Compression tests on non-standard historic mortar specimens

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SUMMARY: In historical structures, mortar does not occur in the thickness required for the manufacture of standard test specimens, and is not subjected in these structures either to flexure or to compression in a way similar to standard test conditions. For this reason in ITAM innovative methodologies have been developing for testing mortars taken from historical structures – masonry joints or floors. The paper presents the approach adopted for compressive tests and their evaluation. It has been known for a long time that the size of a testing specimen has a significant influence on the measured strength, and numerous forms for transferring the attained characteristics of concrete and cement mortars to the standard test values have been proposed. It has been concluded that the correction functions depend mainly on the length of the specimen base edge, on the slenderness or height to base edge length ratio, and on the quality (compression strength) of the mortar. The strength attained on non-standard samples is higher than the strength measured on standard specimens, if: i) the height (or thickness) to base length ratio decreases, ii) the base length decreases, and iii) the standard compression strength decreases. Little work has been done on pure lime mortars and on specimens less than 2 cm in thickness. Therefore the authors carried out a series of tests on lime mortar specimens of differing slenderness, differing base length and differing quality (strength). For the above mentioned cases the correction factors have been developed. The attained experimental data were further compared to the results of numerical analysis based on use of models developed for soil mechanics. This model was calibrated with the experimental results and the necessary mechanical characteristics (modulus of elasticity and Poisson ratio) were determined by means of digital image correlation technique from photographic records of surface deformations.

KEY-WORDS: cement mortar, compression test, lime mortar, low slenderness, metakaoline mortar

INTRODUCTION

Research into original historic mortars has traditionally focused on studies of their chemical and mineralogical composition or their appearance features, rather than on their mechanical characteristics. Such an approach has been limited by the problem that it is not technically possible and it is indeed unacceptable from the conservation point of view to extract test specimens of the large volume required by the testing standards, and also by a lack of reliable non-standard testing methods for small-size specimens.

Recently, some new non-standard testing approaches and more developed techniques have led to improvements in investigations of the mechanical characteristics of historic mortars (Drdácký et al. [1]). These new testing methods have been applied in research into historic mortars in several European countries, and have made it possible to study and trace changes in mortar characteristics through the centuries, in relation to regional diversities and material influences (Drdácký and Slížková [2]). The tests not only provide data for complex databases of historic mortars but are also a suitable engineering tool for assessing the mechanical characteristics of one of the basic components of any masonry.

While the specific methodology for testing flexural strength has been developed by the first author in nineties and summarized, for example in (Drdácký [3]), the compression strength test methodology has been studied as a continuation of much older research carried out in relation to the tests on concrete. Compressive testing of mortars in historic buildings is problematic. It is clear that conventional standard mortar tests yield more or less meaningless results, which are practically useless for assessing the current safety of, or the threat to, a historic structure. Mortar in historic structures is not subjected to compression in a way similar to the test conditions. Therefore the development of alternative non-standard approaches has been attracting the attention of materials engineers. There has been increasing pressure in recent times to change the methodology of tests of mortars taken from historic masonry, and to apply experience from soil and rock mechanics to this field, i.e. to test mortars under triaxial stress state conditions which, naturally, are much more exacting and require appropriate instrumentation. However, these triaxial tests are quite expensive and it is not a simple matter to prepare the test specimens. Therefore, a simpler approach was adopted some years ago, and it is still of interest.

The methodology for tests on small specimens is influenced by several factors. Firstly, by the fact that the real size of the mortar sample taken from the historic structure – the masonry – is usually less than 20 mm in thickness. Manufacturing the specimen for the compression test (cutting a cube) has a significant influence on the properties of the sample, as it basically disturbs the surface strata and reduces the strength. In addition, manufacturing a small cube is very laborious and time-consuming. In most cases, the compressed surfaces need to be supplemented with a levelling layer. For this reason, specimens in the shape of irregular mortar “cakes” from the masonry joint have been studied for compression tests in recent times, too, e.g. Binda et al [4].

