

USING MORTAR JOINTS TO REDUCE STRESSES IN REFRACTORY STRUCTURES – MEASUREMENT AND MODELLING EXPERIENCE

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INTRODUCTION

Refractory structures in the steel industry are supported by the steel shell or the foundation. Upon heating the lining expands. Often expansion joints are built in to allow the refractories to expand without damage to the supporting construction. The mortar joint is also known to give provision for the expanding masonry. This aspect is not yet fully accountable and the design of mortared linings is still based on experience.

A properly designed mortar joint will act as a "smart" expansion allowance. Gradual softening of mortar at higher temperatures relieves thermo-mechanical stresses at locations where it is most needed. Too stiff mortar, on the other hand, in combination with insufficient expansion provisions, may be a cause of lining failure.

To realise the full potential of the mortar joint to reduce thermal stresses one needs to understand its thermo-mechanical behaviour. This can be achieved by combining laboratory tests with computer analysis of lining structures. Laboratory tests should disclose typical behaviour of the material when it is exposed to different loads (e.g. temperature, force). This material data serves as input for a computer model. The computer analysis predicts temperatures and stresses in the lining.

In the reported study compressive behaviour of mortars of two types was investigated. Aluminosilicate and carbon based mortars were measured. The data obtained were used in computer models of several refractory structures. The analysis results of a blast furnace hot blast main are illustrated here. During the work a special emphasis was placed on the methodology for compressive testing of mortars and on the implementation of the test results into the computer code.

COMPRESSIVE TESTS

State of the art

Mortar is a complex material. Throughout the life of the joint the components of mortar – aggregates and the binding system – undergo a series of physical-chemical transformations. These transformations influence the properties of the material. Due to this the behaviour of the mortar joint is not determined exclusively by the operating conditions in the furnace. Preparation of the mortar and its thermal history also influence the behaviour of the joint.

As for any granular material the stress-strain behaviour of mortar is determined by the lateral constraints. The degree of lateral constraint is determined by the joint geometry – the length and the thickness. Thus, a thin joint can be much stronger than a cubic sample.

Ideally mortar should be tested in such a way that all features of its behaviour are accounted for in a uniform and reproducible manner. In literature the majority of research on compressive behaviour of mortar joints has been reported for civil construction mortars [1, 2]. The tests are performed either on mortar samples shaped as cubes or cylinders, or on an assembly with bricks. Such an assembly consists of several bricks with mortar joints in between. Industrial tests are performed on fully hardened samples. Academic investigations also test materials at different stages of maturity. For refractory mortars the most typical test set-up is a single mortar joint between two parts of brick. This set up is used to perform refractoriness under load tests. Usually refractoriness under load tests simulate gravity loads of unconstrained lining. If thermal expansion is constrained the lining is exposed to loads that in many times exceed the gravity loads. Material behaviour in various conditions of constrained expansion can be predicted from compressive stress strain curves. The stress strain tests expose the sample to gradual loading, while stresses and strains in the sample are registered. The test is conducted until material fails. Stress strain measurements on refractory mortars have been reported in [3, 4].

Measurements

Compressive tests reported here were performed using the sandwich sample geometry. The sample consisted of two ceramic discs of high strength corundum and a layer of mortar in between. The reason for using the corundum discs instead of the parts of refractory brick was to prevent overlapping of the brick and mortar deformations. The uniform thickness of the mortar was ensured by a special device holding the discs apart until the mortar was hardened. The hardening took place at room temperature for 24 h. Then the sample was positioned in the furnace attached to a

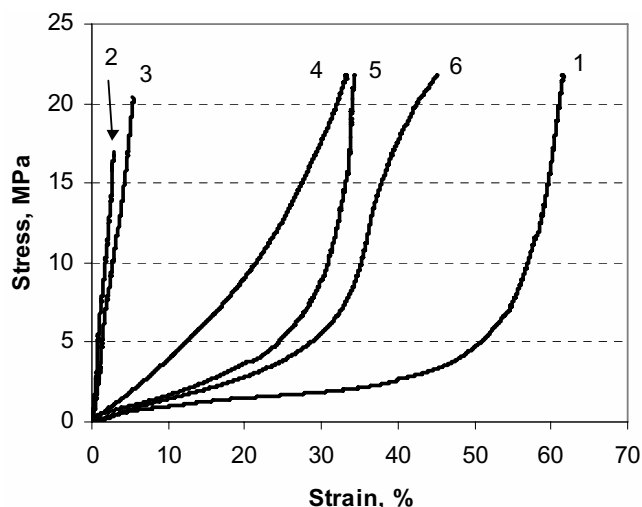


Fig. 1 Compressive stress-strain curves of the aluminosilicate mortar B. The test temperature: 1 – 20 °C, 2 – 600 °C, 3 – 800 °C, 4 – 1000 °C, 5 – 1200 °C, 6 – 1300 °C.

