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An integrated experimental-numerical study of the performance of lime-based mortars in masonry piers under eccentric loading

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HIGHLIGHTS

- Mortars containing metakaolin are stronger than pure-lime or lime-cement ones.
- Mortar strength can be increased by the addition of crushed bricks.
- Hydraulic reactions are promoted by water retained within brick fragments.
- Mortars with metakaolin and crushed bricks produce strong masonry.
- Mortar compressive strength is key parameter influencing the masonry strength.

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ABSTRACT

The paper focuses on the performance of various lime-based materials, alternative to Portland cement mortars, intended for application in repairing historic structures when subjected to mechanical loading. Results of basic material tests indicate that the use of metakaolin as a pozzolanic additive produces mortars with superior strength and sufficiently low shrinkage. Moreover, mortar strength can be further enhanced by the addition of crushed brick fragments, which explains the longevity of Roman concretes rich in pozzolans and aggregates from crushed clay products such as tiles, pottery, or bricks. An integrated experimental-numerical approach was used to identify key mortar parameters influencing the load-bearing capacity of masonry piers subjected to a combination of compression and bending. The simulations indicate increased load-bearing capacities for masonry piers containing metakaolin-rich mortars with crushed brick fragments, as a result of their superior compressive strength.

1. Introduction

Ancient structures embody the culture and stories of people, who built, used and lived in them. This charm attracts tourists to the sites with well-preserved cultural heritage, which in turn has an enormous positive impact on the economy of the region. From this reason, the conservation and restoration of architectural heritage is encouraged in the majority of countries. However, an inappropriate intervention can cause a huge harm, and therefore the authorities established numerous requirements on the procedures and materials used for the conservation and repairs.

A vast number of ancient structures are made of masonry, being a traditional construction material that exhibits an extraordinary durability if an adequate maintenance is provided. Masonry bed joints are usually the weakest link and the deterioration and damage concentrates there. It has been established that the mortars used for repairs should be compatible with the original materials; serious damage to a number of historic masonry structures has been caused by an extensive use of Portland cement mortar over the past decades. The intention for its use was to avoid the inconveniences connected with the originally used lime-based mortars, such as slow setting, high shrinkage and low strength [1]. However, the use of the Portland cement mortars has been reconsidered for their low plasticity, excessive brittleness and early stiffness gain [2–5]. Moreover, the relatively high content of soluble salts that leach over time [4,5,3] can severely damage the original masonry units because of large crystallization pressures [6,7] and produce anaesthetic layers on their surface.

The strict regulations with respect to the Portland cement use led to the exploitation of traditional additives to lime-based mortars, such as volcanic ash, burnt clay shale [8] or increasingly popular metakaolin [5]. These additives, known as *pozzolans*, have been

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used since the ancient times in combination with lime to improve a moisture and free-thaw resistance of mortars [9], to increase their durability [1,5] and also their mechanical strength [10,11]. The use of pozzolans is essential not only for bed joint mortar but also for rendering ones, because pure-lime mortars suffer from enormous shrinkage cracking that has a negative aesthetic impact and can even cause spalling of the facade surface layers [12].

If there was no natural source of pozzolans available in the region, ancestors tried to find alternatives. Phoenicians were probably the first ones to add crushed clay products, such as burnt bricks, tiles or pieces of pottery, to the mortars in order to increase their durability and strength. Crushed bricks were often added to mortars used in load-bearing walls during the Roman Empire [13] and Romans called the material *cocciopesto* [14]. Cocciopesto mortars were then extensively used from the early Hellenistic up to the Ottoman period in water-retaining structures to protect the walls from moisture, typically in baths, canals and aqueducts [15,16]. The brick dust was mainly used for rendering, while large pebbles up to 25 mm in diameter appeared mainly in masonry walls, arches and foundations [17]. However, our previous studies [18–20] revealed that the positive impact of ceramic fragments should not be attributed to the formation of hydration products due to limited reactivity, but rather to their compliance which limits shrinkage-induced cracking among aggregates and ensures a perfect bond with the surrounding matrix.

The presented study was focused on the investigation of various mortars commonly used for repairs of cultural heritage and their structural performance through comprehensive experimental and numerical analyses. In particular, lime-based mortars with various additives and aggregates, introduced in Section 2, were used in bed joints of masonry piers subjected to a combination of quasi-static compression and bending. The purpose of the experimental analysis, described in Section 3, was to study the failure modes and crack patterns using Digital Image Correlation (DIC), assess the structural performance of individual mortars, and verify the proposed material model used for the Finite Element (FE) predictions, presented in Section 4. The FE analysis was consequently utilized in Section 4.4 to assess the key material parameters influencing the load-bearing capacity, and to study the failure modes of the masonry piers containing mortars with variable properties, subjected to a combination of compression and bending.

2. Materials

Compared to historic limes, today's commercial ones are very pure, despite the very benevolent regulating standard EN 459-1 [21] requiring the mass of CaO and MgO in the commonly used CL-90 lime hydrate higher than 90%. However, the presence of impurities in historic limes mortars was not always harmful [22], since the content of silica (SiO_2) and alumina (Al_2O_3) was responsible for their hydraulic character [23].

