ELSEVIER

International Journal of Minerals, Metallurgy and Materials
Volume 16, Number 5, October 2009, Page 487

Minerals

Determination of discontinuities in marble blocks *via* a nondestructive ultrasonic technique

Ahmet Hakan Onur[1] *and Sefa Bakrac*[2]

1) Faculty of Engineering, Mining Engineering Department, Dokuz Eylul University, 35160 Tinaztepe Buca, Izmir, Turkey
2) MSc in Mining Engineering, Turkish General Directorate of Mineral Research and Exploration, Istanbul Cad. No.63 Bornova Izmir, Turkey
(Received 2008-10-06)

Abstract: Miners working in the marble industry have always been interested in identifying structural weaknesses in marble blocks before they are transported to marble processing plants. To achieve this difficult task, several simple methods have been developed among miners but observation-based methods do not consistently provide satisfactory results. A nondestructive method developed for testing concrete could be used for this purpose. In this study, this simple method based on differences in ultrasonic wave propagation in different materials was presented, and the test results performed both in the laboratory and a marble quarry were discussed.

Key words: nondestructive test; marble; discontinuity; ultrasonic wave

1. Introduction

The velocity of ultrasonic pulses traveling in a solid material depends on the density and elastic properties of that material. The quality of some materials is sometimes related to their elastic stiffness, such that the measurement of ultrasonic pulse velocity in these materials can often be used to indicate their quality, as well as to determine their elastic properties. When ultrasonic testing is applied to marble blocks, its objective is to detect internal flaws that send echoes back in the direction of the incident beam. These echoes are detected by a receiving transducer. The measurement of the time taken for the pulse to travel from the surface to a flaw and back again enables the position of the flaw to be located [1-3].

This ultrasonic testing technique was originally developed for assessing the quality and condition of concrete. One instrument used for this purpose is known as PUNDIT. The apparatus has been designed especially for field testing, being light, portable, and simple to use. Simple correlations between concrete strength, concrete aggregate gradation, water-cement ratio, and curing time have been analyzed using PUNDIT [4]. Several articles have been published on the subject of defining the mechanical properties of several different materials apart from rock by nondestructive test methods based on ultrasonic wave propagation [5-7].

There has been a rapid increase in the demand for natural materials to be used in construction engineering, interior decoration, and urban fitting. Over the years, there has been no shortage of quarried blocks, but problems have been encountered in providing sufficient numbers of high quality marble blocks. Blocks of commercial size are directly extracted from the massif. In the case of homogeneous rocks having constant features, structural discontinuities affect the marketability of the blocks. It is important to identify such abnormalities in the marble before the cutting process is performed in order to save money and time. The possibility of finding these structural defects using ultrasonic pulses has been studied, and promising results were obtained. This study concentrated on the relationship between structural discontinuities and ultrasonic pulse traveling velocities in nonhomogeneous marble blocks. Mathematical formulations were developed to find the exact locations of the surfaces that cause a separation during the cutting process [8-11].

2. Elastic constants and waves

The principle of the ultrasonic testing method is to create waves at a point and determine the time of arrival at a number of other points for the energy that is reflected by the discontinuities between different rock surfaces. The positions of the discontinuities can be

Corresponding author: Ahmet Hakan Onur, **E-mail:** ahmet.onur@deu.edu.tr

deduced from the time of arrival. The basis of these acoustic methods is the theory of elasticity. The elastic properties of substances are characterized by elastic moduli or constants that specify the relationship between stress and strain. The strains in a body are deformations, which produce restoring forces opposed to the stress. Tensile and compressive stresses give rise to longitudinal and volume strains, which are measured as unit changes in length and volume under pressure. Shear strains are measured by deformation angles. It is usually assumed that the strains are small and reversible, that is, a body resumes its original shape and size when the stresses are relieved. If the stress in an elastic medium is released suddenly, the condition of strain propagates within the medium as an elastic wave. There are several kinds of elastic waves as follows.

In longitudinal, compressional, or P waves, the motion of the medium is in the same direction as that of wave propagation. These are ordinary sound waves. Their velocity is given by [12]:

$$V_{\mathrm{p}} = \left(\frac{k4\mu/3}{\rho}\right)^{1/2},$$

where ρ is the density, k the bulk modulus, and μ the shear modulus of the medium.

In transverse, shear, or S waves, the particles of the medium move at right angles to the direction of wave propagation, and the velocity is given by [13]:

$$V_{\mathrm{s}} = \left(\frac{\mu}{\rho}\right)^{1/2}.$$

If a medium has a free surface, there are also surface waves in addition to the body waves. In Rayleigh waves, the particles describe ellipses in the vertical plane that contains the direction of propagation.

