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High performance mortar for ductile seismic-resistant unreinforced masonry systems

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Abstract

The paper presents the results of an experimental campaign aimed at assessing the structural performances of unreinforced masonry systems realized with a novel ductile mortar. The experimental campaign described in the paper is part of the research project "Zero Environmental Risks in Our buildings" (ZERO) whose broad objective is to develop a new class of construction materials and decorative products characterized by high environmental compatibility, i.e. Volatile Organic Compounds (VOC)-free, as well as superior performances in terms of both chemical and mechanical properties. Two mortar formulations, one for thin-joints and one for thick-joints, have been tested under flexural and compressive loads, and their performances compared with those of benchmark mortars available in the market. Masonry assemblies have been realized with different types of hollow clay blocks available in the market, including flat structural and non-structural blocks for thin joints and structural clay blocks for ordinary joints. The results of the experimental tests proved the effectiveness of the innovative ductile mortar in improving both shear strength and shear deformation capacities of unreinforced masonry assemblies.

Key words

Mortar; Unreinforced masonry; Seismic performances; Experimental tests.

1. Introduction

Most of the Italian built heritage constructions is made of unreinforced masonry (URM) or reinforced concrete frames with unreinforced masonry infills. URM panels typically fail in shear when subjected to large horizontal actions due to earthquakes [1, 2]. In-plan shear failure of single panels can be classified as diagonal failure or horizontal sliding within bed joints. For slender panels, also rocking failure may occur [3-5]. The mechanisms of failure are mainly influenced by quality of bricks and mortar, aspect ratio (length/width ratio) and level of axial loads [6, 7]. Simplified formulations for the prediction of shear strengths of URM walls have been proposed by [8, 9].

Shear strength of masonry panels is typically evaluated through different types of experimental tests: (i) shear tests on small assemblies such as "triplets" or other configurations [10]; (ii) diagonal compression tests on squared specimens [11]; (iii) cyclic shear tests on walls subjected to vertical and horizontal loadings.

Atkinson et al. [12] performed shear tests using a direct shear apparatus to evaluate the strength of bed joints comparing old clay bricks with new clay bricks. Different nominal values of axial stresses were applied to obtain values of cohesion and friction coefficient. Values of cohesion were found in the range of 0.1-0.2 MPa for old masonry units, and around 0.8 MPa for new masonry units. Experimental investigations aimed at assessing the shear strength of masonry systems typically used in Italy have been carried out by several researchers. Alecci et al. [7] tested conventional masonry systems realized with standard clay blocks and regular (thick) mortar bed joints (in the order of 10-15 mm) and masonry systems realized with flat clay blocks and thin mortar bed joints (few millimeter thickness, with or without vertical pocket of mortar). The latter case is commonly used when superior thermal and insulating performances are required. The experimental results indicate that the presence of thin mortar bed joint with no vertical pockets leads to a significant reduction of the shear strength with values in the range of 0.1-0.2 MPa and a fragile mechanism of failure. In presence of vertical pockets of mortar, the shear strength typically increases, up to values of around 1.0 MPa. Extensive experimental tests were carried out at the University of Padua [13, 14] to characterize the behavior of thin-joint unreinforced masonry systems. Shear strength values ranged between 0.1 to 0.5 MPa. Specimens with thin mortar bed joints showed higher shear strength (mean increase of 40%) with respect to the traditional ones.

In the present work selected results of the research project ZERO ("Zero Environmental Risk in Our buildings"), funded by the Emilia-Romagna (Northern Italy) region, are presented. In detail, the focus is on the results of the URM research line dealing with the development of an innovative ductile unreinforced masonry system. Section 2 briefly reviews possible solutions and strategies to increase the seismic capacities of URM systems. Section 3 provides an overview of the research project and presents the main purposes of the experimental campaign whose results are then presented in Sections 4 and 5.

2. Strategies for seismic resistant unreinforced masonry systems

2.1 Background

URM walls can be used either to realize masonry constructions or as infill walls for RC frame buildings. In the latter case, extensive research studies have been carried out with the purpose of modeling the complex interaction of infills and frame structure. Nonetheless, most of the actual building codes do not provide explicit design indications for the infills. This is due to the fact that the seismic design is typically conducted neglecting the contribution of infill panels in terms of strength and stiffness, thus being considered as non-structural components only contributing in terms of mass. Recently, some research projects tried to address the need of design guidelines for URM infill walls and proposed strategies to enhance their seismic behavior [15]. A first strategy is based on the use of reinforced plasters made by steel grid mesh or other type of reinforced mesh grids such as CFRP and FRCM [16-18]. A second strategy is based on the concept of completely uncoupling the infill from the structure using flexible joints around the whole wall-frame interface to reduce the infill-frame interaction and thus avoid damage in the infill [19, 20]. However, up to now no practical and experimentally validated solutions have been proposed. A third possibility is to increase the horizontal deformation capacity of the panel. In this regard, the European project INSYSME ("Innovative Systems for Earthquake Resistant Masonry Enclosures in RC Buildings") proposed a new clay masonry infill system obtained by means of sliding bed joints where in-plane deformations concentrate [19]. The idea is grounded on the original solutions proposed by [21, 22]

2.2 Increasing the seismic capacity of URM with a ductile mortar

The principal failure mechanisms of masonry structures subjected to seismic actions, also referred in various international standard codes [23-25] can be classified as follows: (i) rocking failure, consisting of cracking of bed joints while shear is carried by the compressed masonry; (ii) shear cracking, where the peak resistance is governed by the formation of inclined diagonal cracks, usually following the bed and head joints (depending on the resistance of each component); (iii) sliding, due to the formation of tensile horizontal cracks in bed joints. In general, the failure mechanisms depend upon the mechanical properties of the two components: the masonry units and the mortar bed joints [4]. In traditional masonry systems the clay bricks – mortar joint resistance is often limited and characterized by a brittle behavior.

In light of this, two possibilities can be envisaged to increase the seismic capacity of URM systems: (i) increasing the overall joint shear strength by enhancing the shear strength of the single components; (ii) increasing the overall ductility by improving the ductility of the mortar layer.

