PRACTICAL USE OF A NON-DESTRUCTIVE METHOD FOR TESTING REFRACTORIES

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ABSTRACT

The accuracy and advantages of the non-destructive resonant frequency technique (impulse excitation technique) for the final inspection of conventional refractory products are discussed. Mathematical models and correlations for alumina brands are presented.

1. INTRODUCTION

Only a small portion of shaped refractory products, usually high quality, high priced refractories, use non-destructive testing (NDT) for final inspection. The larger volume of conventional products are still inspected the destructive way. The low cost of the refractories tested, the compliance with the ASTM standards, the time-consuming development of the statistical correlations and occasionally difficult interpretation of the non-destructive readings are the major forces against a broad acceptance of the NDT methods as a standard quality control tool.

2. QUALITY CONTROL PARAMETERS IN THE FINAL INSPECTION AND THE NDT CONTRIBUTION

The final inspection of any conventional shaped refractory product is usually limited to the random examination of dimensional accuracy, porosity, density, and one property from the category of strength, either cold modulus of rupture or cold crushing strength. Based on the inspection results, the compliance of each production lot to the internal quality control standards is determined. The disadvantages are obvious. The most apparent are the destruction of the product, late knowledge of the property results, labor expense and small sampling frequency, which many times is statistically insignificant. On the other hand, the NDT can produce more meaningful statistical information about structural integrity, strength, density, porosity, crack location, and even abrasion resistance and hot properties of refractory products.

The Ultrasound Method and Resonant Frequency Technique are probably the two most versatile methods which are presently used for inspection testing of refractories The Ultrasound Method is commonly used for the testing of the structural integrity of the slide gates. The Resonant Frequency Technique is a fast tool for determining the Modulus of Elasticity (E). E correlates to a number of physical properties. How these correlations can be utilized for practical purposes of final inspection is the subject of the following discussion.

3. RESONANT FREQUENCY TECHNIQUE

The dynamic Modulus of Elasticity Ed [7] relates to the resonant frequency according to the equation:

$$Ed = \frac{10^{-7}}{981} \quad 4\ L^2\ N^2\ d \qquad \{1\}$$

where: L = Dimension of the specimen
N = Frequency
d = Density

Depending on the position of the sample and the direction of the vibration, the desired resonance can be measured in any one of three modes : flexural, longitudinal, or torsional. For the majority of the refractory shapes, the flexural mode is the most suitable.
It also yields the simplest interpretation of the results.

The frequency of the flexural resonance vibration of the tested solid sample with a near rectangular cross-section relates to the Modulus of Elasticity [2] according to the equation:

$$Ed = \frac{0.94642\ p\ l^4\ R^2}{t^2}\ T \qquad \{2\}$$

where: p = density of the sample
l = length of the specimen
R = resonance frequency
t = cross-sectional dimension in the direction of vibration
T = correction factor

T, according to [2], relates to the shape of the specimen and to Poisson's Ratio:

$$T = 1+6.585(1+0.0752\mu+0.8109\mu^2)(t/p)^2 -0.868(t/l)^4$$

$$- \frac{8.34(1+0.2023\mu+2.173\mu^2)(t/l)^4}{1+6.338(1+1.14081\mu+1.536\mu^2)(t/l)^2} \qquad \{3\}$$

μ = Poisson's ratio

Equations {2} and {3} and some other modifications are the basis for many available computer programs and allow for easy computation of Ed from the resonance frequency readings. In addition, the equipment for the determination of the resonant frequency is usually supplied with the appropriate software.

After successful calculation of the Ed, the information about the density and porosity of the tested sample is within reach. Presumably, Ed is directly related to the volumetric composition of the brick:

$$Ed = aVp + bVs \qquad \{4\}$$

where: Vp, Vs are volumetric % of the solids and pores in the sample.
a, b are constants generated from the experimental results.