Love waves are another type of surface waves. These are observed when the S wave velocity in the top layer of a medium is less than that in the substratum. The particles oscillate transversely to the direction of the wave and parallel to the surface. Love waves are thus essentially shear waves.

The frequency spectrum of body waves in the earth extends from about 15 to about 100 Hz; surface waves have frequencies lower than about 15 Hz [14]. For the method described in this study, P waves are of importance as an exploration tool. For the materials like concrete and marble, the useful frequency range is from 20 to 250 kHz.

3. Application of pulse velocity testing

For assessing the quality of marble blocks by the ultrasonic pulse velocity measurement, it is necessary to use an apparatus that generates suitable pulses and accurately measures the time of their transmission through the material. The instrument indicates the time taken for the earliest part of the pulse to travel from the transmitting transducer to the receiving transducer when they are placed at suitable points on the surface of the material. The distance that the pulse travels in the material must be measured to determine the pulse velocity:

$$\text{Pulse velocity}=\frac{\text{Path length}}{\text{Transit time}} \tag{1}$$

Fig. 1 shows how the transducers may be arranged on the surface of the specimen. The transmission can either be direct, indirect, or semi-direct.

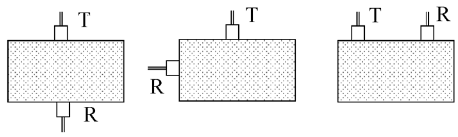

Fig. 1. Methods of propagating ultrasonic pulses.

The direct transmission arrangement is most useful since the longitudinal pulses leaving the transmitter are propagated mainly in a direction normal to the transducer face. The indirect arrangement is possible because the ultrasonic beam of energy is scattered by discontinuities within the material tested, but the strength of the pulse detected in this case is only about 1% or 2% of that detected for the same path length when the direct transmission arrangement is used. The purpose of the current study is to develop a method to be used in a stone quarry, so semi-direct and indirect transmissions should used as the main measurement techniques since it is sometimes very difficult to find free faces to place transducers on the working area in a quarry.

Pulses are not transmitted through large air voids in a material, and if such a void or discontinuity surface lies directly in the pulse path, the instrument will indicate the time taken by the pulse that circumvents the void by the quickest route. It is thus possible to detect large voids when a grid of pulse velocity measurements is made over a region in which these voids are located. By using this phenomenon, acoustic methods can be used to test rock strata and provide useful data for geological surveys.

4. Laboratory work on simulated models

A concrete model was designed in the laboratory to investigate the behavior of ultrasonic pulses traveling through a simulated discontinuity surface inside the block. A wooden surface was cast into the block with the dimension shown in Fig. 2.

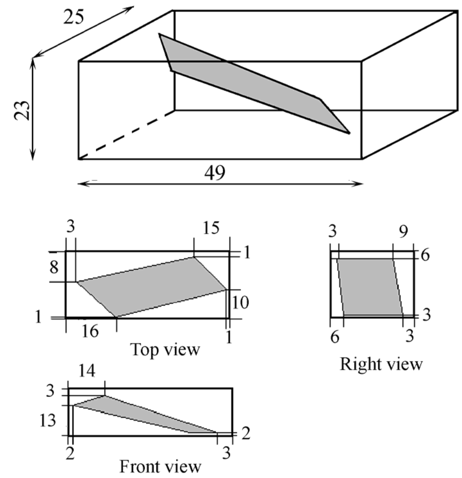

Fig. 2. Prepared concrete blocks and the dimension of the discontinuity surface (unit: cm).

Before assessing the effects of the simulated discontinuity on pulse velocity, pulse velocity measurements were made near the simulated surface. These measurements give the real pulse velocity for the prepared concrete block. For this purpose, three direct measurements from three free surfaces were obtained. The result is given in Fig. 3.

For later use, a linear equation was fit to the line shown in Fig. 3.

$$T=2.52L-3.39\ (\mu s) \tag{2}$$

where T is the measured pulse traveling time, and L is the length between probs.

In this equation, 2.52 is the slope of the linear line; however, –3.39 can be interpreted as the pulse velocity measurement error because T never takes negative values when the length L is equal to 0.

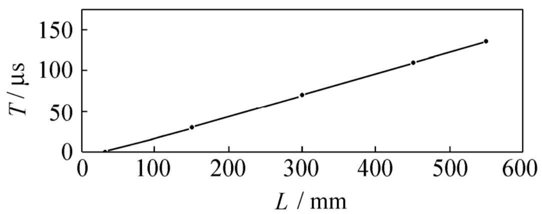

Fig. 3. Pulse velocity determination for the homogenous concrete block.