3. Research project ZERO: general objectives and URM research line

The research project ZERO has been funded within the Emilia-Romagna region PORFESR 2014-2020 Call and coordinated by Litokol Spa [26]. The broad objective of the project was to develop a new generation of raw materials (such as resins, additives, catalysts) and products (both decorative products and finishes such as glues, primers for pavements and structural mortars) for the construction industry. The outcomes of the research should be characterized by high environmental compatibility (VOC-free) and superior performances in terms of both chemical and mechanical properties.

The project is grounded on the results of a previous research project named "ITALICI", funded by the Italian Ministry of Development within the research program "Industria 2015". The main outcome of the project was the development of a high performance structural mortar with high ductility, hereafter referred to as "maltablock", which was patented in 2016. One specific goal of project ZERO is to develop an improved VOC-free formulation of the patented "maltablock" mortar and to verify, through extensive experimental tests, its performances when used to realize URM panels. The experimental campaign has been conducted by the URM research line of the project at the CIRI Building & Constructions Lab of the University of Bologna between 2017 and 2018.

The first specific objective of the URM research line was to develop an URM system with thin horizontal mortar layers and flat perforated clay units (phase 1). Indeed, such solution offers significant advantages in terms of energy efficiency and has been widely adopted over the last decade both for URM buildings and for masonry infills in RC frame systems. Nonetheless, the last major earthquakes occurred in Italy (Emilia Romagna 2012 and Central Italy sequence 2016-2017) showed that URM systems with thin horizontal bed joints suffered damages due to brittle behavior of the thin joints [27-29]. Mainly for this reason the last update of Italian building code [25] introduced severe limitations in the use of URM panels with thin mortar bed joints, which restricted their use in regions with low seismic hazard. The development of a new thin joint masonry system with improved seismic performances could, thus, help to overcome these issues. In addition to the first phase of experiments (phase 1), a further campaign (phase 2) has been carried out in 2018 to start investigating the performances of a different "maltablock" formulation, specifically developed for standard (5 to 10 mm thickness) mortar bed joints.

During phase 1, devoted to the characterization of masonry systems with thin mortar bed joints, different types of flat clay blocks have been tested, including flat hollow structural clay blocks (voids percentage less than 45%) to be adopted for structural walls, and flat hollow clay blocks with improved thermal performances (voids percentage less than 55%) to be adopted as infill panels in RC frame buildings. Experimental tests included direct shear tests on small masonry assemblies ("triplets" [10]), diagonal compression tests on squared masonry specimens of 1.00 x 1.00 m^2 surface [11], and uniaxial centered compression tests on small walls [30]. During phase 2, direct shear tests on triplets have been performed to characterize masonry assemblies with thick mortar bed joints and hollow clay blocks. For all tests, the performances of the masonry specimens realized with the innovative mortar have been compared with those of specimens realized with the same blocks and benchmark mortars available in the market.

In both phases, the mechanical properties of the "maltablock" mortar have been verified through three-point bending tests on prismatic specimens and uniaxial compression tests on cubic specimens according to UNI EN 1015-11 [31].

Table 1 provides the main characteristics of the different specimen typologies in terms of mortar type, clay block and performed tests. The specimen ID univocally identifies each single specimen: the first two capital initials indicate the mechanical test performed on that specimen (direct shear "DS", diagonal compression "DC", or centered compression "CC"); letters "s" and "ns" indicate the type of clay blocks adopted (either structural or non-structural); the capital initials "M" and "B" identify the type of mortar used (respectively "maltablock" and benchmark), while the last initials refer to the joint thickness ("t" for thin, "T" for thick). The final number within round brackets indicates the number of identical specimens tested.

Table 1: Summary of specimens characteristics tested during the experimental campaign.

Mechanical test	**Block type**	**Mortar type and layer thickness**	**Specimen ID**
Direct shear test - DS	Structural – s	"Maltablock" thin - M-t	DS-s- M-t (6)
Direct shear test – DS	Structural – s	Benchmark thin - B-t	DS-s- B-t (1)
Direct shear test - DS	Non-structural – ns	"Maltablock" thin - M-t	DS-ns- M-t (6)
Direct shear test – DS	Non-structural – ns	Benchmark thin - B-t	DS-ns- B-t (1)
Diagonal compression - DC	Structural -s	"Maltablock" thin - M-t	DC-s-M-t (2)
Diagonal compression - DC	Structural – s	Benchmark thin - B-t	DC-s-B-t (2)
Diagonal compression - DC	Non-structural - ns	"Maltablock" thin - M-t	DC-ns- M-t (3)
Diagonal compression - DC	Non-structural – ns	Benchmark thin - B-t	DC-ns- B-t (3)
Centered compression - CC	Structural – s	"Maltablock" thin – M-t	CC-s- M-t (3)

Centered compression -CC	Structural – s	Benchmark thin – B-t	CC-s- B-t (1)
Direct shear test - DS	Structural – s	“Maltablock” thick – M-T	DS-s- M-T (18)
Direct shear test - DS	Structural - s	Benchmark thick – B-T	DS-s- B-T (3)

4. High performance mortar

To develop the VOC-free formulation of “maltablock”, an experimental campaign has been carried out by Litokol Spa [26] from 2016 to 2018 to obtain a mortar capable of maximizing the ductility, while maintaining a target minimum compression strength of 5 MPa. “Maltablock” chemical formulation has been designed using the Design of Experiment (DoE) technique allowing to systematically and efficiently evaluate the effects and mutual interactions of different factors on the performance of a process [32].

The ductility has been evaluated from the experimental tests on thin specimens by considering the equivalent elastic-plastic (EP) response curve (red thick line in Figure 1). From this, the ductility is computed as the ratio between the equivalent ultimate displacement ($d_{u,eq}$) and the equivalent yielding displacement ($d_{y,eq}$): $\mu = d_{u,eq} / d_{y,eq}$. The yielding point of the equivalent elastic-plastic system is obtained through an energy criterion by equating the areas above and below the EP curve.

The mechanical properties of the mortar have then been experimentally evaluated at the CIRI Building & Constructions laboratories of University of Bologna (UNIBO labs).

