Experimental set-up for mortar / brick interface strength characterization at high temperature

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Abstract

The interface between bricks and mortar is often the weakest part of refractory masonries. Then, the prediction of the refractory lining damage requires the knowledge of the strength of this interface at high temperature. This paper proposes to use a slant shear test and a new tensile test device to characterize the brick/mortar interface from room temperature up to 1450°C. The slant shear test allowed measuring ultimate compressive and shear stresses and deducing temperature dependent parameters of Mohr-Coulomb failure criterion. The tensile test allowed identifying the tensile cut-off. For materials tested with these set-ups, internal friction angle shows a weak dependence on temperature, while cohesion and tensile strength decrease sharply over 900°C.

1. Introduction

In the steel-making industriy, the large chemical reactors are composed of many different linings from inner to outer: the working lining in contact with slag or gas, the safety lining, the insulating lining, and so on as far as outer metal timbering. Parts of the lining of these vessels consist of refractory masonries, with or without mortar. In the case of masonry with mortar, cracks occur most of the time at the unit-mortar interface because it is the weakest link of the assembly(1). This observation has led to the development of a homogeneous equivalent material with behavior depending on the "joint state": sound or broken.(2,3,4,5)

In refractory applications, due to thermal solicitations and shape of the vessels, refractory unit-mortar interface should crack under tensile load, usually denoted mode I fracture and under shearing load, denoted mode II. It is therefore necessary to characterize the refractory brick/mortar interface in modes I and II from RT up to 1500°C. Then, two specially-designed devices are proposed: the high-temperature slant shear test and an especially dedicated tensile test.(6)

2. Strength criterion

The mode I failure corresponds to a classical Rankin criterion (i.e. tensile cut-off) while the brick/mortar interface shear strength dependence to the normal stress applied to the interface corresponds to a friction-type behavior, classically described by the Mohr-Coulomb yield function. Then, it leads to a yield surface described by two lines in the plane (σ_n, τ):

$$\begin{aligned} f_{MC}(\boldsymbol{\sigma}) &= \tau - c + \sigma_n \tan\varphi \quad (\forall \sigma_n \leq 0) \\ f_R(\boldsymbol{\sigma}) &= \sigma_n - f_t \quad (\forall \sigma_n > 0) \end{aligned} \tag{1}$$

where $\boldsymbol{\sigma}$ is the stress tensor, τ is the shear stress associated to the considered interface, σ_n is the normal stress to the interface, c is the cohesion, φ is the friction angle and f_t is the tensile strength.

3. Materials

An interface is defined by the couple of brick and mortar. In this work, two couples were considered (Tab 1). The first one is made of dense silica bricks with a silica based mortar, denoted A. The second is composed of high alumina bricks with a chemically bonded high alumina mortar, denoted B. Silica bricks were stabilized into cristobalite while alumina bricks were stabilized into corundum.

Table 1: Chemical composition of refractory bricks and mortar

w. %	A		B	
	Brick	Mortar	Brick	Mortar
SiO_2	95	95		
CaO	< 3	< 1		
Al_2O_3	< 1.5	< 1	89	86
Na_2O				2.75
N			4.8	
Fe_2O_3	<1			< 0.25

Green mortars were shaped between the two half samples before 24 hours curing at RT and 24 hours drying at 110°C. Shear strength has been characterized for each specimen, whereas the tensile strength has been measured for B only.

3. High-temperature tensile test

The tensile strength f_t can be deduced from different tests[7,8,9] but direct tensile test remains the best method to study the mode I fracture behavior. The set-up developed here has been specially designed to address the alignment of the loading chain including the specimen in the special case of brick-mortar interface characterization.

The assembly is made up of a couple of cylindrical refractory units joined with mortar. Two wires inserted in the unit and going through thanks to double holes make possible the block to be clamped.[6] Each wire is made of nickel-chromium alloy to resist high temperature and stress. Both wires are griped to specific clamps out of the furnace (see fig.1). The wire's diameter is chosen to resist stress while being flexible enough to ensure the alignment of the loading "chain". Using these specific clamps and wires makes it possible the specimen to be aligned with the force direction.

Tensile tests were performed using a universal testing machine equipped with a high-temperature furnace (AET Furnace - 1500°C, ref. OF 25 957 Type SP). The force is measured with a classic load cell. A cooled device is set between the furnace and the load cell. Displacement of the crosshead is also measured.

Figure 1: High temperature tensile test set-up

Samples are obtained by core drilling. Then the core samples are ground thus allowing drilling coaxial hole. The couplet is assembled using a mould ensuring the alignment between both cylinders and the control of mortar thickness. Then the samples are air-dried during 24 hours. The larger specimens compatible to furnace dimensions are currently cylindrical units of 20 mm in diameter and 25 mm long with a joint of 3 mm thick.

The tensile test starts in putting the specimen into the furnace, tightening and clamping it through the wires, heating up to the set point value at a rate of 700°C/h and stabilising. Then, the force measured is reset to zero and the test starts applying a displacement to the upper crosshead.

