages of cement mortar masonry. In case of Brazilian tests of cores with 45° inclined joint, they assumed that the load split into normal and tangential components on the mortar joint. This led to the hypothesis of infinitesimal thickness of the mortar joint, reducing it to a non-dimensional interface between the bricks.

On the other hand, Benedetti and co-workers [18] proposed an alternative interpretation of the stress state inside the diametral mortar joint of the cylindrical specimen, by considering the whole mortar layer, instead of reducing it to an interface. In this case, it was possible to introduce into the mechanical interpretation of the test also the mutual interaction between the two circular segments of brick and the mortar in the joint. Such interaction induces a three-dimensional state of stress to the mortar. The graphical interpretation of each test requires the drawing of Mohr's circles representing the complete stress state in the mortar at failure. Most recent experimental studies by the same authors [13–15] showed the possibility of carrying out different Brazilian tests by varying the inclination of the diametral mortar joint. In this way, different shear-compression states can be applied to the mortar, corresponding to different Mohr's circles on the Mohr's plane. The Mohr's circles related to the Brazilian tests were complemented with those corresponding to compression tests on the mortar, e.g. using the double punch test (DPT). Finally, all the Mohr's circles representing mortar at failure under different stress conditions were used to derive the Mohr's failure envelope by means of a least square method.

All the aforementioned studies about Brazilian tests on cores with inclined diametral joint showed that the mode of failure of the specimen is strongly dependent on the type and strength of mortar. In case of low-strength lime mortar, the failure was characterized in most cases by a fracture crossing the mortar joint at the core's centre and involving the upper and lower brick–mortar interfaces at the sample extremities (combined sometimes with detachment of a small brick wedge close to the load), see Fig. 1a. This mode of failure was called "parasymmetric" or "centrally symmetric" [13] and it was observed in experimental programs carried out with low-strength mortars, like in [13] with lime mortar with compressive strength of 1.9 MPa, and in [16] with lime-cement mortar with compressive strength from 1.8 MPa to 2.5 MPa. These ranges of strength values are actually representative of the behaviour of typical low-strength historical mortars. For higher strength mortars, different types of failure were observed. Failures resulting from either splitting of the core or pure shear sliding along the brick–mortar interface (Fig. 1b) were observed in [19], with a cement-lime mortar with higher strength of 7.8 MPa, that could be hardly considered representative of a low-strength historical mortar. Other experimental results presented in [16] also showed an almost vertical crack, splitting the bricks parallel to the load direction (Fig. 1c), for a high-strength cement mortar.

This paper presents an experimental program intended to reproduce in the laboratory the MDT of historical masonry by means of in-situ sampling and subsequent laboratory testing of small specimens. Proper material components were chosen in order to reproduce those typically employed in historical masonry with low mechanical properties, i.e. handmade clay bricks and lime mortar. The manufacturing and curing of lime mortar were carefully executed using traditional building techniques in controlled laboratory conditions. Each material component was tested in order to obtain a comprehensive characterization of its mechanical behaviour. Then, the selected materials were used to build two masonry walls. After the necessary period of curing and hardening to reach a sufficient strength of the material, the extraction of cylindrical samples was carried out by core drilling. A novel dry extraction procedure, based on an air cooling system, was adopted as an alternative to common wet core drilling in which water could spoil the lime mortar joints in the samples. Brazilian tests were carried out on 90 mm diameter masonry cores by varying the inclination of the diametral mortar joint with respect to its original horizontal position. DPTs were also executed on mortar joints extracted from the same walls. A comprehensive micromechanical interpretation of the different experimental tests is presented. Finally, an integrated methodology is proposed to obtain a full characterization of the mechanical properties of mortar, considering the redundant results derived from all the different types of experimental tests executed. A meaningful contribution of the study is the proposal of a failure criterion for mortar based on Mohr's parabolic law, as well as an alternative simplified linear