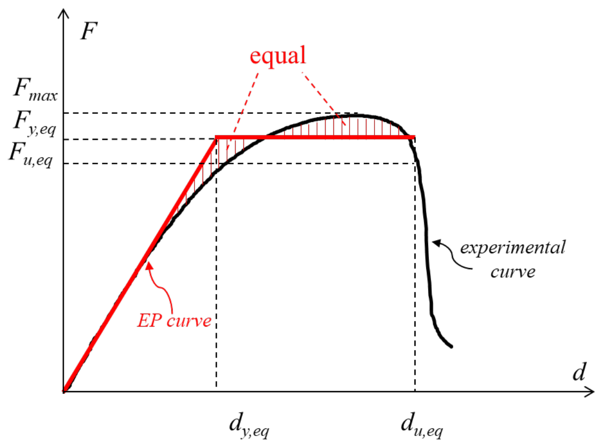
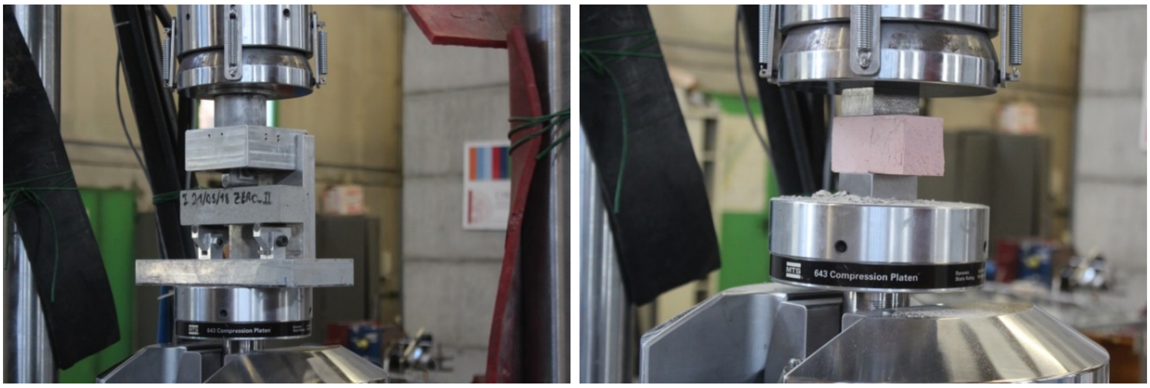


Figure 1: Qualitative force-displacement response and equivalent elastic-plastic response

4.1 Experimental verification at UNIBO labs: tests set-up

The experimental verification of the mechanical properties of “maltablock” has been performed through standard three-point bending tests and centered compression tests [31] on mortar prisms with nominal dimensions equal to 40 x 40 x 160 mm^3. The tests have been performed using a servoidraulic machine capable of applying vertical loads on specimens, equipped with 100 kN load cell (with an accuracy of class 0.5) and a linear displacement sensor. A total number of 30 prismatic specimens have been tested, 21 of which realized with the formulation for thin bed joints and the remaining 9 with the formulation for standard (thick) bed joints.

The prismatic specimens have been first tested under three-point bending, then the two halves further tested under centered compression. An overview of the test results is presented in Section 4.2. Figure 2a and b present the set-up for the two tests.



(a) (b)

Figure 2: Experimental set-up for the mortar characterization (a) three-point bending test; (b) centered compression test.

4.2 Test results

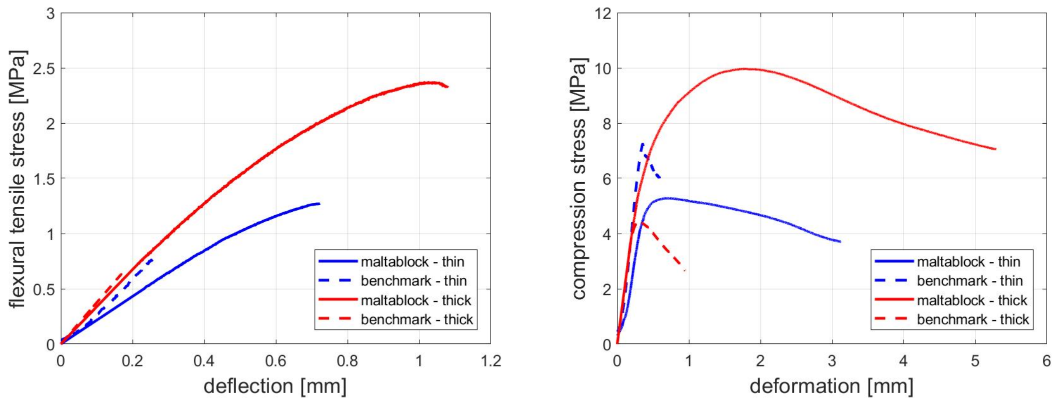
In this section the main results obtained from the tests on mortar are presented. For the sake of comparisons, two benchmark mortars available in the market have been also tested. The benchmark mortar for thin bed joints is a special mortar for thin bed-joint masonry walls of class M10T according to EN 998-2 [33]. The benchmark mortar for standard (thick) bed joints is a standard cementitious mortar of class GM5 according to EN 998-2 [33].

The behavior under tensile and compression loads has been derived through three-point bending tests according to the procedure of EN 1015-11 [31] and compared with that of the two benchmark mortars. Table 2 reports the test results in terms of mean values and coefficients of variation (COV) for the compression strength ($f_{fc,m}$), flexural tensile strength ($f_{fl,m}$) and ductility in compression (μ_c). “Maltablock” specimens for thin bed joints achieved tensile strength values between 2-4 MPa, compression strength values between 4-6 MPa and ductility in compression around 3. “Maltablock” specimens for thick bed joints evidenced the highest strengths (larger than 5MPa in flexure and larger than 10 MPa in compression) and ductility values around 5.0. The two benchmark mortars did not show a significant ductility. In addition to the improved ductile behavior, the two formulations of “maltablock” show a higher flexure/compression strength ratio (values around 0.5-0.6) with respect to the benchmarks (0.2-0.3).

Table 2: Test results on mortar specimens.