Tensile tests were performed on samples B at three temperatures: 20, 900 and 1200°C. For RT, the tests were performed with a rate of 0.5 mm/min whereas for high-temperature test, the speed rate was tuned to 30 mm/min to avoid the creep of the wires. The tensile strength f_t is estimated according to equation:

$$f_t = \frac{4F_{max}}{\pi(D^2-d^2)} \quad (3)$$

where F_{max} is the maximum load reached before the fracture of the sample, S is the area of the transverse section, D and d are the outer and the inner diameters of the cylindrical unit respectively.

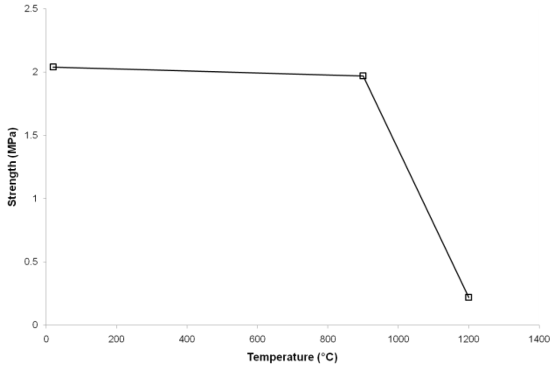

Figure 2: Tensile strength versus temperature for specimen B

Figure 2 summarizes the evolution of tensile strength with temperature for specimen B. The tensile strength remains nearly stable from RT up to 900°C. Over this value, the strength decreases sharply. Results of sensitivity study established that the uncertainty is lower than 5% on the tensile strength[6].

3. High temperature slant shear test

To achieve the identification of the Mohr-Coulomb's parameters, dedicated devices have been developed in the civil engineering field. Tests on two bricks pasted by one mortar joint[10,11] or on three bricks pasted by two mortar joints[12,13] are the most used. In this work the high temperature constraint induces two major difficulties: firstly, the set-up must be compact enough to be put in a furnace; secondly, the loading device must stand against high temperature. As presented on **Erreur ! Source du renvoi introuvable.**, a possible solution to overcome these difficulties is to perform a compressive slant shear test on two bricks pasted by one inclined mortar joint[6]. This design allows applying normal and shear stresses at the interface with a usual compression device. The same test has been used coupled to optical measurements at RT to characterize the equivalent interface stiffness in function of the mortar slant angle.[14] The limits of this test at RT and the influence of different shapes and material parameters have been studied by Austin.[15]

Figure 1: Specimens A after slant shear test at 1080°C

The local normal and shear stresses applied on the brick/mortar interface are driven by the slant of the joint:

$$\begin{cases} \sigma_n = \frac{F}{S}\cos^2\alpha \\ \tau = \frac{F}{S}\cos\alpha\sin\alpha \end{cases} \quad (4)$$

where F is the global applied force, S is the specimen transverse area and α is the angle between mortar joint and the plane normal to the compressive loading axis. Equations (4) are rigorously right as long as the crack initiates at the interface. To produce a shearing fracture instead of a compressive one, the angle must maximize the ratio of shearing stress to normal compressive stress. The identification of the cohesion and internal friction angle requires at least three different angles. The specimen shape was parallelepiped of section 35x35 mm^2. Its total height depends on the angle but need to be lower than height of homogeneous temperature in the furnace. Detailed dimensions of specimens are summarized in Table 2.
The samples A were first heated up to 1000°C for a dwell of one hour to stabilize the mortar. Then, samples were heated up or cooled down to the temperature of the test. A second dwell of half an hour was done before performing the test. The tests were performed at 800°C, 1080°C and 1350°C. The samples B were heated up to 450°C at a rate of 350°C/h, then up to 650°C at a rate of 125°C/h and finally to the temperature of the test at 325°C/h. A dwell of one hour was done at the temperature of the test before performing the experiment. Tests were performed at RT, 900°C and 1450°C.
The tests were performed on a classical press with usual compressive device. The cross bar speed rate was tuned to 0.5 mm/min. Figure 1 presents typical fractures after testing at high temperature. With few exceptions, cracks were clearly localized at the interface. The exploitation proposed here with equations (4) is thereby available only for brittle and quasi-brittle fracture localized at the interface or, at least, initiated at the interface.

	A	B
Section (mm^2)	35x35	
Mortar thickness (mm)	4	3
α (deg)	45	45
	55	55
		60
	65	65
		70

Table 2: Specimen dimensions for slant shear test

Erreur ! Source du renvoi introuvable. presents typical load versus displacement curves obtained recording these data during the test for specimen B. The different curves correspond to different joint slants tested at the same temperature.
The decrease of the maximum load value with the increase of the joint slope is not clearly observed. As illustrated later, it does not prevent to determine reasonably Mohr-Coulomb parameters. Nevertheless, because of the material scattering, the lack of data may lead to use all the experimental data carefully.

