Sonic Testing of Refractory Brick

Tests were performed with random batches from three suppliers of ladle brick to determine linear relationships between physical characteristics and the modulus of elasticity. This testing method is of prime importance for studying parts whose proper in-service behavior is essential

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An object's modulus of elasticity is a function of its properties. These properties depend on the manufacturing process. Several methods exist to determine the modulus of elasticity:

- Stress-deformation curve;
- Ultrasonic testing;
- Sonic testing.

When working with a stress-deformation curve the deformation of refractory material is slight, thus measurements are imprecise and small. Ultrasonic and sonic testing methods are much easier to perform. For complex shaped objects, the sonic method better determines properties and imperfections because it involves the total volume of the object. Being directional, the ultrasonic method requires several measurements per object.

The sonic testing method has been used for years to:

- Detect the appearance of cracks as a result of thermal shock;
- Study property variations of a lot as a function of resonant frequency;
- Test and sort parts where guaranteed performance is required.

Resonant frequency measurements were performed at the European company, Sacilor-Sollac Steelworks Products Test Laboratory, using Grindo-Sonic equipment on loan from the Minerals & Refractories Laboratory, Nancy, France. Tests were done on different lots of ladle brick to determine the feasibility of the sonic testing method, and to pinpoint correlations between physical properties and the modulus of elasticity.

Measurement principle

The modulus of elasticity E, or Young's Modulus, can be derived either from the stress-deformation curve (static modulus of elasticity E_s) or from the natural resonant frequency action of a longitudinal torsional or flexural vibration (dynamic modulus of elasticity E_d).

Determining the modulus of elasticity from the stress deformation curve: the static modulus of elasticity E_s is the relationship between stress and deformation. For low stress, it is equal to the tangent at the origin of the force-deformation curve. The static modulus is given by the formula:

$$E_s = \frac{\sigma}{\frac{\Delta L}{L}} = \frac{\sigma}{\epsilon} = tg\,\alpha$$

where:

- E_s = **static modulus of elasticity**
- σ = **stress**
- ϵ = **deformation**
- L = **length**
- α = **angle at the origin of the force deformation curve**

As noted earlier, refractory product deformations are slight and these testing method results are imprecise. In addition, this method requires rigid equipment to measure only the product deformation—without measuring the deformation of test rig.

Determining the modulus of elasticity from the resonant frequency: a sample set into vibration with a frequency of n will start vibrating only at its resonance frequency n, where amplitude is maximum. This resonant frequency depends on the sample's dimensions, its density and the modulus of elasticity. The dynamic modulus of elasticity E_d can be obtained from the formula:

$$E_d = \frac{10^{-7}}{981} .4\ L^2 .N^2 .d$$

where:

- E_d = **modulus in GPa**
- L = **dimension in cm**
- N = **frequency in Hz**
- d = **density in g/cm 3**

The modulus of elasticity (E) is determined by an object's resonant frequency in a longitudinal or flexural vibration mode. Two methods exist to determine the resonant frequency N of a sample:

- Detecting the maximum amplitude of the vibrations by continuously changing the excitation frequency;
- Measuring the sample's natural frequency after impulse excitation.

Excitation by continuous vibration

Whatever the mode of vibration chosen, a low frequency generator transmits vibrations to the sample through a transducer. A receiver, coupled to a millivolt meter, will monitor the amplitude of the vibrations. An oscilloscope verifies the sample's natural frequency. Increasing the amplitude of vibrations for different excitation frequencies allows one to determine the maximum, corres-

Calculating the modulus of elasticity

ponding to the resonant frequency.

This method also allows one to determine the internal friction of the material and, therefore, its damping capacity, which avoids the amplitude of the vibration becoming infinite when the resonant frequency is reached. It is possible to evaluate the internal degradation caused to the sample by determining its damping capacity. This can be done by measuring the logarithmic decrement:

$$\delta = \log_e K \quad \text{where } K = \frac{An}{An\text{-}1}$$

$$\delta = \pi \frac{\Delta N}{N} \quad \text{where } \Delta N = N_1 - N_2$$

where: A = amplitude of the vibration
N_1 and N_2 = frequencies for $A_{max} / \sqrt{2}$
N = frequency for A_{max}

In flexure, changing the receiver's position on the sample permits localizing the nodal zones and the vibration maxima.

Impulse excitation

The energy acquired after shock excitation by a sample that can oscillate freely will be dissipated in the form of a vibratory movement and will reach its natural vibration quickly. A piezoelectric vibration detector held at one end of the sample will capture the generated damped sinusoidal wave form.

