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# Mechanical properties of fired-clay brick masonry models in moist and dry conditions

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**Abstract.** Rising damp is one of the main issues affecting masonry buildings. However, its consequences on the mechanical performance of masonry structures are not so largely explored. In this paper, the compressive and shear behaviour of masonry triplets, manufactured with solid fired-clay bricks and cement-based mortar, is investigated in dry and moist conditions. The results are interpreted on the basis of the features of the single materials, from both a mechanical and microstructural point of view.

**Keywords:** Brick masonry: Cement mortar; Rising damp; Compressive strength; Shear strength; Triplets; Microstructure.

## Introduction

The presence of moisture from different sources (capillary rise, infiltration, condensation, wind-driven rain) is one of the most widespread phenomena affecting masonry buildings all over the world [1]. Moisture causes several defects in building materials, such as the detachment of paints and renders as well as the crumbling of bricks and mortars due to frost and salt damage [2]. It also threatens the livableness of the buildings due to poor indoor comfort (mould growth, high indoor relative humidity, etc.), as highlighted also in the European 'Construction Products Directive' 305/2011, where the need of avoiding damp presence in building materials is indicated as a key requirement for healthy buildings.

Besides these negative effects, the presence of water in the pores may influence the mechanical properties of building materials. The role of moisture in enhancing the crack growth in materials containing silica fraction (e.g. concrete, stone, mortar and brick), was elucidated in [3], where the ability of water to react with the newly formed Si–O bonds on the crack surface was discussed. In the case of concrete, the effect of moisture on strength for different strain rates was investigated, highlighting the key role played by this factor (see, e.g., [4] and [5]).

In the case of masonry structures, the presence of rising damp and salts may cause the deviation of the mechanical properties from the expected 'ideal' behaviour [6]. Indeed, the assessment of the structural behaviour of masonry in its actual on-conditions has recently received a great attention, with particular reference to the issue of salts damage [7] and to the state-of-conservation of joint mortars [8-9]. This concern is well understandable considering that a large part of the building stock in Europe and in other countries, often characterized by medium-high seismic risk, is built in masonry [10].

In the present paper, the effect of moisture on the compressive and shear behaviour of masonry is investigated, by purposely manufacturing masonry triplets with fired-clay bricks and cement-based mortars. After two months of curing, half of the triplets were partially immersed in tanks and let to absorb water by capillarity for one week, thus reproducing the occurrence of rising damp. After that time, the triplets in moist conditions were immediately subjected to compressive and shear tests. In the latter test, a purposely designed apparatus for applying a pre-compression load and for checking its permanence during the test was used.

## Materials and methods

**Materials.** Commercial solid fired-clay masonry bricks 250 × 120 × 55 mm$^3$ were used for the tests. The cement-based mortar was prepared in a Hobart mixer (EN 196-1), using Portland limestone cement (CEM II B 32.5 LL) and quartz sand (<2 mm), according to a volume ratio 3:1. A volume of water equal to that of the cement was used for achieving a suitable fresh-state workability. Mixing was carried out following the procedure in EN 196-1.

**Masonry triplets.** Triplets with three bricks and two mortar joint layers (10 mm-thick) were manufactured (Figure 1a). Each brick was cut in two halves, that were used one for manufacturing the 'dry' triplet and one for manufacturing the 'moist' triplet. This procedure allowed to obtain, by using three bricks, two fully comparable triplets (one to be tested in dry conditions and one in moist conditions), thus overcoming the problems connected to the unavoidable difference among bricks even belonging to the same batch. Prior of the triplets manufacturing, the bricks were immersed in water for two days, to prevent them from absorbing the water from the fresh mortar joints.

The triplets were left to cure in laboratory (20±2 °C) under a polyethylene sheet for two months. Afterwards, half of the triplets were oven-dried at 50°C ('DRY' series) and half was placed (the mortar joints horizontal) in water for a depth of about 30 mm for one week, in order to allow capillary suction to occur ('MOIST' series).

