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Influence of freeze–thaw cycles on mechanical properties of historical brick masonry

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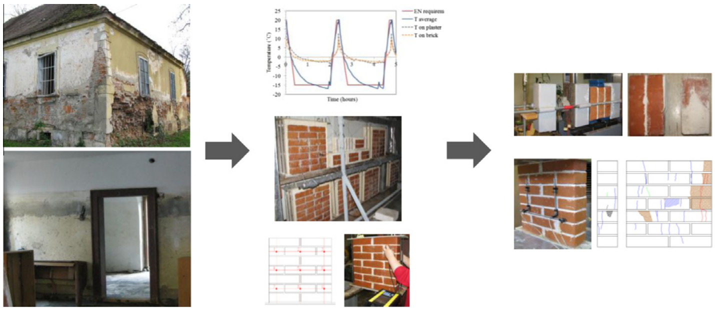
HIGHLIGHTS

- Stronger bond between bricks and mortar is formed by “weaker” mortar M3a compared to M1.
- After freezing and thawing, UV is significantly reduced, indicating the damage of specimens.
- Influence of freeze–thaw cycles on mechanical properties of brick masonry as a composite is evaluated.
- By triplets, angle of internal friction is reduced after freezing and thawing indicating the damage.
- By wallets, freeze–thaw damage reflects in reduction of stiffness but has no significant effect on compressive strength.

GRAPHICAL ABSTRACT



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ABSTRACT

The research presented in this paper focuses on influence of freeze–thaw cycles accompanied by simultaneous moistening on mechanical properties of historical brick masonry. In order to evaluate the rate of reduction in mechanical properties of the masonry due to freezing and thawing, a series of brick wallets built of solid brick and lime mortar or lime-slag mortar representing an actual building envelope was subjected to testing. Besides testing the wallets and triplet specimens as a mortar–brick composite, mortar prisms and brick units were also tested separately. Wallets built with either of analysed types of lime-based mortar were able to withstand 50 freeze–thaw cycles without any effect on their mechanical properties. After 150 freeze–thaw cycles, the damage of brick surface and mortar joints increased, but had no significant effect on the compressive strength of the wallets. However, in case of wallets built with lime-slag mortar, freeze–thaw damage reflected in the reduction of modulus of elasticity. The results indicate that both tested mortar types have the potential in reconstruction and repair works carried out on historical masonry in areas exposed to freezing and thawing.

1. Introduction

Historical masonry buildings, like the rest of the building fund, are subjected to different climate conditions such as cycles of freezing and thawing, precipitation and temperature fluctuations which can affect their durability or even mechanical properties [1]. The most exposed part of the building is it‘s envelope which consists out of render and plaster as decorative and protective

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layers and wall as a structural element. In Slovenia, most historical buildings in rural areas are built out of stone, both in case of residential as well as in case of more important buildings. In urban areas, however, brick masonry prevails. In general low strength lime mortars with the lime:sand volume proportion of 1:3 is used to bind the stone or brick masonry units [2]. Archaeological post-excavation analyses in Slovenia revealed, that also hydrated lime with pozzolanic additives such as volcanic tuff and crushed bricks were used when preparing mortars [3]. From the end of the 19th century onwards most of the masonry buildings in Slovenia were built with lime-cement mortar which was stronger, had a quicker setting and was therefore seen as a better choice. Compared to cement-based mortars which are considered to be more resistant to freezing and thawing [4], traditional lime-based mortars are more porous, have a higher water absorption rate and relatively low strength characteristics. Regardless the type of used mortar, the question whether climatic conditions such as freeze–thaw cycles accompanied with simultaneous moistening could cause reduction of mechanical properties of stone or brick masonry and what would the rate of reduction in mechanical properties be, remains.