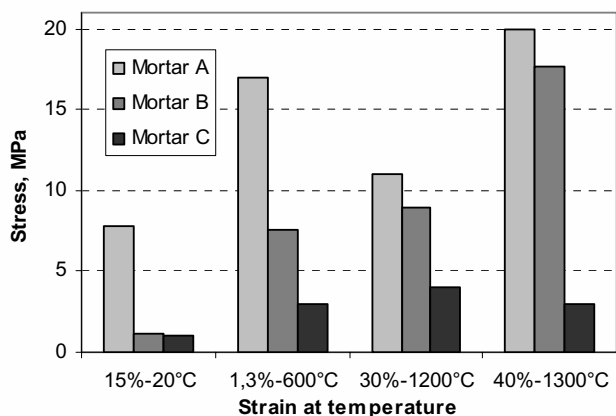


Fig. 2 Stresses in the samples of three aluminosilicate mortars at fixed temperature and compressive strain values. The stress-strain curves for mortar B are presented in fig. 1.

Tab. 1. Chemical composition of mortars, wt. %.

	Al ₂ O ₃	SiO ₂	Alkali
Mortar A	70	20	3
Mortar B	43	52	3
Mortar C	50	42	4

testing machine. The sample was heated up at the rate of 4 °C/min and under the constant axial pressure of 0,01 MPa. A strain-controlled load of 0,002 mm/sec was applied.

Three aluminosilicate mortars were tested (Table 1). In all the mortars the binding agent was water glass, the maximum grain size was 0,5 mm. The thickness of the mortar layer in the samples was 2 mm. The sample diameter was 50 mm. Compressive stress-strain curves for one of the tested mortars are presented in fig. 1. The test at room temperature shows significant compressibility of the joint (some 50 %). With increasing temperatures mortar becomes stiffer. At 600 °C the stiffness of mortar joint is approx. 0,5 GPa. This is two to three times higher than the stiffness of a light insulation brick. Further temperature increase causes gradual softening, which is seen in the measurements

performed at 1000, 1200 and 1300 °C. It is interesting to note that during the test at 600 °C part of the curve obtained from a single layer sample entered the negative strain range. At low stress levels displacements of a thin and stiff sample is comparable with those of the testing machine. This problem was solved using a sandwich sample with multiple mortar layers (curves 2, 3 fig. 1).

The tested mortars show different resistance to compression. In fig. 2 the higher the stress the lower is the compressibility of the material. The stresses in the mortar A are highest at all temperatures. A joint of such material will give the lowest compensation for expanding bricks. A FEM model can be used to see whether a certain expansion provision is sufficient for a lining.

FEM MODEL

A thermo-mechanical finite element model was used to investigate the stresses and temperature distribution in the hot blast main of a blast furnace. The modelled lining consisted of 3 concentric layers of refractories. The layer at the hot face was dense Andalusite bricks. The back-up layers were made of two qualities of lightweight insulation bricks. Several alternative designs were investigated. The designs had different layouts of expansion provisions. Mortar joints were used as circumferential expansion allowances. Felt layers were to allow for radial expansion.

A 2D unit cell model was built (fig. 3). The finite element code ANSYS was used for the purpose. The model depicts a segment of the hot blast main lining and the steel shell. The segment size equals half the width of the Andalusite brick with the mortar joint. Mechanical boundary conditions simulate the behaviour of the joint. They only restrict expansion in the circumferential direction. Outward displacement and the consequent opening of the gaps between the bricks is unconstrained. Shaped refractories were modelled as linear elastic. The mortar behaviour was defined by stress-strain pairs obtained from compressive tests.