**Methods.** Prisms having size 55 × 55 ×160 mm$^3$ were obtained from the solid bricks by sawing. These prisms were used for the determination of compressive strength and static elastic modulus, according to EN 9730-3. The results obtained are the average of three prisms. Standard 40 × 40 ×160 mm$^3$ prisms (EN 196-1) were manufactured with the same cement-based mortar used for the triplets, for the determination of compressive strength and static elastic modulus (as an average of three prisms), performed according to "method 2" of EN 13412.

The microstructure of mortar and brick was then assessed in terms of total open porosity and mean pore radius by means of mercury intrusion porosimetry (MIP) with a Porosimeter 2000 Carlo Erba and Fisons Macropore Unit 120. Brick and mortar samples were taken from the triplets by chisel fragmentation.

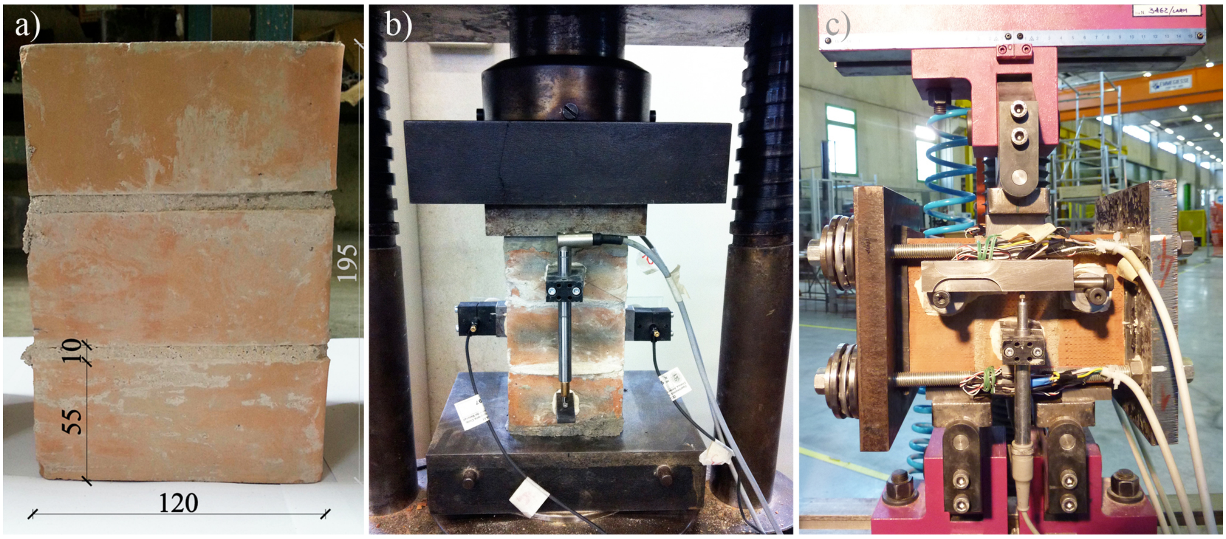


**Figure 1.** (a) Geometry of masonry triplets (sizes in mm); (b) compressive strength test and (c) shear strength testing apparatus.

**Compression test on the triplets.** Compression test was performed on both DRY and MOIST triplets (four samples for each condition), following a procedure adapted from EN 1052-1. Triplets were preferred with respect to the assemblies suggested by the standard (specimens with five bricks), in order to use the same specimen geometry for both compression and shear tests, hence to make the comparison between the results more clear. Prior to the tests, triplet top and bottom were covered with a 5 mm layer of one-component high strength cement-based grout, in order to ensure a regular contact with the testing machine plates and avoid stress concentration due to asperities, that could alter test results. Grout was left to cure for two days on each side of the sample, then triplets were oven-dried at 50°C until constant weight. Afterward, MOIST triplets were left to soak water for one week, as described above.

Two longitudinal and two transversal LVDTs were applied to each triplet as shown in Figure 1b, to monitor vertical and horizontal displacements and to detect the possible occurrence of bending stresses.