However, it has been known since the 19th century that the size of a testing specimen has a significant influence on the measured strength, and numerous forms for transferring the attained characteristics of concrete and cement mortars to the standard values have been proposed. There exists a rich bibliography on size effects recorded when testing small concrete cubes or cylinders. The research related to testing of concrete is still incomplete, because no unique and general theoretical background fully explaining the size effect has been established. However, Horký and Dohnálek [5], in 1982 analyzed 80 papers and compared the historical results with their own experiments. They concluded that the correction functions depend mainly on the length of the specimen base edge, on the slenderness or height to base edge length ratio, and on the quality (compression strength) of the mortar. The maximum grain size of the sand is not as important as other factors, e.g. the testing arrangement (eccentricity and/or testing frame end plates, and their friction characteristics, (Schickert [6], Konvalinka [7],)). The strength attained on non-standard samples is higher than the strength measured on standard specimens, if: i) the height (or thickness) to base length ratio decreases, ii) the base length decreases, and iii) the standard compression strength decreases. However, all earlier literature reported on concrete or cement mortars, and little work has been done on pure lime mortars and specimens less than 2 cm in thickness. A review of results of tests on cement mortars, which was based on a literature survey, was published by Drdácký [8] who developed correction coefficients applicable for assessment of equivalent standard compression strength from the tests on non-standard specimens.

The above mentioned correction coefficients were developed for poor lime mortar, therefore, a new experimental programme was designed and carried out, which included other lime mortars, namely lime-metakaoline and lime-cement-metakaoline mixtures. Further, the most up-to-dated numerical models for soil behaviour have been used for theoretical investigations of the behaviour of low slenderness test specimens during compression.

EXPERIMENTAL INVESTIGATIONS

The pilot tests on poor lime mortar included a series of non-standard specimens of various height to base length (further only slenderness) ratio which are presented in Fig.1. The specimens were loaded in compression and their surface photographed in order to acquire full field records of surface displacements related to the corresponding stress calculated from the measured load force. Image correlation technique was used to evaluate the displacement and to calculate the materials characteristics – the modulus of elasticity and the Poisson's ratio (Vavřík et al. [9]). The results of pilot tests served for planning of a new series of experiments and for calibration of a numerical model described further in this contribution.

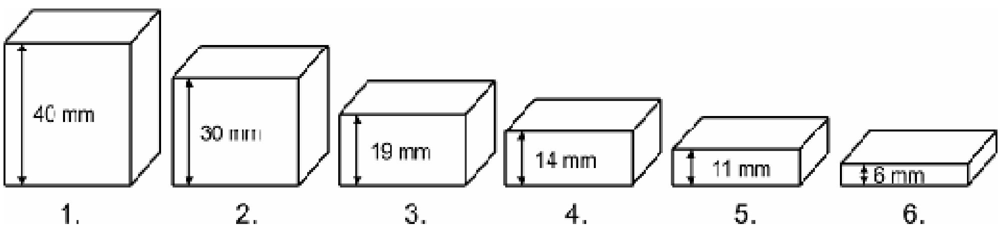


Figure 1. The specimens tested at pilot experimental investigations [8].

Test specimens

The new series of tests aimed at study of the base length effect and the mortar strength effect on the variation of the ultimate compressive loads attained on non-standard specimens of various slenderness ratio. It was expected that the both above mentioned effects are of subtle nature and need to be studied on specimens of a quite distinctive geometrical characteristics. Therefore, the base lengths accepted for the tests varied from 20 mm through 40 mm to 60 mm. Larger specimens are not realistic and smaller specimens would be very much affected by the size of sand grains. The strength variations were achieved using mortars of different binder dosage as well as different binder type, namely lime, lime-metakaoline and lime-metakaoline-portland cement mixtures. The nominal geometrical and material characteristics are given in Table 1 and Table 2. A total of about 132 prisms, 17 flat round plates and 12 cubes of different base dimensions and aspect ratios made from three batches of mortar were tested in direct compression. Three shapes were considered in each types of mortar proportion. All specimens prepared from each batch of mortar were cured under identical conditions before testing at the same age.

