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# An experimental evaluation of prediction models for the mechanical behavior of unreinforced, lime-mortar masonry under compression

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ABSTRACT

This paper contributes to the understanding of lime-mortar masonry strength and deformation (which determine durability and allowable stresses/stiffness in design codes) by measuring the mechanical properties of brick bound with lime and lime-cement mortars. Based on the regression analysis of experimental results, models to estimate lime-mortar masonry compressive strength are proposed (less accurate for hydrated lime (CL90s) masonry due to the disparity between mortar and brick strengths). Also, three relationships between masonry elastic modulus and its compressive strength are proposed for cement-lime, hydraulic lime (NHL3.5 and 5), and hydrated/feebly hydraulic lime masonries respectively.

Disagreement between the experimental results and former mathematical prediction models (proposed primarily for cement masonry) is caused by a lack of provision for the significant deformation of lime masonry and the relative changes in strength and stiffness between mortar and brick over time (at 6 months and 1 year, the NHL 3.5 and 5 mortars are often stronger than the brick). Eurocode 6 provided the best predictions for the compressive strength of lime and cement-lime masonry based on the strength of their components. All models vastly overestimated the strength of CL90s masonry at 28 days however, Eurocode 6 became an accurate predictor after 6 months, when the mortar had acquired most of its final strength and stiffness.

The experimental results agreed with former stress–strain curves. It was evidenced that mortar strongly impacts masonry deformation, and that the masonry stress/strain relationship becomes increasingly non-linear as mortar strength lowers. It was also noted that, the influence of masonry stiffness on its compressive strength becomes smaller as the mortar hydraulicity increases.



## 1. Introduction

Masonry has historically been a common and successful means of cladding and loadbearing structures. Today, it constitutes a considerable proportion of buildings worldwide that are often of historic and cultural significance. Masonry is a heterogeneous material with a complex, non-linear, anisotropic behavior (when compared to materials such as concrete or steel) which can be attributed to the different material components and the abundant interfaces. For centuries, masonry was bound with lime mortars. However, as most limes build strength slowly mainly by carbonation, they were superseded, first by hydraulic limes, and then by Portland Cement (PC) which develops strength quickly on hydration. However, for over two decades, there has been a renewed focus on the use of hydrated and hydraulic lime-mortars for repairs and new building. This paper intends to contribute to the understanding of the characteristics of lime-mortar masonry. The knowledge of masonry strength and deformation characteristics is important as these determine masonry performance over time and allowable stress and stiffness in design codes for new building.

Mechanical properties and behavior are well documented for cement mortar masonry but there continues to be a paucity of literature on the performance of lime-mortar masonry. Masonry compressive strength and other mechanical properties can be measured experimentally in the laboratory however, the tests are intense in materials and labor. This lead to a search for analytical relations to predict masonry strength based on the properties of masonry components (which can be taken from manufacturers specifications or tested at a lower cost). This paper experimentally measures the compressive strength, modulus of elasticity and stress–strain behavior of fired-clay brick masonry bound with mortars of varying strength and stiffness including hydrated lime

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**Table 1**
Summary of models for the estimation of masonry strength

| Source reference | Model | |
|---|---|---|
| Eurocode 6 [8,22] | $f'_m = 0.5 f_b^{0.7} f_j^{0.3}$ | (2) |
| Bennett et al. [17] | $f'_m = 0.3 f_b$ | (3) |
| Dayaratnam [18] | $f'_m = 0.275 f_b^{0.5} f_j^{0.5}$ | (4) |
| MSJC [19] | $f'_m = (400 + 0.25 f_b)/145$ | (5) |
| Kaushik et al. [10] | $f'_m = 0.63 f_b^{0.49} f_j^{0.32}$ | (6) |
| Gumaste and Venkatarama Reddy [20] | $f'_m = 0.317 f_b^{0.866} f_j^{0.134}$ | (7) |
| Hendry and Malek [21] | $f'_m = 0.317 f_b^{0.531} f_j^{0.208}$ | (8) |

(CL90s), natural hydraulic lime (NHL) and a cement-lime mortar (M6). Regression analysis was applied to the experimental results and models for the estimation of lime-mortar masonry compressive strength proposed. A general model was derived and alternative models that consider strong hydraulic and weak limes only were also proposed with different fitnesses. In addition, cement masonry models, previously documented in the literature, were reviewed and their appropriateness for the description of lime-mortar masonry assessed by comparing the experimental results from this study with the values calculated using these models. Also, using regression analysis, equations are developed for the estimation of the elastic modulus of lime-mortar masonry; and stress–strain curves are derived for the various types of lime-mortar masonry. Finally, stress–strain estimation models in the literature are compared with the experimental stress–strain relationships determined in this research.

### 1.1. Behavior of masonry under uniaxial compression

Zucchini and Lourenço [1] developed a homogenization model where they summarize the behavior of brick masonry under compression including simple compression failure theories in former research [2,3] and experimental results by former authors [4–7], who, using experimental data, suggested several analytical relations to estimate masonry strength and deformation which depend on the compressive and tensile strengths of bricks and mortar and other factors. As explained by Zucchini and Lourenço [1], when weak mortars are in place, the non-linear (plastic) deformation of the mortar starts very early on loading, while the brick plastic behavior begins later. The brick is in a tension–compression–tension state, while the mortar is in a tri-axial compression state because of the lateral confinement of the stiffer brick. As a result, the joint suffers some negligible damage in tension but it is the failure of the brick in tension that leads to masonry failure. According to McNary and Abrams [4], under compression, a softer mortar increases the lateral tensile stress applied to the brick decreasing the stiffness of the masonry. These authors also noted that the relation between stress and strain becomes increasingly non-linear as mortar strength lowers.

Zucchini and Lourenço [1], further explain that when the mortar is stiffer but still weaker in compression than the unit, the brick does not fail in tension because the difference in stiffness between the two components is not sufficient for the brick to reach its limit strength and the masonry fails due to the crushing of the brick. Finally, when the mortar is much stiffer and stronger than the unit, the plastic flow starts earlier in the brick due to the higher mortar strength. The much greater mortar stiffness yields a tension–tension–compression state at the joint which damages the mortar in tension, but the masonry failure is driven again by the crushing of the brick.

These authors conclude that, if the brick compressive strength is sufficiently high, the brick fails in tension and masonry strength is sensitive only to the unit tensile strength. However if the brick strength drops, the masonry failure mode changes from unit cracking in tension to unit crushing in compression with a 14% reduction of the masonry strength. Therefore, according to these authors, only the brick compression strength affects masonry strength; the other properties of the components can only change the deformation path of the masonry.

In historic and traditional fabrics bound with lime mortars the mortar is generally considered weaker, less stiff and more deformable than the masonry units. However certain hydraulic limes, over time, can achieve a greater strength and stiffness than certain pressed, solid or frogged, fired-clay bricks.