Mortar type	mean $f_{fc,m}$	COV $f_{fc,m}$	mean μ_c	COV μ_c	mean $f_{fl,m}$	COV $f_{fl,m}$	strength ratio
	[MPa]	[-]	[-]	[-]	[MPa]	[-]	[-]
“maltablock” - thin	4.89	0.1	3.24	0.36	2.85	0.16	0.58
benchmark - thin	7.6	0.29	/	/	2.16	0.23	0.28
“maltablock” - thick	10.18	0.1	5.32	0.07	5.35	0.07	0.53
benchmark - thick	4.65	0.04	/	/	1.61	0.07	0.35

Figure 3 displays selected stress-deformation curves of “maltablock” and benchmark specimens as obtained from the experimental tests to highlight the typical response of each type of mortar. Figure 3a refers to three-point bending tests curves, while Figure 3b refers to the centered compression tests curves. All stress-deformation curves of “maltablock” evidence a good ductile behavior, with a deformation capacity up to 6 time larger than the one exhibited by the corresponding benchmark mortar.



(a) (b)

Figure 3: Reference experimental tests curves: (a) three-point bending tests: (b) centered compression tests.

5. The ductile masonry system

The present Section illustrates the results of the wide experimental campaign carried out between 2017 and 2018 at UNIBO labs to assess the mechanical response of URM assemblies made with “maltablock” mortar bed-joints.

5.1. Tests set-up

As anticipated in Section 3.2, the experimental campaign included the following types of tests: direct shear tests on "triplets", diagonal compression tests on squared walls, and uniaxial centered compression tests on small walls.

The direct shear tests on "triplets" specimens have been performed according to UNI EN 1052-3 [10] with the purpose of assessing the strength and ductility of "maltablock" bed joints realized using different types of flat clay blocks. As far as thin bed joints are concerned, one high-performance structural block and one high-performance thermal block, e.g. non-structural type, were used. As far as standard (thick) bed joints are concerned, three types of structural clay blocks from three different producers were used. For each block type, 6 identical specimens were realized with "maltablock" bed joints (to obtain more reliable results following UNI EN 1052-3 [10]) and one with the benchmark mortar. Thus, 14 specimens with thin bed joints and 21 specimens with standard (thick) bed joints have been tested. Direct shear tests have been conducted with zero lateral axial load under displacement control setting a constant velocity of 0.02 mm/s imposed by a hydraulic universal machine with a maximum load capacity equal to 500 kN. The specimens have been instrumented on both sides with two Linear Variable Displacement Transducers (LVDTs) monitoring the relative vertical displacement (sliding) between the central and the two external blocks (Figure 4a).

Diagonal compression tests have been performed according to ASTM E519-10 [11] to evaluate the shear behavior of square masonry panels. The objectives of this first series of diagonal compression tests are twofold: (i) obtain first indications on the behavior in shear of the different assemblies and (ii) try to correlate those results with the performances of the mortar bed-joints. The results of those tests can be also used for future interpretations and detailed comparisons making use of numerical simulations. The nominal dimensions of the square panels are 1 x 1 m^2. Each specimen differs from the others in terms of type of mortar (either "maltablock" or benchmark) or type of clay blocks (structural and non-structural flat clay blocks with different percentage of voids and different dimensions). Five different types of clay blocks (all from the same producer) have been considered, for a total number of 10 specimens (5 specimens with "maltablock" and 5 with benchmark mortar). The specimens realized with structural clay blocks present, in addition to horizontal mortar joints, vertical pockets of premixed standard mortar according to Eurocode 6 [24]. The tests have been performed with a force-control apparatus of maximum capacity of 6000 kN imposing a load rate of 0.2-2 kN/s. The URM panels were instrumented on both sides with two LVDTs of nominal length of 1100 mm, to measure vertical and horizontal elongations (i.e. along the main diagonals of the specimens, as displayed in Figure 4b).

(a) (b) (c)

Figure 4: Experimental set-ups: (a) for direct shear tests, (b) for diagonal compression tests, (c) for uniaxial centered compression tests.

The uniaxial compression tests have been performed on small URM walls having nominal dimensions of 600 mm (width), 1000 mm (height) and 250 mm (thickness) according to UNI EN 1052-1 [30]. A total of 4 walls have been realized adopting structural clay blocks and thin mortar bed joints, 3 of which using "maltablock" mortar, one with benchmark mortar. In addition to the horizontal mortar bed joints, vertical pockets of premixed standard mortar have been realized as well, according to Eurocode 6 [24]. The tests were performed under load-control with an apparatus of maximum capacity of 6000 kN and imposing a load rate of 0.2-2 kN/s. The panels were instrumented on both sides with LVDTs of nominal length of 500 mm to measure vertical and horizontal elongations (Figure 4c).

5.2. Test results

In the present Section, the main results obtained from all the experimental tests performed on the URM assemblies are illustrated.

5.2.1. Results of direct shear tests on masonry assemblies with thin mortar bed joints

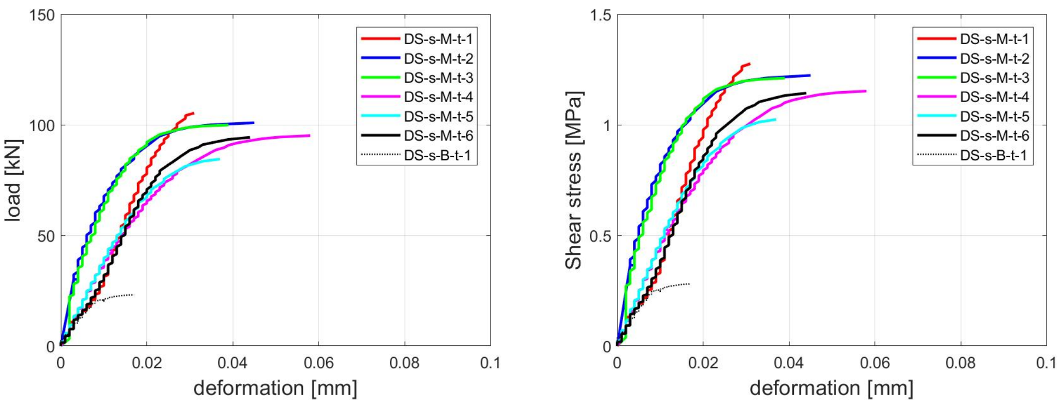
The results of direct shear tests on "triplets" specimens according to UNI EN 1052-3 [10] allowed to obtain average performances of masonry assemblies with "maltablock" mortar joints based on 6 tests for each specimen type. The main test results are summarized in Table 3 in terms of initial shear strength under zero compressive stress (f_{v0}) and ductility (μ). The results are grouped for specimen types.