Triplets were loaded at a 10 MPa/min loading rate, so that failure could occur in 30 minutes, as recommended by the standard. The load was applied in three steps until half of the expected failure load (determined by preliminary tests) was reached, then the specimens were loaded until failure. At each step, the load was kept constant for two minutes.

**Shear test on the triplets.** Shear test was performed on four DRY triplets and four MOIST triplets, by means of a testing apparatus adapted from EN 1052-3 (see Figure 1c). In particular, pre-compression load was applied by four threaded rods connected by to two thick metallic plates. This device was preferred to a single central rod and lateral plates as suggested in the standard, in order to make possible the detection of rotations or torsions that may occur during the test. Strain gauges were applied to each rod. The specific setting of the testing apparatus and the modifications respect to the standard were necessary. In fact, the aim of the standard is to evaluate only the peak load value, while the scope of this study was to measure the magnitude of shear and pre-compression loads and to record the displacement of the central brick during the whole test, including the post-peak behaviour of the samples.

A pre-compression of 1 MPa was applied by properly tightening each rod, so that shear-failure would occur following the Mohr-Coulomb law.

After applying the pre-compression, triplets were loaded in displacement control at a 0.25 mm/min rate and the displacement of the central brick was recorded by LVDTs previously positioned on the two sides of the triplets, as shown in Figure 1c. All data were recorded until a 4 mm displacement of the central brick was reached. All triplets were sanded prior to the test in order to ensure a good contact with the testing apparatus and to avoid stress concentration in protrusions.

## Results and discussion

Mechanical and microstructural properties of brick and mortar are reported in Table 1. As expected, brick exhibits a higher compressive strength (37 MPa) with respect to mortar (19 MPa) and lower elastic modulus and Poisson's coefficient.

In terms of microstructural features, the total open porosity of brick, mainly owed to coarse pores (mean pore radius 0.85 μm), is much higher than that of the mortar. Total open porosity and mean pore radius of brick are very close to those typical of historical masonries, hence confirming that the materials chosen for the tests can be considered representative of the situation that can be found on site. Cement mortar, as expected, is much less porous with respect to brick and is composed by thinner pores.

**Compression test results.** In Figure 2, two representative curves related to a DRY sample and a MOIST sample are shown. Results of the compression test are summarized in Table 2. As a consequence of the damp presence inside the material pores, compressive strength is subjected to a decrease (-6 %), while static elastic modulus slightly increases. Variations in static elastic modulus, however, are not relevant, also considering the quite high standard deviation found four the MOIST triplets.

The decrease in the samples resistance is due to the fact that water filling the materials pores is incompressible, and hence exerts overpressures on the pores surface, boosting crack formation and propagation. Sensitivity to the presence of moisture is known to depend on the characteristics of the material under examination, and, in particular, to the amount and shape of the porosity (i.e. marble, where micro-cracks are present between the grains, is very sensitive to the presence of water, allowing further cracks opening and propagation [11]). The overpressures are expected to be more relevant in the mortar layers as thinner pores result in a lower mobility of water inside the material and hence to higher pressures, possibly leading to cracking [12]. Conversely, bricks, whose porosity is essentially cylindrical, are less sensitive to moisture presence. However, chemical reactions between Si-O groups of the bulk and water [3] and possible sliding of crystals [12], might enhance the material susceptibility to moisture related decay.

For this reason, the sensitivity of the mortar and the brick towards moisture presence might be different (cement mortar characteristics are expected to be more affected from the presence of water in the pores), but the resistance of both materials is affected by moisture presence, hence explaining the drop in compressive strength of the MOIST triplets. Further studies about the sensitivity of bricks and cement mortars alone are currently in progress.