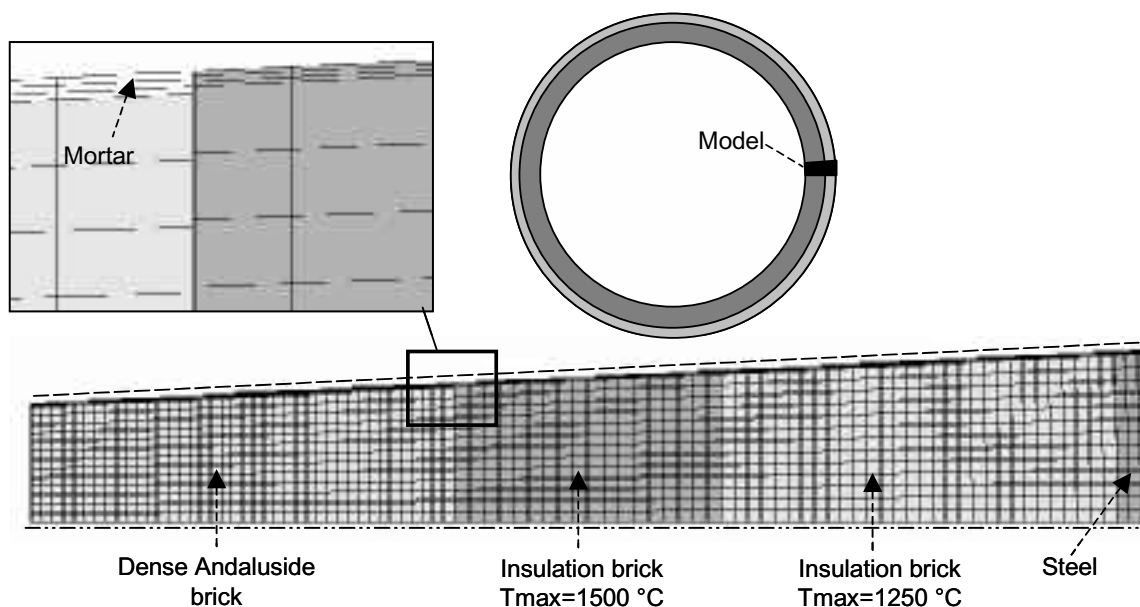


Fig. 3 Unit cell model of a hot blast main. Dot and dashed line marks the symmetrical boundary constrains, dashed line shows the special boundary constrains that simulate joint behaviour.

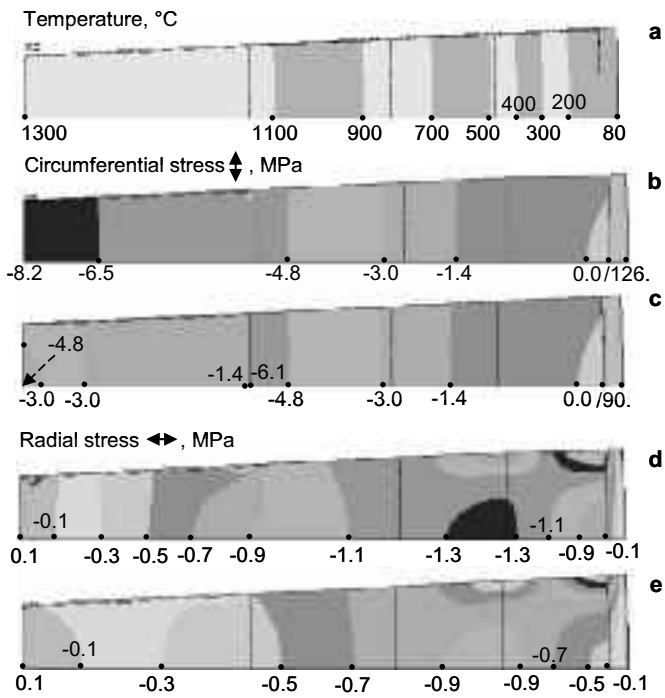


Fig. 4 Temperature (a), circumferential (b,c) and radial (d,e) stresses predicted by FEM model. Lining with 2 mm thick radial mortar joint (c,e), lining without mortar (b,d).

Some representative results from stationary FEM analyses are shown in fig. 4. The behaviour of the lining with and without a mortar joint between the Andalusite bricks is compared. The mortar joint has little effect on the temperature distribution in the lining. In both linings the highest temperature gradients are in the lightweight insulation bricks. There the temperature drops from 1100 to 80 °C. The layer of Andalusite bricks is exposed to temperatures between 1300 and 1100 °C. At these temperatures mortar already starts to soften. Comparing the circumferential compressive stresses near the hot face one can see that in the lining with the mortar joint the stresses are almost 40 % lower.