The frequency, based on a certain number of cycles starting from a chosen beginning, is measured in relation to the frequency of a reference quartz crystal. An electronic circuit will display a proportional number at a factor to the inverse of the resonant frequency. Knowing the mass and geometry of the sample, the modulus of elasticity can be calculated.

The modulus of elasticity is a function of the resonant frequency and the sample's mass and geometry, or its shape factor. The shape factor is known and simple for bars or cylinders. With more complex shapes, the shape factor can be determined after measuring the modulus of elasticity for a bar shape out of the same material.

In a homogeneous object, a variation of less than 0.5% in several consecutive measurements of the same part is typical when measuring refractories. If the object is heterogeneous, the variation will be higher than 0.5% as it relates to the envelope of the irregular sinusoid. Finally, a cracked object will give dispersed values between different measurements.

Samples and tests

Six lots of fireclay brick were at our disposal from three different manufacturers in two different formats—types 2P10 and 3P10 (trapezoidal brick in the direction of thickness). For each manufacturer and for each type of brick, seven pallets of 240 brick each were chosen.

Five brick were selected from each pallet for visual inspection and to check dimension and weight. For the sonic test, 25 additional brick were selected from each pallet.

Based on the results of the sonic test, we selected 10 good brick from each lot. Results obtained were used to determine the apparent brick density, overt porosity, cold modulus of rupture, cold crushing strength and the weight loss under turbulence after 500 rotations. This method of selection increased the standard deviation and the deviation coefficient of the sample chosen. However, it allowed us, with only a limited number of costly and time-consuming tests, to find the relationship between physical properties and the modulus of elasticity.

Statistically, such a selective procedure is not permitted. Yet because we only were verifying known principles, testing on a limited number of samples was desired.

Results obtained

Histograms were developed representing the number of brick within the same intervals of resonant frequency or class for each manufacturer format. For each lot there are histograms for:

- The 210 brick tested;
- The first 35 brick with aspect, dimension and weight controls;
- Brick with a clear crack discovered during visual inspection (always as a function of the Grindo-Sonic reading).

A distribution similarity is found,

Table 1. Physical Properties as a Function of Modulus of Elasticity

type size	Manufacturer	Apparent Density	Overt Porosity (%)	Cold M.O.R. (daN/cm²)	Cold Crushing Strength (daN/cm²)	Weight loss under turbulence (%)
2P10	A	y=0.000313 x +2.02 r=0.79	y= −0.06 x + 22.11 r=0.83	y=1.91 x + 36.85 r=0.62	y= −0.82 x + 251 r=0.10	y= −0.23 x + 19 r=0.42
	B	y=0.00233 x +2.15 r=0.61	y= −0.11 x + 17.20 r=0.65	y=2.74 x + 27.25 r=0.82	y=1.60 x + 315 r=0.13	y= −0.08 x + 13.62 r=0.10
	C	y=0.00322 x + 2,08 r=0.79	y= −0.21 x +18.09 r=0.94	y=4.09 x − 11 r=0.79	y=19.1 x + 315 r=0.86	y= −0.31 x + 16.36 r=0.81
3P10	A	y=0.0125 x + 1.92 r=0.96	y= −0.29 x + 24.16 r=0.69	y=3.06 x + 21.53 r=0.97	y=12.43 x + 106.5 r=0.94	y= −0.93 x + 29.22 r=0.86
	B	y=0.00339 x + 2.12 r=0.73	y= −0.03 x + 17.55 r=0.87	y=0.85 x + 54.55 r=0.90	y=4.24 x + 216 r=0.64	y= −0.32 x + 24.22 r=0.84
	C	y=0.00427 x + 2.05 r=0.73	y= −0.20 x + 18.08 r=0.87	y=3.34 x + 16.97 r=0.90	y=9.63 x + 248 r=0.64	y= −0.37 x + 17.51 r=0.84

The ladle brick from manufacturer A are siliceous-argillaceous, 24% to 30% alumina; those of manufacturer B, 24% to 29% alumina; and brick from manufacturer C with 18% alumina.