Direct modification of the equation {4} are:

$$Ed = aVp + b(100-Vp) \qquad \{5\}$$

and

$$Ed = 100b - (a-b)Vp \qquad \{6\}$$

100b and (a-b) are constants, so the equation {6} can be rewritten as:

$$Ed = A + BVp \qquad \{7\}$$

where 100b = A and (a-b) = B

Equation {7} tells that the Modulus of Elasticity is linearly related to the porosity of the brick.

Similar procedure would result in relation:

$$Ed = C + DBd \tag{8}$$

where Bd is the bulk density of the brick.

There are two existing options that relate the modulus of elasticity to the modulus of rupture (MOR). MOR relates directly to resonant frequency:

$$MOR = a\ e^{bR} \tag{9}$$

or, according to {3}, directly to Ed:

$$MOR = G + KE \tag{10}$$

The coefficients a and b from {9} must be generated for every shape and brand of the brick, G and K from {10} are valid for the whole brand, regardless of the shape. To simplify the actual final inspection, it is easier to work with the equation {10}. This leads to having only one set of empirical equations : {7}, {8} and {10} for one mix composition.

4. DEVELOPMENT OF THE "BRAND" EQUATIONS AND SHAPE FACTORS

The next step is to generate the required coefficients A, B, C, D, G and K for the equations {7}, {8} and {10}. The equations represent a linear relationship between one independent variable and can be easily calculated through statistical regression analysis on any group of experimentally attained data.

As an example, the Ed data for 70% alumina brick (size 229 x 114 x 63 mm) were correlated to the porosity, bulk density and modulus of rupture values from conventional destructive tests. The statistical regressions resulted in a set of equations:

$$\text{Porosity} = 26.12 - 0.35Ed \tag{11}$$

with $r = 0.893$

$$\text{Bulk density} = 2.2989 + 0.00953Ed \tag{12}$$

with $r = 0.871$

$$MOR = 81.73 + 57.74Ed \tag{13}$$

with $r = 0.935$

"r" is the probability index which describes the accuracy of the regression to a straight line. The optimum value of the r index is 1. In our case, the r values from the regression studies indicate a fair degree of correlation, especially if we consider the fact that an experimental group of brick utilized for the regression correlations consist of 50 bricks.

Equations {11}, {12} and {13} are valid for the majority of other brick shapes. We experienced very consistent calculated values for porosity, bulk density and MOR with the actual readings from the conventional destructive tests. For some shapes, the distribution of the NDT results was consistently shifted to the left or to the right from the median value of the results attained through the conventional destructive way.

The simple shape factors:

$$Fn = (100 - DEV)/100 \qquad \{14\}$$

were implemented for these cases.

n = index referring to the shape and property.

DEV = (NDT reading - Destructive reading) and represents an average deviation between the NDT and destructively attained results from a statistically significant group of samples.

In this example, the investigation of a 25 brick group of #2 wedges (229 x 114 x 76 mm) from different manufacturing lots showed a consistent shift of the NDT porosity results compared to the results from the destructive tests. The average deviation was -4.4%, which according to {14} resulted in a shape factor F = 1.044.

Equations {11}, {12} and {13} for the specific brick shape of our 70% alumina brand can be adjusted accordingly:

$$\text{Porosity} = Fn(26.12 - 0.35Ed) \qquad \{15\}$$

$$\text{Bulk density} = Fn(2.2989 + 0.00953Ed) \qquad \{16\}$$

$$\text{MOR} = Fn(81.73 + 57.74Ed) \qquad \{17\}$$

It has to be pointed out that the equations {15}, {16} and {17} are valid for only one brand and one distinctive manufacturing process. The raw material selection and the firing conditions could especially affect the values of the regression coefficients.

CONCLUSION

Through resonant frequency measurements of conventional shaped refractory products, the dynamic Modulus of Elasticity (Ed) can be determined. Mathematical models can correlate the dynamic Modulus of Elasticity to properties which are now determined through destructive testing.

Non-destructive testing is a valuable quality control tool for final inspection testing of conventional shaped refractory products. This provides an accurate and cost-effective means of assuring desired final properties.

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