**Table 1**. Mechanical and microstructural properties of the materials used for manufacturing the triplets.

| | Compressive Strength | Static Elastic Modulus | Poisson's Coefficient | Total Open Porosity | Mean Pore Radius |
|---|---|---|---|---|---|
| | $\sigma_C$ [MPa] | E [GPa] | ν [/] | OP [%] | $r_a$ [μm] |
| Brick | 36.6±1.4 | 11.8±1.2 | 0.10±0.02 | 32.7±3.4 | 0.85±0.14 |
| Mortar | 18.5±0.5 | 18.4±1.2 | 0.19±0.02 | 23.8±3.4 | 0.14±0.02 |

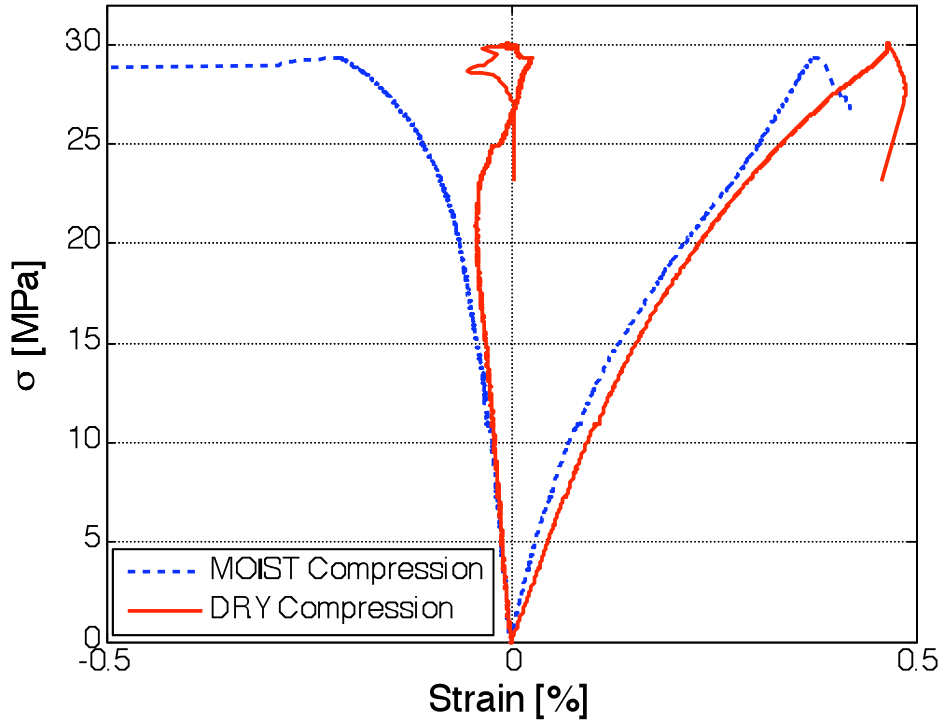


**Figure 2.** Stress versus strain for the compression test.

**Table 2**. Compressive strength and static elastic modulus of masonry triplets.

| | Compressive Strength | Static Elastic Modulus |
|---|---|---|
| | $\sigma_C$ [MPa] | E [GPa] |
| DRY triplets | 31.8±0.7 | 11.4±1.2 |
| MOIST triplets | 29.8±2.0 | 12.4±2.4 |

**Shear test results.** In Figure 3, representative curves related to a DRY sample and a MOIST sample are shown. Results of the shear test are summarized in Table 3. Average peak value $\tau_a$ of the triplets was determined as the ratio between the maximum shear load registered ($\tau_m$) and the precompression ($\sigma$) stress registered at the peak. Both $\tau_m$ and $\sigma$ were determined referring to the effective area of the section, keeping into consideration the progressive decrease that the contact sections experience due to sliding. The peak load of DRY samples was found to be higher than that of MOIST ones, hence suggesting that the presence of water inside the pores has lowered the shear resistance of the triplets, as seen in the case of compressive strength resistance.

The displacement corresponding to the peak load of each specimen was recorded as well, and the average for all the specimens is reported in Table 3, listed as $d_a$. The higher displacement at peak of MOIST samples with respect to DRY ones indicates that the pre-peak behaviour of MOIST samples is less steep, as a lower peak load value is reached for a higher displacement.