Table 1. Overwiew of geometrical characteristics of the tested specimens

specimen	nominal width a	nominal length a	nominal height h	nominal slenderness h/a ratio
	[mm]	[mm]	[mm]	[1]
lime	20	20	5, 7, 12, 15, 20	0,25; 0,35; 0,6; 0,75; 1
	40	40	12, 15, 20, 30, 40	0,30; 0,375; 0,5; 0,75; 1
	60	60	12, 20, 30, 40, 60	0,2; 0,333; 0,5; 0,75; 1
	round plate D = 60 mm		12	0,2; 0,3
lime - metakaoline	20	20	5, 7, 12, 15, 20	0,25; 0,35; 0,6; 0,75; 1
	40	40	12, 15, 20, 30, 40	0,30; 0,375; 0,5; 0,75; 1
	60	60	12, 20, 30, 40, 60	0,2; 0,333; 0,5; 0,75; 1
	round plate D = 60 mm		12	0,2; 0,3
lime – metakaoline – Portland cement	20	20	5, 7, 12, 15, 20	0,25; 0,35; 0,6; 0,75; 1
	40	40	12, 15, 20, 30, 40	0,30; 0,375; 0,5; 0,75; 1
	60	60	12, 20, 30, 40, 60	0,2; 0,333; 0,5; 0,75; 1
	round plate D = 60 mm		12	0,2; 0,3

Table 2. Mixture proportions of the tested mortars

type of mortar	ratio of components by volume				
	sand	lime putty	metakaoline	Portland cement	water
lime	3	1	0	0	0
lime - metakaoline	8	2	1	0	0,480
lime – metakaoline – Portland cement	6	1	0,5	0,5	0,357

The setting and hardening of thicker specimens was forced using various techniques, especially by immersion into solution of the ammonium carbonate and drying under controlled temperature and humidity conditions. Nevertheless, there has not been achieved full carbonation of the bulky specimens when checked by phenolphthalein tests. However, this phenomenon has been experienced by several authors, too. On the other hand the lime mortars with hydraulic components may suffer from a lack of water if cured according to the standard procedures and the slender specimens might not be adequately and comparatively hydrated (Veiga [10]), which was observed during the reported experiments, too. The work was partly carried out as a Graduation Thesis of the third author within the international Master Course SAHC [11] and, therefore, the specimens could not be let to mature for longer time than available. The specimens were tested after 100 days of maturing.

Experimental set-up, testing and evaluation

The specimens were tested in electromechanical (up to 100 kN capacity) and servohydraulic (up to 250 kN capacity) testing frames and loaded with a constant crosshead velocity which attained a value of 0.45 mm/min. The crosshead displacement was measured by LVDT sensors which enabled to draw the load-displacement diagram, and the surface displacement was recorded optically. The test set-up arrangement is seen in Fig.2.

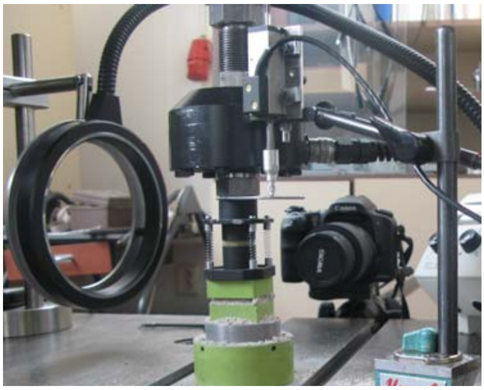


Figure 2. Compression test set-up.