Table 2. Distribution of Physical Properties

Type size	Manuf.		Apparent Density	Overt Porosity (%)	Cold Modulus of Rupture (daN/cm²)	Cold Crushing Strength (daN/cm²)	Modulus of Elasticity (kN/mm²)	Weight loss under turbulence (%)	Notes
2P10	A	$\bar{m}$	2.021	21.49	57.74	239	11.79	16.3	Very homogeneous population
		σ	0.006	0.34	5.83	15.4	1.83	0.9	
		σ m	0.3	1.6	10.1	6.5	15.5	5.4	
	B	$\bar{m}$	2.19	15.46	72.3	341	16.43	12.24	
		σ	0.014	0.0	12.5	44.5	3.72	3.5	
		σ/m	0.65	3.9	17.3	13	22.7	28.9	
	C	$\bar{m}$	2.157	12.69	94.47	564	25	8.2	
		σ	0.025	1.46	32.86	134	6.44	2.49	
		σ/m	1.14	11.5	34.8	23.85	25.8	30.4	
3P10	A	$\bar{m}$	2.039	21,43	50.63	225	9.52	20.35	
		σ	0.032	1.05	7.96	33.4	2.5	2.7	
		σ/m	1.59	4.9	15.7	14.8	26.5	13.4	
	B	$\bar{m}$	2.217	16.69	78.3	335	28	15.38	2 Population Families
		σ	0.05	0.55	16	85	9.3	7.26	
		σ/m	2.4	3.3	20.4	25.4	33,2	47.2	
	C	$\bar{m}$	2.13	14.	84	441	20.1	9.88	
		σ	0.027	1.06	16.9	68	4.5	2.09	
		σ/m	1.25	7.6	20.1	15.5	22.5	21.1	

Whatever the format for homogeneous lots, the modulus of elasticity and the mechanical properties at room temperature increase in the order of the suppliers: A, B and C. The dispersion also increases in the group of samples chosen to obtain the maximum variation of properties.

whatever the number of brick in the sample, including brick with cracks. This means a limited number of brick will represent the lot. In addition, it means there is no interference of the reading with the level of noted defects because cracked brick also are distributed.

A more in-depth study is necessary to determine whether the sonic method is capable of a valid aspect control.

The more normal the distribution, the lower the standard deviation coefficient (see lot 2P10A example). The distribution is bimodal when two production batches are mixed, as in lot 3P10B. Brick with a high modulus of elasticity (low reading) have a high density, a few having cracks parallel to the large face. Brick with a low modulus of elasticity are colored differently. They are more porous and have a lower density. Finally, the distribution can be more or less dissymetric as is the case with 3P10A, accordant with a more or less high-standard deviation coefficient.

Physical properties

The values of the elastic moduli, the apparent density, the overt porosity, the cold modulus of rupture and the cold crushing strength, as well as the weight loss under turbulence were measured.

The modulus of elasticity is expressed in kN/mm² or GPa. The turbulence test places a cube with an edge of 50 mm of the material under study in a metallic cube of 300 mm, which rotates around one of its diagonals. The cube's weight loss is measured after a number of rotations. This test also indicated the cohesion of the material undergoing repeated shocks.

A good correlation between the different properties and the modulus of elasticity was obtained—except in two specific cases (see Table 1). In these cases, the variation in modulus of elasticity was limited (2P10A), meaning the results are closely grouped. Or, this dispersion was high because the distribution was bimodal, and there are two families of samples (3P10B). These correlations are most significant for manufacturer C.

The apparent density, the modulus of rupture and the cold crushing strength increase with the modulus of elasticity. Porosity and weight loss under turbulence decrease, therefore, cohesion increases.

Comparing products of different chemical and mineral compositions only can be viewed with caution, however. The in-service behavior of the product of manufacturer C was superior to the others tested.

As for the selective brick group tested destructively, the dispersion is sensitively the double of the different lots as a whole.

Conclusions

The sonic test performed at room temperature on a random lot of refractory products with given characteristics (i.e. quality, shape and dimension) provides information on the variation of the lot and mechanical property values at room temperature.

This quick determination of the resonant frequency, which permits investigation of a large number of pieces, does not replace aspect and dimension controls. It is complementary and can be done simultaneously. Also, a small crack in the edge of an object will have no influence on the modulus of elasticity, but can be the beginning of a rupture under thermal shock.

Where guaranteed performance is essential, the sonic measurement allows systematic control and selection of identical objects, but only after acceptance limits have been established through experimentation. □

Editor's note: This article has been adapted from a revised edition of a paper presented in 1980 to the Refractories Commission of the ATS by Dr. Jean Petit. Resonant frequency measurements were preformed at Sacilor-Sollac with a Grindo-Sonic instrument on loan from the Minerals & Refractories Laboratory. The Sacilor-Sollac steelmaking group has plants at Dunkerque, Florange and Fos-sur-Mer, France. Destructive tests were performed at the Science Faculty of Nancy, France.

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