Table 3: Direct shear tests on "triplets" masonry specimens with thin mortar bed joints.

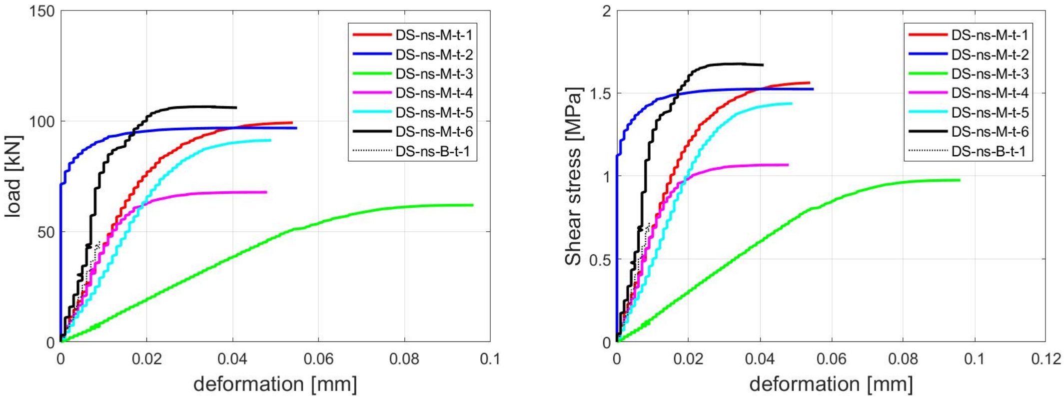
Specimen	Masonry type	mean f_{v0} [MPa]	mean μ [-]
DS-s-M-t	"Maltablock" thin joint + structural block	1.17	2.71
DS-s-B-t	Benchmark thin joint + structural block	0.51	/
DS-ns-M-t	"Maltablock" thin joint + non-structural block	1.38	3.64
DS-ns-B-t	Benchmark thin joint +non-structural block	0.72	/

As expected, the specimens made with "maltablock" bed joints showed the highest performances in terms of both shear strength and ductility. More in detail, the specimens with non-structural blocks evidenced slightly larger strengths (1.38 MPa vs 1.17 MPa) and ductility (3.64 vs 2.71) values with respect to specimens with structural blocks. Instead, the specimens realized with the benchmark mortar showed lower values of shear strengths (0.72 MPa for the specimens with non-structural blocks and 0.51 MPa for specimens with structural blocks) and absence of ductility.

Figure 5 shows the response curves in terms of applied load vs deformation (Figures 5a and c) and shear strength vs deformations (Figures 5b and d) for both assemblies with structural and non-structural clay blocks. The thick continuous curves refer to the 6 tests performed on the specimens realized with innovative "maltablock" mortar, while the unique thin dotted line refers to the test performed on the benchmark specimen. It should be noted that stresses are computed considering net areas (excluding the area of voids) according to UNI-EN 1052-3 [10]. This explains why the peak loads for specimens realized with structural clay blocks tend to be slightly higher than the non-structural ones.



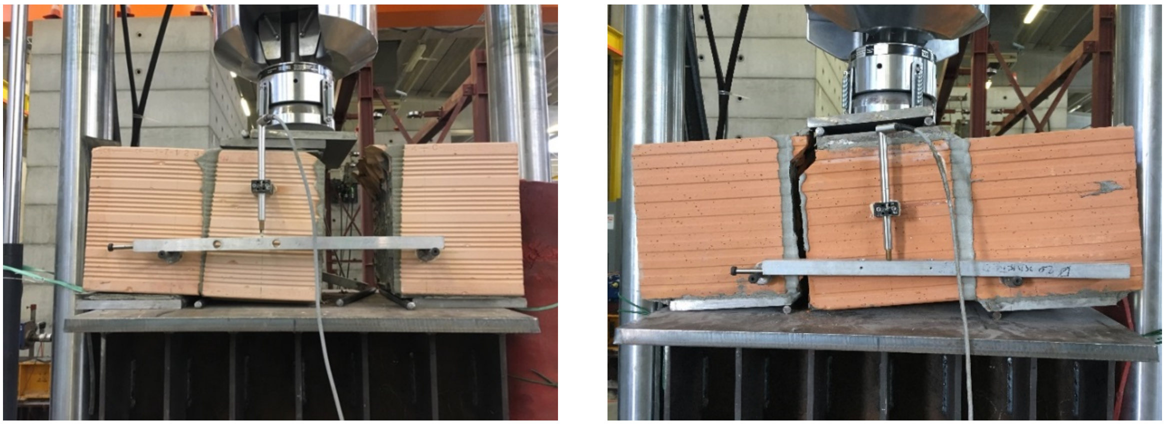
(a) (b)



(c) (d)

Figure 5: Direct shear tests on masonry "triplets" realized with thin layers of mortar and: structural clay blocks - (a) load-deformation, (b) shear stress-deformation; non-structural clay blocks – (c) load-deformation, (d) shear stress-deformation.

The two typical modes of failure encountered are rupture due to sliding shear along the joint and rupture involving failure of clay blocks as well (Figure 6).



(a) (b)

Figure 6: Typical rupture pattern of direct shear tests on "triplets": (a) sliding shear; (b) rupture along clay blocks.

5.2.2. *Results of diagonal compression tests on masonry assemblies with thin mortar layers*

The diagonal compression tests performed on squared masonry walls according to ASTM E519-10 [11] allowed to obtain additional information regarding the behavior in shear (strength, deformation and ductility capacities) of panels with "maltablock" thin mortar bed joints when coupled with different types of flat clay blocks (structural and non-structural blocks with different dimensions and texture).