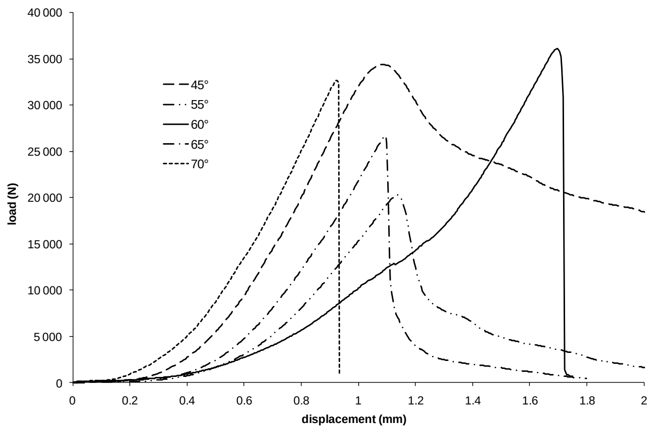

Figure 4: Load versus displacement curves for specimen B with different joint slopes at 900°C

Erreur ! Source du renvoi introuvable. presents Mohr-Coulomb graph extracted from load versus displacement curves on specimen A at the different tested temperatures. The points clearly define a straight line that allows identifying cohesion and friction angle for each temperature. The difference between 1080°C and 1350°C is small, whereas a real difference appears for the cohesion between 800°C and 1080°C. Moreover, the friction angle seems not to be influenced by the temperature.

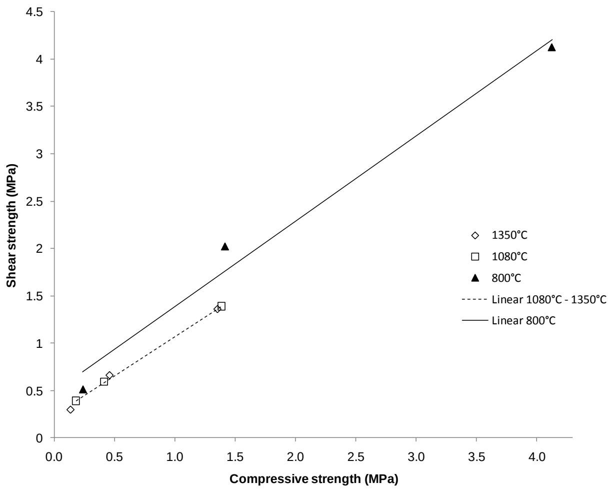

Figure 5: Mohr-Coulomb line for specimen A.

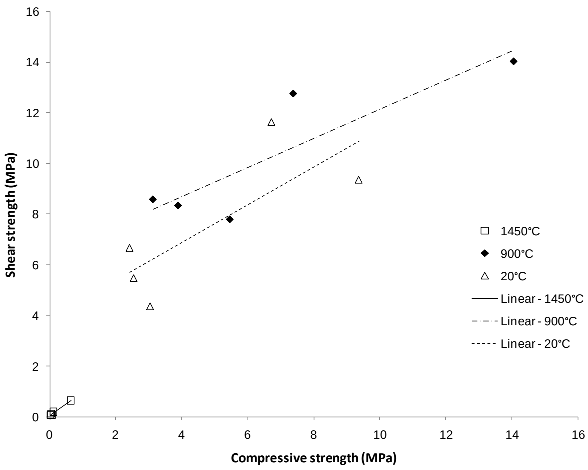

Figure 6: Mohr-Coulomb line for specimen B.

Erreur ! Source du renvoi introuvable. presents Mohr-Coulomb graph extracted from load versus displacement curves on specimen B. Despite a huge discrepancy, shear and normal strengths are close to follow a Mohr-Coulomb law and reach a maximum at 900°C before falling close to 0 MPa at 1450°C. The discrepancy is mainly due to damage propagation in the mortar instead of crack propagation along the interface.

4 Conclusions

Experimental characterization of the strength of mortar/brick interface is a key point as the unit-mortar interface is often the weakest link of the assembly. Currently, there is a real lack of data concerning the refractory masonry strength. Two set-ups and the associated sample shapes were developed to measure the tensile strength and the compressive shear strength.

A special tensile test with dedicated clamping devices has been designed to measure the tensile strength of interface and tests were performed in temperature range from RT up to 1200°C. For the compressive shear fracture, the slant shear test was carried out in the temperature range from RT up to 1450°C to identify the Mohr-Coulomb parameters of the mortar brick interface in function of the temperature.

These first results concerning the strength of interface at high temperature should be carefully taken because of the assumption on the prevailing failure mode. This assumption will be reinforced by a further dedicated work.

In conclusion, both experimental set ups proposed here allow the setting of a complete characterization of the brick/mortar interface strength at high temperature. These devices may contribute to enlarge the knowledge on the ultimate strength evolution with temperature of such interfaces.

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