Strength characteristics of porous materials vary depending on the level of moisture in the material [5]. Amde who investigated the effect of moisture on compressive strength and modulus of elasticity of brick masonry [6], found that the presence of moisture significantly reduces the compressive strength and the modulus of elasticity of masonry. Authors who have studied the effect of moistening and drying of walls without the additional freezing and thawing [7] concluded that the mechanical properties of brick masonry saturated with water (which could be caused by flooding during heavy rainfall), after drying to the initial level of humidity, do not change significantly. Certain level of damage and change in mechanical properties of masonry may be expected due to transport, evaporation and crystallization of soluble salts during moistening and drying cycles [8,9]. However, the presence of salt crystals within the pores does not always have negative influence on structural behaviour of masonry [10]. Greater damage may occur by the porous and water permeable materials such as brick or stone when saturated with water and exposed to freezing and thawing. In actual conditions, such critical case could occur after floods in autumn or even winter, followed by winter with freezing cycles during the night and thawing cycles during day time. Such sequence of climatic events took place in Slovenia in the last years after the floods that occurred in the autumn and winter between the years 2007 and 2012. In case of the stone masonry walls, at least where stone types such as granite, marble and diorite, were used for construction of the walls, major damage due to freeze/thaw cycles is not to be expected. In the case of more porous and lower quality types of stone such as sandstone and tuff, freezing and thawing may cause some damage. Freezing and thawing could be a greater problem in the case of brick masonry, particularly if walls are not protected by render. There are three main theories on the possible mechanisms of frost deterioration of the materials due to freezing and thawing to be found in the literature. The first one is the hydraulic pressure theory presented by Powers [11] where the hydraulic pressure was supposed to arise because of the 9% increase in volume at ice formation. The closed container theory suggested by Fagerlund [12] applies to a special case where the permeability and the ductility of the material is zero. The last one is the ice lens growth theory [13] described in the case of cement stone, with a structure composed of very small particles separated by narrow pores. The most important properties of the material to be considered when assessing the freeze–thaw resistance are its mechanical properties (deformability and strength) and physical properties (permeability and porosity) [14]. The porosity and especially the pore-size distribution are considered to be the key parameters in assessing the durability of different building materials subjected to weathering phenomena such as freezing and thawing [15]. In the case of bricks the critical parameters which influence their resistance to freezing and thawing are porosity and pore-size distribution, moisture content, modulus of elasticity, tensile and compressive strength, presence of flaws and degree of firing [16].

Many contributions in the literature [14,16–19] deal with evaluation of freeze–thaw damage on specimens such as mortar prisms, brick units or in some cases brick–mortar prisms. In most studies frost damage from the repetitive freeze–thaw cycles is evaluated as a reduction in strength or deterioration of surface of the specimens representing one of brick masonry constituent materials (mortar, brick units). The main aim of the test campaign presented in this paper was to evaluate the influence of freeze–thaw cycles on mechanical properties of brick masonry as a composite. The influence of freeze–thaw cycles on durability and mechanical properties of the brick masonry was evaluated at different degrees of exposure to altering freeze–thaw cycles and simultaneous wet-dry cycles. Focus was placed on the walls built of solid brick and lime mortar with or without mineral additives, which, besides stone masonry walls, represent the typical structure of the historical buildings envelope in Slovenia.

2. Test specimens, freeze–thaw procedures and performed tests

A large number of specimens built out of solid clay bricks and two types of lime based mortar was subjected to the tests. All together 24 wallets with dimensions of 51 × 52 × 12 cm, 40 triplet specimens and 32 mortar prisms with dimensions of 4 × 4 × 16 cm were built (Fig. 1). Solid bricks with the lowest compressive strength that were available on Slovenian market were used. Burning temperature of bricks was between 900 and 930 °C. Properties of bricks determined by MIP were as follows: bulk density 1800 kg/m^3, apparent (skeletal) density 2690 kg/m^3, total pore area 1.84 m^2/g, median pore diameter (volume) 1.901 μm and porosity equal to 33%. Water absorption amounted to 12.9% (Table 2). Lime putty and limestone sand were used for the preparation of mortars. Lime putty was burned and slaked in the traditional way, and was aged for more than 4 years. Limestone sand had a maximum grain size of 4 mm. Half of tested specimens was built with pure lime mortar (M1), and the other half with mortar with the addition of ground granulated blastfurnace slag-GGBS (M3a), which was a by product of a steel plant in Trieste, Italy. Since GGBS is basically a waste, a byproduct in the production of iron, its usage is reasonable from both environmental and economic point of view. Furthermore, binders based on lime and slag have been successfully applied in some historical constructions [20]. Both mortars M1 and M3a were composed taking into account volumetric ratio lime putty:sand 1:3. The share of dry binder in lime putty amounted to 44%. According to this amount, 40% (by mass) of GGBS was added in case of mortar M3a, in order to obtain adequate water retentivity of the mortar in fresh state and compressive strength in hardened state. In relation to the mass of other constituents, the share of additional kneading water amounted to 4.5% by mortar M1 and 4.6% by mortar M3a. In this way adequate consistence of the mortars was obtained, reflected in flow table value equal to 145±5 mm [21]. Mixing procedure was as follows: sand (and GGBS in case of M3a), lime putty and additional kneading water.

Wallets, bricks, mortar prisms and triplet specimens were subjected to freeze–thaw tests at the age of 180–384 days.

Freeze–thaw tests were performed by two standard methods. A small number of specimens (12 bricks and 6 mortar prisms) were subjected to freeze–thaw cycles according to [22] ("JUS standard").