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Bending Strength of Mortars Containing Crushed Brick Particles

Pavel Tesárek[1,a], Václav Nežerka[1], Tomáš Plachý[1] and Pavel Padevět[1]

[1] Department of Mechanics, Faculty of Civil Engineering, CTU in Prague, Thákurova 7, 166 29, Praha 6, Czech Republic

[a] tesarek@fsv.cvut.cz

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Abstract. Crushed bricks were added into lime-based mortars since the ancient times. These mortars proved to be durable and resistant to earthquake loading. The compliance of the crushed brick particles results in a reduction of stress concentrations around aggregates during mechanical loading and shrinkage cracking. The damage development during the three-point bending was investigated using a 2D plane-stress nonlinear finite element analysis utilizing isotropic damage model. The results were compared to the experimentally obtained data and the study revealed that the numerical model is able to capture trends observed during the experimental testing. Both, numerical and experimental, analyses indicate that the addition of crushed brick makes the mortars more compliant and does not contribute to a strength reduction.

Introduction

Phoenicians were probably the first ones to add also the fragments of crushed bricks or pottery into their mortars [1] and the technology was later adopted by the Romans who used these mortars especially in baths and aqueducts. One reason could have been to increase the hydraulicity of the mortars [2], but the hydraulic reactions on the lime-crushed brick interface is relatively weak to significantly enhance the mechanical properties.

In our study, numerous simulations of three-point bending and splitting tests were carried out, in order to investigate the fracture mechanical properties of the samples, stress concentrations around various aggregate types and to observe the failure mechanism. Computationally less demanding analytical homogenization methods used e.g. in [3] for an investigation of mortars containing crushed brick particles cannot reveal the failure and post-peak behavior.

The purpose of the Finite Element Analysis (FEA) was not to simulate the experiments, it should have just indicate the trends and show the failure mechanism. This approach is much more time and cost efficient compared to an old fashioned purely experimental analysis.

The study revealed that low the low stiffness of crushed bricks contributes to increased durability and limited stress concentrations around aggregates.

Finite Element Model

The plane-stress numerical simulations were carried out in the OOFEM finite element code [4]. An isotropic damage model with linear softening [5] was used for the modeling of the matrix phase and crushed brick aggregates, while the sand aggregates and elastic regions (denoted “I” in Fig. 1) near supports and nodes with prescribed displacements were modeled as isotropic and elastic. Their stiffness was determined using the Mori-Tanaka scheme [6,7]. The equivalent strain used for the failure criterion was determined based on Mazars norm, which accounts only for the positive part of the strain tensor.

The aggregates of round shape in case of sand particles and angular shape in case of crushed brick particles were placed only in the area of the expected crack propagation in a relative volume fraction c_{agg} = 0.4. Each aggregate type was represented by the fine (passing the sieve opening d_0 = 1.0 mm) and coarse (d_0 = 2.5 mm) monodisperse particles. The material properties of individual components, considered in the analysis are summarized in Tab. 1.

Tab. 1: Properties of matrix and aggregates modeled in FE model

	Young's modulus E [GPa]	Poisson's ratio ν [-]	tensile strength f_t [MPa]	crack opening at complete failure w_f [m]
matrix	3.2	0.2	1.5	10^{-6}
elastic regions (I)	9.0	0.2	∞	∞
bricks	8.0	0.2	3.4	10^{-6}
sand	60.0	0.2	∞	∞

The material properties of individual constituents were determined from our own measurements, except for sand [8,9]. The matrix phase was represented by a brittle lime-based paste and its properties were determined from our own experiments [10].

a) bending test (coarse sand particles)

b) splitting test (fine crushed brick particles)

Fig. 1: Detail of mesh for FEA and pattern of crack caused by mechanical loading

Specimens for Three-Point Bending Test

The study was focused on lime-based mortars, with their matrix composed of lime and metakaolin in the mass ratio 7 : 3, reinforced by sand or crushed brick particles. The size fractions of the aggregates are specified in Tab. 2.

Tab. 2: Particle-size distribution of sand and crushed brick particles in prepared mortar samples.

diameter [mm]	0.125 – 0.25	0.25 – 0.5	0.5 – 1.0	1.0 – 2.0	2.0 – 4.0
amount [%]	10.7	20.0	26.7	29.3	13.3

The mortar samples were cast in standard prismatic molds 160×40×40 mm and after 120 days of curing the unnotched specimens were subjected to a three point bending test by means of prescribed displacement in the middle of the span between supports located 140 mm apart.

The stiffness of the hardened mortar samples was determined by the resonance method, usually providing slightly higher values of the Young's modulus in comparison to a static testing [11].

Results and Discussion

The results of the numerical analysis clearly indicate that the use of crushed brick particles increases the ductility of the tested specimens, which could be observed especially in the three-point bending test simulations.