The compressive strengths were calculated from the measured ultimate loads and real cross section areas given by measured actual dimensions of individual specimens. The modulus of elasticity was checked at the lime mortar only by means of digital image correlation and it reached value of 1600 MPa. For this evaluation an optimum measurement base was selected during the DIC analysis. For comparison, the modulus of elasticity or rather deformability characteristics of the weak mortar oscillated between 125 and 225 MPa when acquired from the overall displacement of the whole specimen between loading plates (involving also local contact irregularities and micro damage).

The round plates were loaded only partially between two square plates 20 mm by 20 mm and 40 mm by 40 mm, in order to study the possibility of testing and evaluation of mortar irregular plates as suggested, e.g. by Binda et al. [4], see Fig.3. The slenderness ration in such a case was calculated as the plate thickness to the edge length of the loading plate.

Figure 3. Concentrated compression tests on the round „cake-like“ specimen.

Experimental results

The extent of the paper does not allow for a detailed presentation of all results. Let us mention the most important facts and the tendencies which have been learned. It was observed from the course of loading that the behaviour of all the specimens was non-linear. The unloading branch tends to zero residual stress. For the evaluation of the influence of the specimen geometry only the ultimate loads or the calculated strengths were used.

As expected the measured ultimate loads increased with the decrease of the height to base length ratio (slenderness). This phenomenon is further dependent on the mortar quality and the base length. The results are presented for the sake of brevity in graphical representation in Figs. 4, 5 and 6. From the Figures it is clearly seen that the above mentioned tendency already known from the previous tests has been proved. However, the effect of the base length is less pronounced in the case of weaker mortars compared to the stronger cement gauged mortar specimens. The effect of the standard mortar strength on the measured values

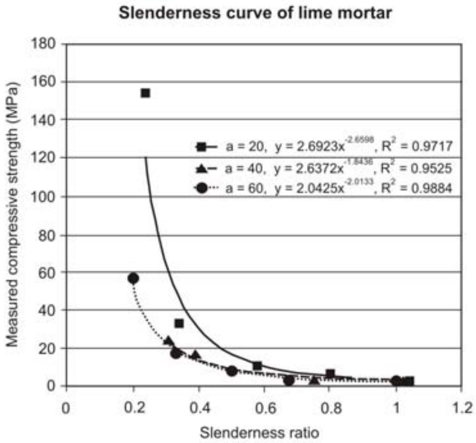


Figure 4. Dependence of the measured compressive strength of lime mortar on the slenderness and the base length.

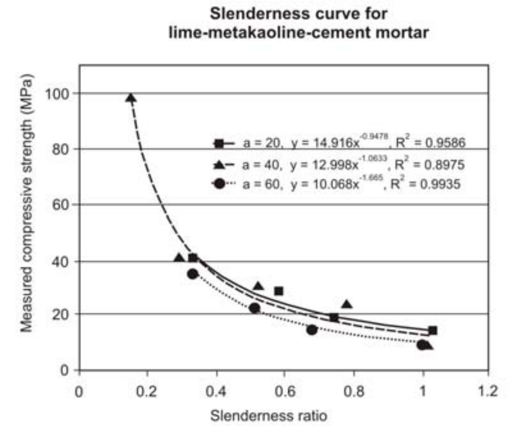


Figure 5. Dependence of the measured compressive strength of lime-metakaoline mortar on the slenderness and the base length.

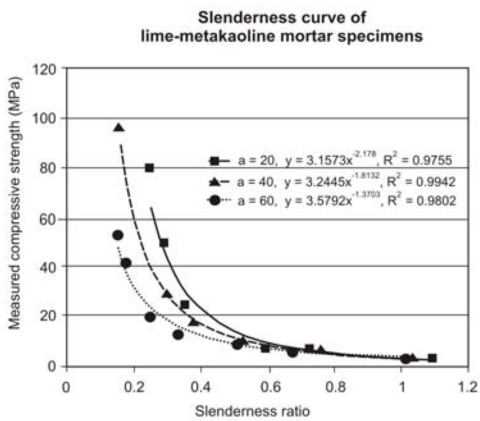


Figure 6. Dependence of the measured compressive strength of lime-metakaoline-portland cement mortar on the slenderness and the base length.