The inconveniences connected to the use of modern lime, such as limited binder strength, slow hardening, enormous shrinkage, and consequent cracking and poor cohesion between the mortar and surrounding masonry blocks [12] can be overcome by the use of reactive additives rich in aluminosilicates, such as metakaolin or Portland cement. While metakaolin has been generally accepted by the restoration community [5,22], the use of Portland cement is on decline and the authorities for cultural heritage in many countries prohibit its additions to repair mortars [2,3,7]. According to a few studies, calcium-silicate-hydrates (CSH) and calcium-alu minum-silicate-hydrates (CASH) are the main hydrated phases formed at the room temperature after the pozzolanic reaction of metakaolin and $Ca(OH)_2$ [24–26]. The metakaolin presence in lime-based mortars results in an enhanced strength and durability [18], while the vapor transport properties are superior to the mortars containing Portland cement [7].

Beside the addition of pozzolans, shrinkage can be efficiently reduced by increasing the content of inert aggregates, since the stiff inclusions restrain the volume changes of the surrounding matrix [12,27], which is more pronounced in the case of bigger inclusions [28]. However, large stiff pebbles are responsible for a formation of microcracks [20]. that have a negative impact on the mortar integrity and reduce the mortar strength and stiffness [1,23,29]. Moreover, the shrinkage-induced cracking of mortars poor in pozzolans, or containing unsuitable aggregates, limits their use as renderings because of their poor aesthetic performance [30].

Even though it is generally accepted that the presence of sand aggregates increases the resistance of mortars against mechanical loading, there is a threshold beyond which any addition of aggregates makes the mortar weaker due to excessive microcracking and loss of cohesion between the grains and the surrounding matrix [1]. By experience, the 1:3 binder to aggregate volume ratio has been established as the most suitable for repair mortars, providing a reasonable strength, shrinkage and porosity. Based on the study by Stefanidou and Papayianni [28] it seems most favorable to use the sand of grain-size ranging between 0 and 4 mm, resulting in mortars of the highest strength.

Vitrivius, Roman author, architect and engineer, who lived in the first century BC, recommended in his *Ten Books on Architecture* to add some portion of crushed bricks into mortars in order to increase their durability and strength. According to Silva et al. [31], the amorphous components of brick fragments, mainly represented by aluminosilicates, are able to react with lime and make the interfacial surface alkaline. The reaction products are supposed to give mortars a hydraulic character, and fill the voids and discontinuities in the thickness of about 20 μm from the interface between the crushed brick fragments and the surrounding matrix [32,33]. However, such processes can take place only if the ceramic clay is fired at appropriate temperatures between 600 and 900 °C [34], and the mortar is hardening in a sufficiently wet environment [35] for a considerable amount of time [32]. Even if the reaction takes place, the reaction-rim thickness is very limited and does not have any significant impact on the mortar properties, as proven by the results of nanoindentation of ancient mortar samples in our previous work [19]. More importantly, the relatively compliant crushed brick fragments relieve the shrinkage-induced stresses and reduce the number of microcracks within the mortar matrix [36,20].

Beside the positive impact of crushed brick fragments on the mechanical properties and durability of the cocciopesto mortars, the use of crushed bricks brings another benefit—the use of waste by-products from ceramic plants leads to a cost reduction and production of a more sustainable material.

2.1. Prepared and tested mortars

For our study, we used a commonly available white air-slaked lime (CL90) of a great purity (98.98% of CaO + MgO). The most frequent particle diameter found in the lime hydrate was equal to 15 μm and its specific surface area, determined by the gas adsorption, was equal to 16.5 m^2/g. The finely ground burnt claystone metakaolin, rich in SiO_2 (52.1%) and Al_2O_3 (43.4%), was chosen as the pozzolanic material. Both constituents, lime and metakaolin were produced in the Czech Republic and the detailed chemical composition is listed in [18]. Portland cement CEM I 42.5 R produced in Radotín, the Czech Republic, was used as an alternative to metakaolin. The selected Portland cement was rich in CaO (66%), SiO_2 (20%), Al_2O_3 (4%), Fe_2O_3 (3%), SO_3 (3%) and MgO (2%), as provided by XRF analysis [18].

Beside the investigation of metakaolin and Portland cement additions on the mechanical properties of lime-based mortars, the study was also focused on the influence of aggregate composition. River sand of grain size ranging between 0 and 4 mm from Zálezlice was selected based on experience as the most suitable for the application as the bed joint mortar. The industrially produced crushed brick fragments of the grain-size 2–5 mm, from a brick plant Bratronice, the Czech Republic, were chosen based on results of previous studies [37] and experience of authors acquired by analyses of ancient mortar samples [17,38,32]. The grain size distribution of the sand and crushed bricks aggregates, obtained by a sieve analysis, is presented in Fig. 1.

The mass ratio of lime and metakaolin/Portland cement was equal to 7:3 in all mortars. The amount of water was adjusted so that the fresh mortars fulfilled the workability slump test in accordance with ČSN EN 1015-3 [39] and the mortar cone expansion reached 13.5 ± 0.3 cm. Such consistency ensured a sufficient workability while keeping the water to binder ratio (w/b) as low as possible to avoid shrinkage cracking. The amount of aggregates was designed based on our experience, previous studies [1,23,28] and results of micromechanical modeling [20] towards high strength and acceptable shrinkage. The composition of the tested mortars is summarized in Table 1.

The crushed bricks aggregate retains more water than sand (see the water/ dry mass ratio records in Table 1). Based on such finding, we conjecture that the presence of water-retaining crushed bricks can promote the hydraulic reactions within the binder, and increase mortar strength and stiffness.

3. Experimental testing

The experimental testing consisted of two stages—first the individual components, i.e. the mortars and masonry units, were subjected to series of three-point bending and compression tests in order to acquire the data necessary for the calibration of the FE model. The second stage involved a full-scale compression test of masonry piers.