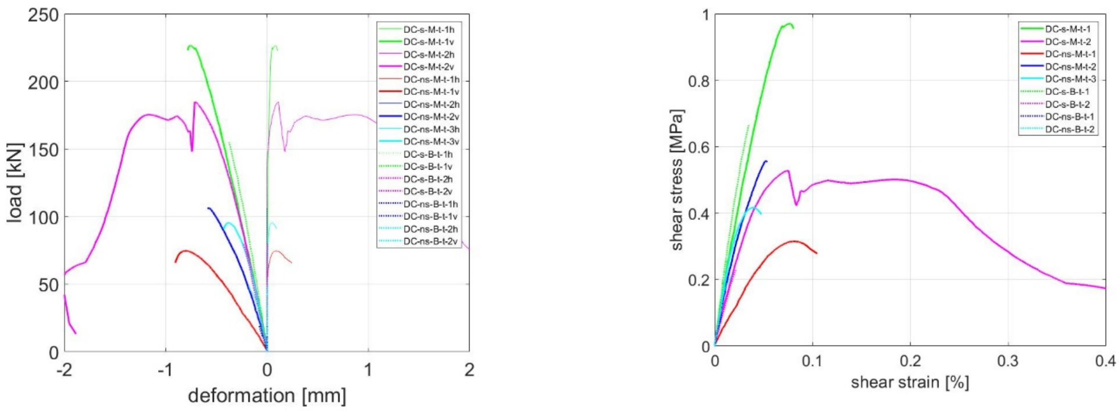
Overall performances in terms of average ultimate load (F_u), shear strength (τ_{DC}), shear modulus (G) and ductility (μ) are given in Table 4. Shear strength and shear strain are calculated according to the formulations provided by ASTM E519-10 [11]. Results are grouped for specimen types. It has to be noted that one specimen with benchmark mortar (DC-s-B-t-1) failed during transportation phase and was not been tested.

Table 4: Diagonal compression tests on masonry walls.

Specimen type	Masonry type	mean F_u [kN]	mean τ_{DC} [MPa]	Mean G [MPa]	mean μ [-]
DC-s-M-t	"Maltablock" thin joint + structural block	205.53	0.75	1510.53	3.68
DC-s-B-t	Benchmark thin joint + structural block	117.40	0.45	1776.52	/
DC-ns-M-t	"Maltablock" thin joint + non-structural block	92.14	0.43	1379.58	1.75
DC-ns-B-t	Benchmark thin joint +non-structural block	34.19	0.16	1953.16	/

In general, as expected, the specimens realized with "maltablock" and structural blocks exhibited the largest shear strength (average value equal to be 0.75 MPa) and an average ductility around 4. The average shear strength of the corresponding specimens realized with benchmark mortar results to be equal to 0.45 MPa, with fragile rupture. The specimens realized with "maltablock" thin bed joints and non-structural blocks showed an average shear strength of 0.43 MPa with a reduced ductility (less than 2). The corresponding specimens realized with benchmark mortar showed an even reduced average shear strength (0.16 MPa) with fragile ruptures.

Figure 7 provides the response curves in terms of applied load vs vertical (thick lines) and horizontal (thin lines) deformation (Figure 7a) and shear stress vs shear strain (Figure 7b). It can be noted that one specimen realized with "maltablock" mortar joints and structural clay block (DC-s-M-t-2) exhibited a quite good ductile behavior. Figure 8a provides a picture of the typical rupture encountered in most of the specimens, e.g. sliding failure along the vertical diagonal. Figure 8b gives a photo of the rupture of the specimens realized with non-structural clay blocks and "maltablock" thin bed joints, e.g. failure along the vertical diagonal involving rupture of the clay blocks.



(a) (b)

Figure 7: Diagonal compression tests on masonry walls: (a) load-deformation and (b) shear stress-shear-strain.

(a) (b)

Figure 8: Diagonal compression tests on masonry walls: (a) typical rupture pattern; (b) rupture along clay blocks.

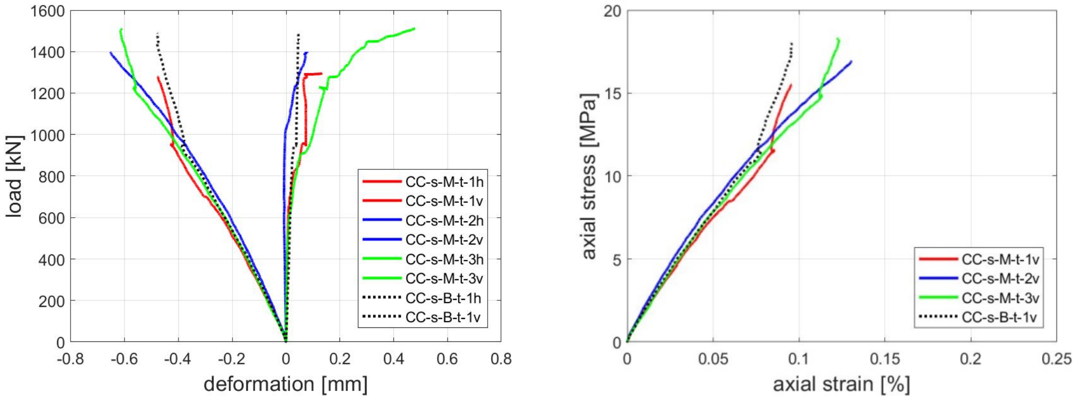
5.2.3. Results of uniaxial centered compression tests on masonry assemblies with thin mortar layers

Uniaxial centered compression tests were performed on masonry walls according to EN 1052-1 [30] with the purpose of evaluating the behavior in compression of assemblies realized with "maltablock" and compare them with the corresponding benchmark assemblies. Table 5 provides global results in terms of mean compressive strength (σ_{CC}) and elastic modulus E. The average values of strength and elastic modulus were not significantly influenced by the type of mortar.

Table 5: Centered compression tests on masonry walls.

Specimen	Masonry type	mean σ_{CC} [MPa]	mean E [MPa]
CC-s-M-t	maltablock thin joint + structural block	17.04	16099.79
CC-s-B-t	Benchmark thin joint + structural block	18.05	15767.57

Figure 9 shows the results of centered compression tests in terms of axial force-deformation curves and corresponding axial stress-strain curves for the 4 masonry walls. The curves show that all specimens exhibited a fragile behavior with rupture at the peak load. The typical rupture encountered in all specimens is crushing failure in compression followed by spalling of the external shells of one clay units. Typically, vertical cracks occurred followed by a sudden failure. However, one specimen realized with "maltablock" (CC-s-M-t-3) evidenced a larger horizontal deformation capacity. The same specimen exhibited also the highest compression strength.