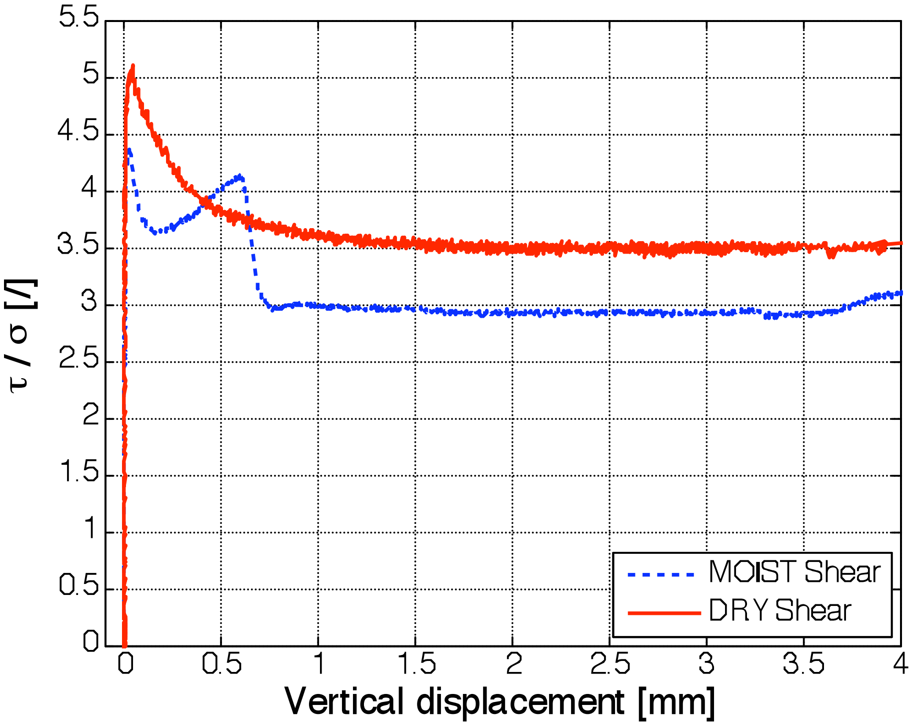


**Figure 3.** Shear/precompression stress versus vertical displacement for the shear test.

The precompression load σ was found to be basically constant until the peak load is reached, then it changes progressively. For this reason, the dynamic friction coefficient, $fc_a$, i.e. the ratio between the shear load and the precompression load, was taken into consideration. The coefficient was measured after the peak load, between 1.5 mm and 4 mm vertical displacement, that corresponds to an almost horizontal part of the diagram. The average of $fc_a$ for DRY and MOIST triplets is reported in Table 3. Dynamic friction coefficient of MOIST samples is lower than that of DRY samples, thus indicating that water boosts the slipping of the contact surfaces.

**Table 3**. Shear behaviour of triplets expressed in terms of average peak value, average displacement at peak value and average dynamic friction coefficient.

| | Peak Load $\tau_a$ [/] | Displacement at Peak $d_a$ [mm] | Dynamic Friction Coefficient $fc_a$ [/] |
|---|---|---|---|
| DRY triplets | 2.3±0.3 | 0.027±0.011 | 1.54±0.07 |
| MOIST triplets | 2.1±0.1 | 0.032±0.003 | 1.39±0.03 |

## Conclusions

The effects of the moisture presence on the mechanical properties of masonries was tested on triplets made by three bricks and two mortar layers, in terms of compressive and shear strength.
The following conclusions can be derived:

- moisture presence significantly lowers compressive strength of masonry, while leaving elastic modulus almost unaltered. The reduction in compressive strength could be ascribed to different mechanisms, ranging from overpressures boosting cracks propagation, to chemical reactions with Si-O groups on the surface of pores as well as to sliding of crystals;
- moisture presence worsens the shear behaviour of triplets, by reducing the peak load and favouring slipping of the contact surfaces. The decrease in the peak load has to be ascribed to overpressures rising from the incompressibility of water, as seen in the case of compressive strength.

In conclusion, the presence of water was found to have an impact on the mechanical behaviour of masonry models, both in terms of compressive strength and shear behaviour.

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