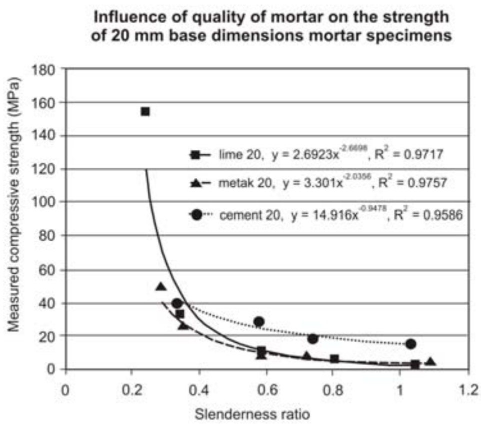


Figure 7. Dependence of the measured compressive strength to the standard strength ratio of specimens with the 20 mm base length on the slenderness and the standard strength (type of mortar).

at different base lengths is presented using dimensionless strength representation – the measured strength to the standard strength ratio, Figs. 7, 8 and 9. Here the influence of insufficient hydration might bias the measured strength on thin specimens made from hydraulic mortars where the standard maturing conditions need not supply the mixture with a sufficient amount of water, especially during hot days.

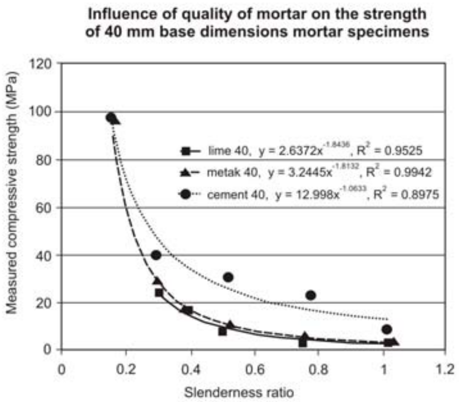


Figure 8. Dependence of the measured compressive strength to the standard strength ratio of specimens with the 40 mm base length on the slenderness and the standard strength (type of mortar).

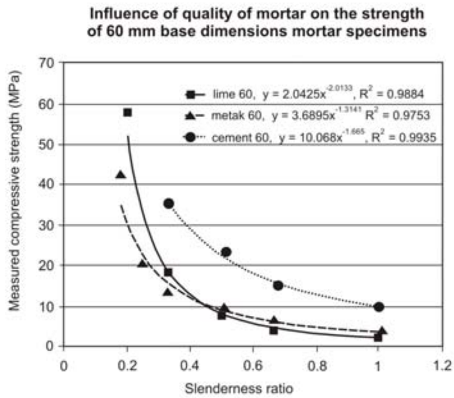


Figure 9. Dependence of the measured compressive strength to the standard strength ratio of specimens with the 60 mm base length on the slenderness and the standard strength (type of mortar).

The correction coefficients for the assessment of an equivalent standard compression strength derived from the tests correspond well with the coefficients presented by Drdácký [8] for a weak lime mortar in the form of

$f_c = f_e / (h/a)^{-1,9114}$

The following exponents were identified from the tests above: -2,2076 for lime, -1,6341 for lime-metakaoline, and -1,065 for lime-metakaoline-cement mortars.

NUMERICAL MODELLING

Numerical simulations proved to be a very valuable tool for handling different problems dealing with production, testing and application of building materials. This holds true for the simulation of the mortar behaviour in a hardened state; however, continuous modeling of mortar behaviour throughout the various stages of “mortar life” has yet not been developed. The need for such a numerical simulation is obvious. The mixing and placement of fresh mortar can have a significant effect on hardened mortar with regard to mechanical performance and durability, as well as other properties.