(a) (b)

Figure 9: Centered compression tests on masonry walls: (a) load-deformation curve; (b) axial stress-axial strain curve.

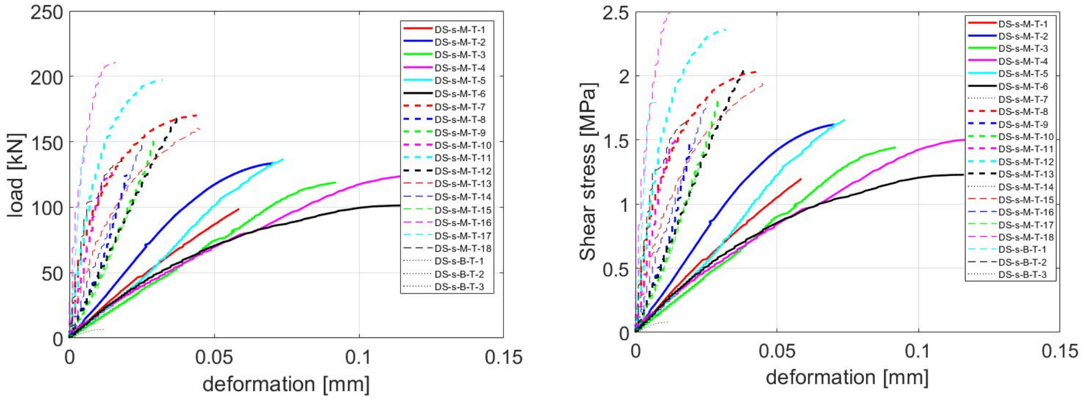
5.2.4. Results of direct shear tests on masonry assemblies with thick mortar bed joints

The last series of triplets tests were performed on specimens realized with standard (thick) mortar bed joints (phase 2 of the whole experimental campaign) according to UNI EN 1052-3 [10]. Table 6 provides global results in terms of mean (over 6 specimens) initial shear strength under zero compression stress (f_{v0}) and ductility (μ). The specimens with "maltablock" bed joints evidence a very large average value of shear strength (1.73 MPa, 50% larger than the values for thin-joints specimens) and a value of ductility around 2. The benchmark specimens, instead, showed a very small strength (0.16 MPa) without any sign of ductility.

Table 6: Direct shear tests on "triplets" masonry specimens and thick mortar bed joints.

Specimen	**Masonry type**	**mean f_{v0} [MPa]**	**mean μ [-]**
DS-s-M-T	"Maltablock" thick joint + structural block	1.73	2.01
DS-s-B-T	Benchmark thick joint + structural block	0.16	/

Figure 10 shows the results of direct shear tests in terms of applied loads vs deformation (Figure 10a) and corresponding shear stress vs deformation curves (Figure 10b). It can be noted that the shear strength is 10 times higher for the specimens realized with the innovative "maltablock" mortar with respect to the benchmark. The typical rupture of these specimens is a clay unit failure that evidenced the very high performances of the mortar bed joints. This mechanism of failure prevented the development of the full ductility capacity of the mortar.



(a) (b)

Figure 10: Direct shear test on masonry "triplets" realized with structural clay blocks and thick layers of mortar: (a) load-deformation; (b) shear stress-deformation.

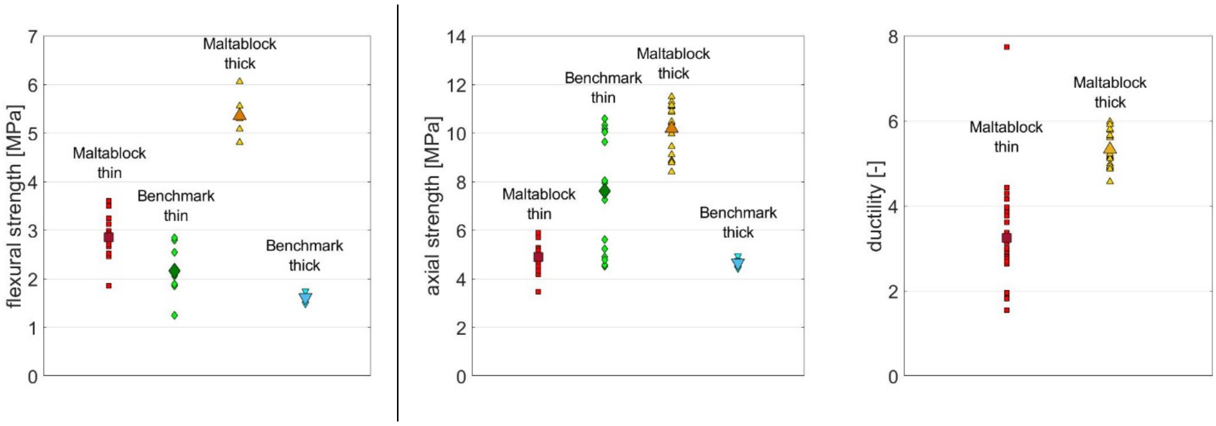
6. Discussion

The results obtained from the experimental tests allowed to identify the main structural performances of URM systems made with "maltablock" and compare them with respect to those of benchmark URM systems. For this aim, Figures 11 and 12 provide overall graphical comparisons of the key mechanical parameters for the mortar itself (in terms of strengths, ultimate deformations and ductility in compression) and for the masonry assemblies (in terms of shear strengths and ductility), respectively. Table 7 summarizes the average values of shear strength and ductility obtained from diagonal compression tests and direct shear tests.

Table 7: Shear strength and ductility from diagonal compression tests and direct shear test.

Masonry type	Diagonal compression		Direct shear	
	shear strength (MPa)	**ductility**	**shear strength (MPa)**	**ductility**
"maltablock" for thin joint + structural block	0.75	3.68	1.17	2.71
benchmark for thin joint + structural block	0.45	/	0.51	/
"maltablock" for thin joint + non-structural block	0.43	1.75	1.38	3.64
benchmark for thin joint +non-structural block	0.16	/	0.72	/
"maltablock" for thick joint + structural block	n.a.	n.a.	1.73	2.0
benchmark for thick joint + structural block	n.a.	n.a.	0.16	n.a.