In circular linings, at the hot face brick's circumferential expansion is constrained by its neighbours. In the radial direction the lining is constrained by the shell. The circumferential compressive stresses in refractories are balanced by tensile stresses in the steel shell. In the radial direction the lining is compressed. Mortar joint absorbs some circumferential expansion at the hot face. Due to this, tensile stresses in the shell and radial compressive stresses are some 30-40% lower in the lining with a mortar joint.

Two designs presented in fig. 4 have no mortar in the joints between the insulation bricks. In these layers the circumferential compressive stresses are predicted to exceed the material strength. The strength of the insulation brick was estimated as 2 MPa. An alternative lining concept was developed. The stresses were reduced below the critical level by applying mortar in the insulation layer. In addition, felt layer was installed between the refractories and the steel shell.

DISCUSSION AND FURTHER DEVELOPMENTS

The measurements reported and their implementation in a FEM model have their limitations. The sample featuring one layer of mortar at certain conditions has only very small displacements. Performing an accurate measurement on such a sample is difficult. If the input into the model is based on the stress-strain pairs the thickness of the modelled joint may only be equal to the thickness of the sample. Due to the difference in the lateral constraint conditions joints of different thickness can have different stress-strain behaviour.

A series of laboratory tests and their simulations was conducted to overcome the observed limits. A resin bonded carbon mortar was used for the purpose. The largest grain size in this material is 0,25 mm. The mortar is self-hardening and may be formed into shapes different from a thin joint. Samples of three shapes were tested – a cylinder, a single layer sandwich and a four layer sandwich. The layers of the sandwich samples were 0,8 mm thick. In the multi-layer sample all layers had the same thickness. The sandwich Corundum plates were square 20x20 mm². The cylinder height and diameter were 30 mm. The test results show that in the range 0-1000 °C the temperature increase causes stiffening of the mortar (fig. 5). Above 1000 °C the mortar stiffness gradually decreases with temperature. The effect of the sample geometry is clearly seen in fig 6. The stress-strain curves of the cylindrical and multi-sandwich samples are linear for low strains. The linear parts of the curves are parallel. The initial non-linearity seen in the curves is typical for compressive tests. It is due to the alignment of the sample and the loading plates. Failure of the material occurs at the end of the linear range of the curve. After failure the cylindrical sample demonstrates softening, while the multi-sandwich hardens. Before failure material is supposed to behave linear-elastically, after the failure plastic deformations take place. The difference in the plastic behaviour is thought to be due to the stress state condition. Stresses in the cylindrical sample are close to a uni-axial distribution. The thin layer of material in the multi-sandwich has a multi-axial stress state as deforming parts of the sample constrain each other in the lateral direction.

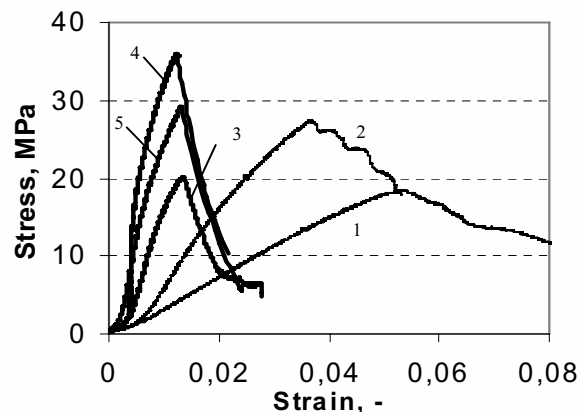


Fig. 5 Compressive curves of the carbon mortar (cylindrical sample). The temperature: 1- 100 °C, 2 – 200 °C, 3 – 600 °C, 4 – 1000 °C, 5 – 1400 °C.