In this paper, the mechanical behavior of lime based mortar under a typical laboratory testing conditions (uniaxial compression) was simulated by means of two-dimensional finite element analysis using finite element software Tochnog Professional. The results were post-processed by using software GID-8.

The simulations have been performed under plane strain conditions, the 3D effects have therefore not been taken into account. The top and bottom end contact of the specimen with the testing apparatus has been assumed to be perfectly rough, i.e. zero nodal velocity in horizontal direction has been prescribed at top and bottom boundaries. The bottom boundary is fixed also in vertical direction. The numerical specimens were loaded vertically with constant velocity applied at the top boundary of the specimen. Axial stresses corresponding to the applied vertical load were found by integration of nodal forces along the top boundary. As in the experiment, zero horizontal forces acting on the vertical sides of the specimens were considered.

The material behaviour was described by an elastoplastic Mohr-Coulomb constitutive model. The strain-softening has not been taken into account, the model therefore aims at predicting the peak strength of lime mortar specimens measured in the experiments, the post-peak softening branch has not been modelled. The boundary conditions assumed (rough top and bottom ends) impose localisation of deformation into shear bands. In order to reduce the effect of the shear band thickness on the calculated results, all simulations with given specimen base length were performed with mesh consisting of elements of the same size.

Three elementary models were created, simulating lime mortar specimens of different base length dimmensions (20 mm, 40 mm and 60 mm). Procedure followed in the simulations was as follows: material parameters influencing the results significantly (Young modulus E, friction angle φ and cohesion c) were calibrated by comparison of experimental and simulated stress-displacement curve for specimens of the highest slenderness ratio (cube specimens). The last two parameters of the Mohr-Coulomb model (ν, ψ) do not have substantial effect on results, they were given constant values. Calibration of the model using data from 40 mm cube specimen is shown in Fig. 10. Different experimental curves in Fig. 10 represent different tests on nominally identical specimens. The model was calibrated to approximate the average experimental response. Also, Fig. 10 demonstrates that the post-peak strain softening has not been modelled. With material parameters obtained from calibration using cube specimens, all other slenderness ratios were modelled (parameters were then kept constant in all simulations). Material parameters used in simulations are given in Table 3.

Table 3. Material parameters used in simulations

E [Mpa]	ν	φ	ψ	c [MPa]
126	0.17	26.4°	13.2°	0.8

Figure 10. Calibration of the model using stress-displacement curve of 40 mm cube lime mortar specimen.

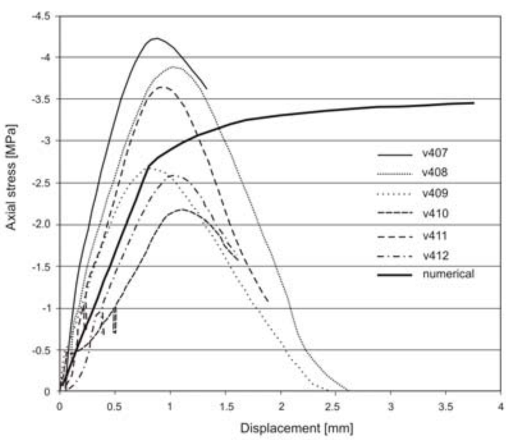


Figure 11 shows typical qualitative comparison of obtained results in terms of vertical displacements, along with the used finite element meshes for two 40 mm base length specimens (cube and 14 mm high specimen). The figure clearly shows different failure mechanism in the case of low and high slenderness ratio specimens. The cube specimen deforms along two clearly identified shear bands, symetrical about the specimen axis. On the other hand, deformation of lower slenderness ratio specimen is more diffuse and homogeneous, without clearly defined shear band.

The different deformation mode causes substantial effect on the calculated peak strength of the specimens, as demonstrated further. Note, however, that this effect influences the results for different slenderness ratios only – scale effect due to different base length of specimens cannot be captured using the chosen simplified approach. However, as will be seen further, reasonable agreement between experiment and simulation is achieved for different base dimensions with single set of material parameters from Tab. 3. This is because the influence of base dimension is in the case of studied specimens less important than the influence of slenderness ratio.