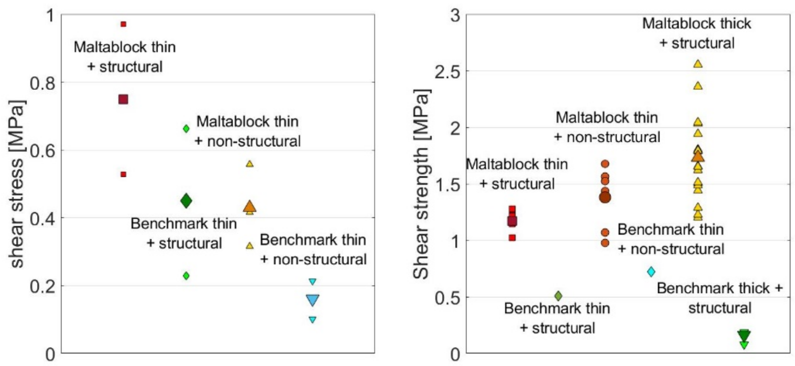
Figure 11 evidences the superior performances of the specific "maltablock" formulation for standard (thick) bed joints in terms of the three key mechanical parameters, e.g. compression strength (on average around 10 MPa), flexural strength (on average around 5 MPa) and ductility in compression (around 5.0).



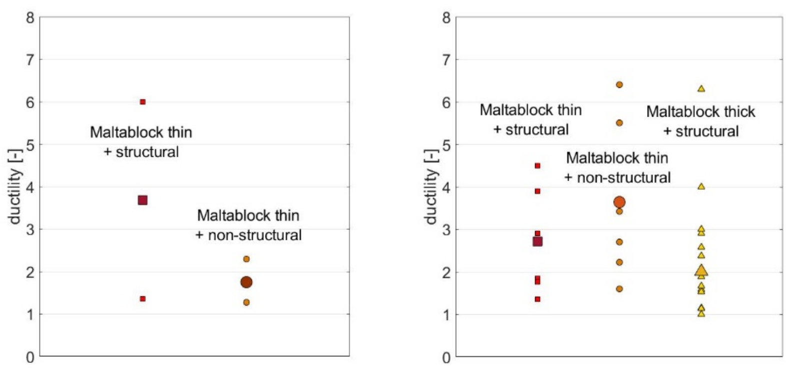
(a) (b) (c)

Figure 11: "Maltablock" vs Benchmark performances: (a) flexural strength; (b) compression strength; (c) ductility in compression.

From Figure 12 and Table 7, it appears that shear strength values from diagonal compression tests tend to be smaller than those obtained from direct shear tests. This is an expected trend since diagonal compression tests induce a complex stress state in the clay bricks – mortar joint interfaces that differs from that of quite uniform shear stress from triplets under pure shear without axial compression.



(a) (b)



(c) (d)

Figure 12: Comparison of masonry performances: (a) shear strength from diagonal compression tests; (c) shear strength from direct shear tests. (c) ductility from diagonal compression tests on masonry specimens; (c) ductility from direct shear tests on masonry specimens.

From the results of the diagonal compressive tests on masonry with thin joints it is found that the use of "maltablock" mortar increases the shear strength of masonry systems of about 60% for both structural and non-structural clay units. From the direct shear test results, it appears that masonry specimens with standard (thick) joints of "maltablock" have a very high shear strength (1.7 MPa on average) which results to be almost 50% larger than the shear strength of specimens with thin joints of "maltablock" (on average around 1.0 MPa) and about 3 and 10 times larger than the average shear strength of benchmark specimens realized with thin and standard (thick) joints, respectively. Thus, the results of the direct shear tests confirmed the first indications obtained from the diagonal compression tests. In addition to the increase in the shear strength, the test results evidence that "maltablock" provides values of ductility for masonry assemblies between 2 to 3.5.

The ductility capacity from direct shear tests of the specimens with thick bed joints results lower than the one developed from the specimens with thin bed joints, despite the higher ductility evidenced by the mortar itself. The reason is the different failure mechanism (failure of clay blocks) encountered on the specimens with thick joints. Thus, the ductility capacity is fully reached when high-strength clay blocks are adopted to realize the masonry units.

Conclusions

The paper presented the results of an experimental campaign for the mechanical characterization of unreinforced masonry (URM) systems realized with a novel structural mortar (called "maltablock") designed to develop a ductile behavior. The main aims of the tests were first to verify the mechanical properties (flexural strength, compression strength and ductility) of the ductile mortar and then to characterize its shear and compressive behavior when used to realize URM assemblies.

The following conclusions may be drawn:

- The innovative mortar formulated for thin bed joints is characterized by a compression strength larger than 5 MPa, a flexural strength larger than 2 MPa and ductility larger than 3, resulting in line with the performance objectives identified in the design phase. The formulation developed for ordinary (thick) bed joints shows even larger strengths and ductility (flexural strength of 5 MPa, compression strength of 10 MPa and ductility larger than 5). Both formulations are characterized by a large flexural/compression strength ratio evidencing a superior structural efficiency with respect to the benchmark.

- Masonry units realized with innovative mortar bed joints evidence shear strength values (from direct shear tests on "triplets") larger than 1 MPa and values of ductility larger than 2.0. The highest strengths are achieved by thick joints with structural blocks.
- Masonry panels realized with innovative mortar bed joints have shear strength values (from diagonal compression tests) of around 0.5 MPa when panels are realized with non-structural blocks and values of around 0.7 MPa when the panels are realized with structural blocks. The latter ones evidence good ductility values as well.
- To exploit the full potential of ductility capacity of the innovative mortar with thick joints, it should be coupled with high-strength clay blocks.

The obtained results indicate that URM panels realized with the innovative thin joints are characterized by enhanced seismic performances that could overcome the typical performances evidenced by this structural system during recent earthquakes. These performances result to be even more promising when the innovative mortar is used to realize standard (thick) mortar bed joints.

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