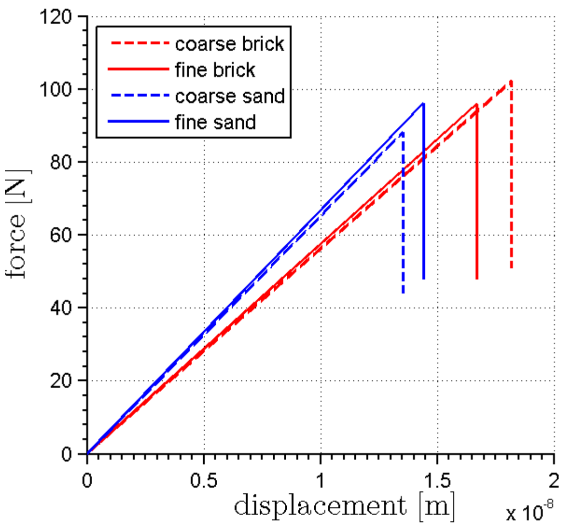

Fig. 2: Results of FEA

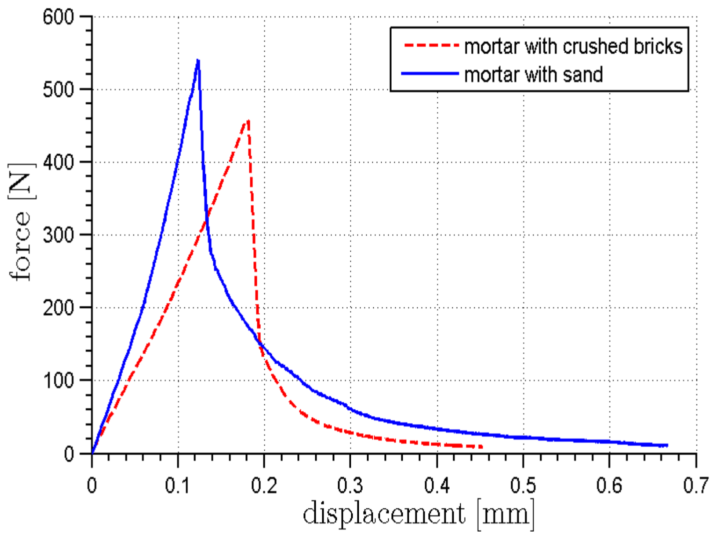

Fig. 3: Typical load-displacement diagrams for mortars containing aggregates in volumetric fraction equal to 0.48 obtained from measurements during three-point bending test

The results of FEA are useful for the indication of trends; however, a 3D analysis accounting for shrinkage cracking and interfacial transition zone around aggregates would provide more reliable data. On the other hand, the computational cost would be incomparable.

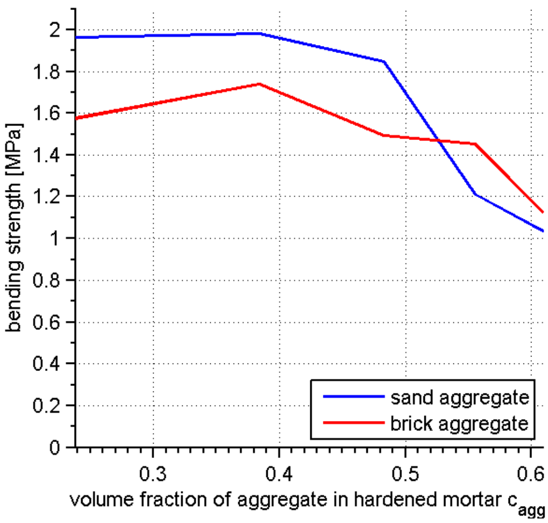

Fig. 4: Dependence of mortar bending strength on volume fraction of aggregates

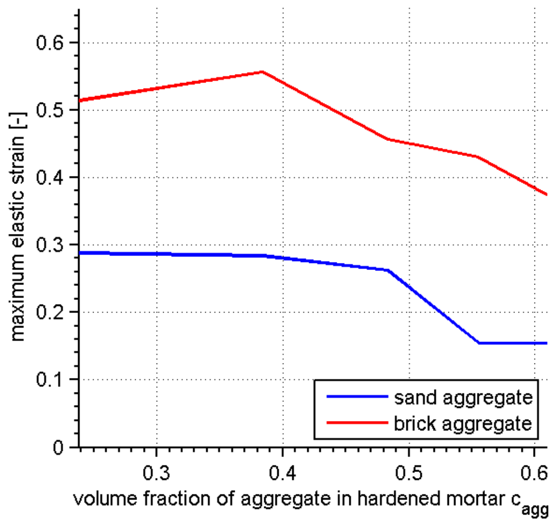

Fig. 5: Dependence of mortar limit elastic strain on volume fraction of aggregates

The experimentally obtained data clearly demonstrate that the samples containing crushed brick particles exhibit a lower stiffness, while the bending strength is reduced only little, see Figs 3 and 4. This could be very advantageous for masonry structures loaded by a differential displacement or subjected to earthquakes, since the maximum elastic strain of the mortars containing crushed bricks is significantly higher, see Fig. 5.

Summary

The addition of low-stiffness crushed bricks, compared to sand particles, makes the mortar more compliant, while retaining the tensile strength. Therefore, the maximum elastic strain of the mortars containing crushed bricks is much higher compared to those containing only sand aggregates.

The study also indicates that the high relative volume of aggregates is favorable, probably due to excessive shrinkage cracking around aggregates. In particular, the samples with high amount of aggregates reached lower values of bending strength and Young's modulus.

The future research should be aimed at optimization of the aggregate composition. For this purpose a modified analytical method complemented by a suitable FE model would be efficient and a further experimental investigation will be necessary.

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