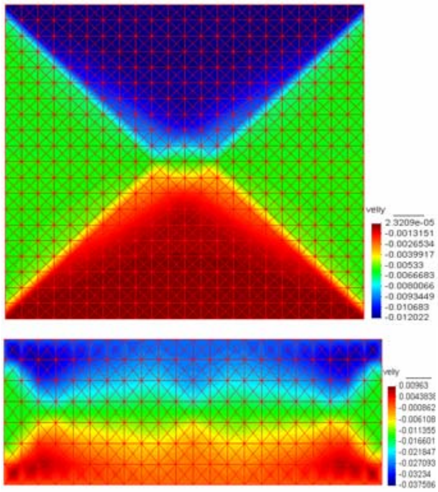
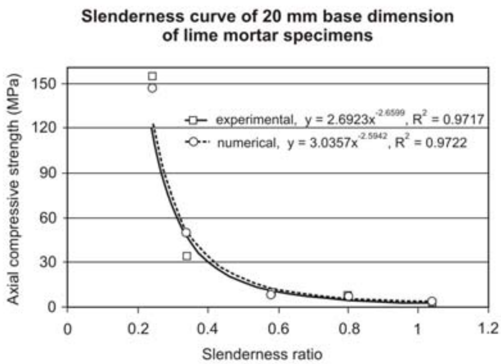
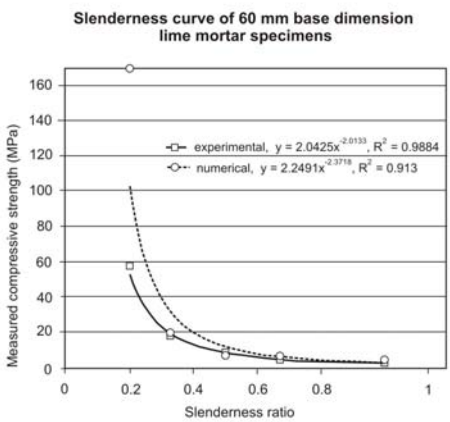


Figure 11. Vertical displacements for 40 mm base specimens of different slenderness ratios (heights of 40mm and 14 mm)

Figure 12 shows the peak strength predicted by the model compared with experimental results for all three base dimensions and different slenderness ratios. It is clear that even the simplified model chosen is capable of capturing the slenderness effect reasonably.





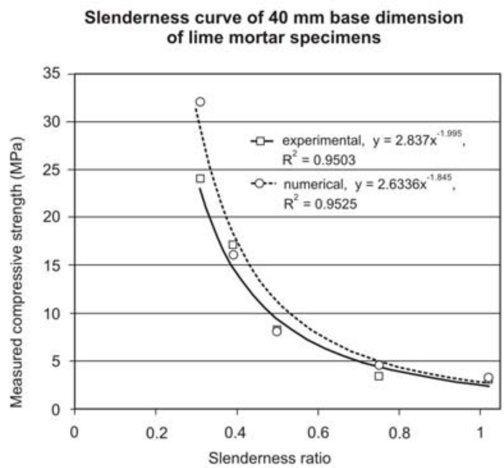


Figure 12. Comparison of computed and measured compressive strengths.

Conclusions

The compression strengths measured on non-standard mortar specimens of slenderness inferior 1 exhibit higher values than those from the standard tests. They can be estimated using empirical correction coefficients dependent on the slenderness, the strength of mortar and the length of the base. The developed approximation can be applied at evaluation of tests on historical mortars which are typically available in thicknesses not allowing for preparation of standard test specimens.

Behaviour of non-standard mortar specimens can be predicted numerically with a reasonable accuracy taking advantage of a description of the material behaviour by an elastoplastic Mohr-Coulomb constitutive model.

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