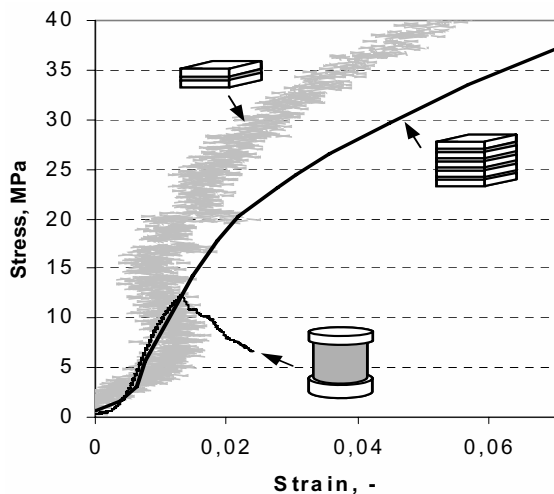


Fig. 6 Compressive curves of the carbon mortar for cylinder, single- and four-layer sandwich samples.

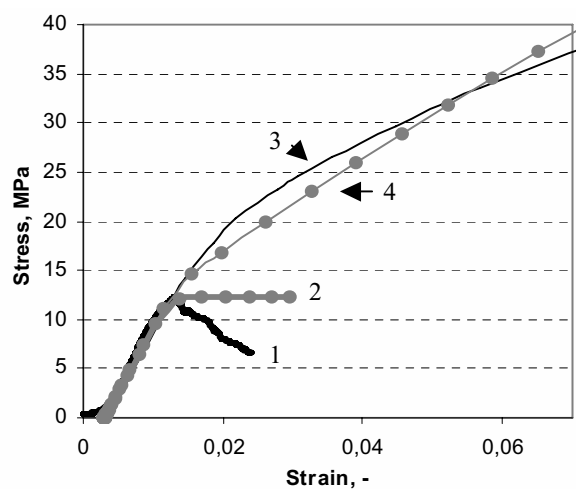


Fig. 7 Compressive curves obtained from laboratory tests (1, 3) and their FEM simulations (2, 4). Cylindrical sample – 1, 2. Multi-layer sandwich 3, 4.

The multi-sandwich sample has proven to be a good alternative in cases when the single layer of mortar is not enough for an accurate measurement. The total displacement of the four-layer-sandwich is four times the displacement of the single layer sample. Therefore the relative measuring error is four times smaller than for the single layer sample.

The optimal way to describe material behaviour in a FEM model is by defining a material law. Concrete and other granular non-metallic materials are often characterised by the law of Drucker-Prager [5]. It was assumed that this would also apply to the mortar. According to this law the compressive behaviour is defined by three parameters – the cohesion and the angles of friction and dilatation. The value of cohesion was obtained from the uniaxial compressive strength. The other parameters demand measurements of lateral stresses and strains. Such measurements seem to be impossible for a mortar joint under high temperatures. To determine the two angles a series of numeric experiments was performed. The experiments modelled the compressive tests of the cylindrical and the sandwich samples. Calculations with different values of the angles were

conducted. The best agreement between the curves produced by the numerical and laboratory tests was achieved when the angles of friction and dilatency were set in the model as 5° and 0° , respectively (fig. 7). Using this approach the material properties can be established for the whole temperature range.

The post failure behaviour of the granular materials can be of two types – hydrostatic compression and shear yield. During the hydrostatic compression the stiffness of the material is rising while the density is increasing. The shear causes separation of the grains and their sliding against each other. The material yielding due to the shear shows gradual decrease of stiffness. The stress strain curves of the carbon mortar (fig. 5, 7) are typical for the shear failure. The curves of the aluminosilicate mortars are of both types (fig. 1). At 600°C and 800°C the mortar shows the shear yield. At other temperatures the hydrostatic compression yield occurs. The law of Drucker-Prager accounts only for the shear failure. To describe the both yield types this law is usually up-graded with the so-called Cap-function of hydrostatic failure.

CONCLUSIONS

In many lining structures it is impossible to use open expansion provisions without a danger for lining integrity. The expansion needs to be absorbed by the structure itself. In this situation properly designed mortar joints can be very effective.

The stress reducing capability of different mortar qualities may differ significantly. Dedicated mortars must be selected for each application. Combination of laboratory tests and numerical modelling gives an opportunity for optimisation of the mortar selection and improvement of the lining design.

For compressive tests of refractory mortars multi-layered sandwich samples are recommended. Drucker-Prager-Cap material law can be used to describe the compressive stress strain behaviour of the mortar. The material parameters for the shear part of this law can be determined by fitting the model simulating the laboratory tests.

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