The measurement of pulse velocities at the points that are not affected by the simulated surface provides a reliable method of assessing the pulse velocity behavior of the homogenous concrete block. It is useful to plot a diagram of pulse velocity contours from the measurement results since this gives a clear picture of the variation extent. It should be appreciated that the path length can influence the recorded variation extent because the pulse velocity measurements correspond to the average quality of the concrete. When an ultrasonic pulse traveling through concrete meets a simulated surface, there is a negligible transmission of energy across this interface so that any air-filled cracks or voids directly between the transducers will obstruct the direct beam of ultrasound energy when the void has a projected area larger than the area of the transducer faces. The first pulse to arrive at the receiving transducer will have been diffracted around the periphery of the defect and the transit time will be longer than that in similar concrete with no defect.

In order to detect the simulated surface, pulse velocity measurements were performed over three different directions through the concrete block on a grid of 2.5 cm× 2.5 cm. The results are given in Figs. 4-6.

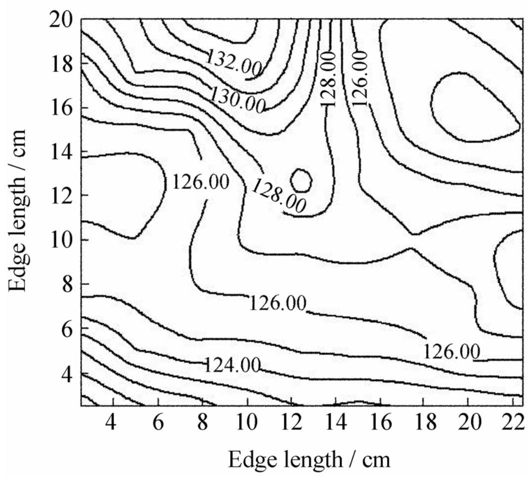

Fig. 4. Contour plotting of the transmission time (μs) taken from the right face.

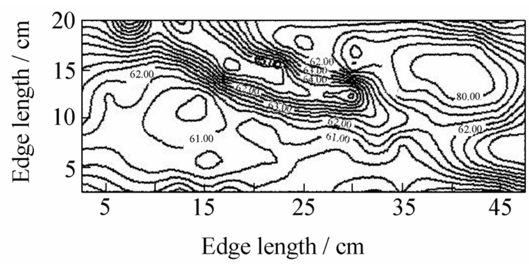

Fig. 5. Contour plotting of the transmission time (μs) taken from the front face of the model.

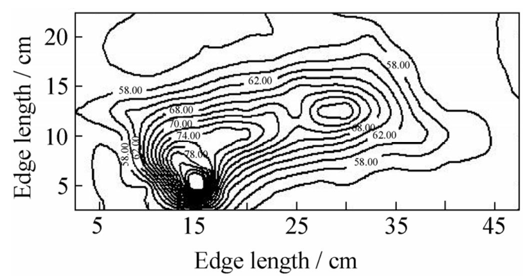

Fig. 6. Contour plotting of the transmission time (μs) taken from the top of the model.

As shown in Figs. 4-6, it is possible to detect the size and the position of the simulated discontinuity surface. Such estimates are more reliable if the discontinuity surface has a well-defined boundary surrounded by uniformly dense concrete.

5. Modeling the boundary of discontinuities

The shape and size of any abnormality in a block can be determined by direct measurements taken from suitably spaced grids. It is important to find the exact position of the surface in marble blocks so that precautions can be taken before the cutting process starts. As stated before, if any discontinuity surface lies in the pulse path, the measured time corresponds to the pulse that follows the shortest path. This is important because any discontinuity causes a time delay compared with the travel time of pulses in homogenous blocks. This case is shown in Fig. 7.

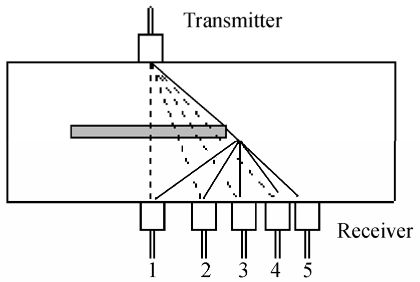

Fig. 7. Cause of time delay of pulses.

Before doing any measurement, the pulse velocity behavior of the homogenous material must be obtained as discussed above. By doing so, it becomes possible to estimate the pulse travel time if no abnormality exists in the block. It is necessary to measure the direct distance between the transmitter and receiver in order to estimate the travel time of pulses. The pulse velocity measuring device gives the minimum traveling time between two points. The pulse velocity is obtained by dividing the path length by the transit time. There will be a difference between the measured pulse velocity and the velocity obtained from Eq. (2) by applying path length L in it. This difference is an indicator of a time delay caused by longer traveling distances due to an obstacle in the travel path (dashed and direct lines in Fig. 7). The time delay will be used later to find the correct position of the defect surface in 3D.

Fig. 8 depicts the situation clearly. In this figure, there are two types of curves on the graph. The linear curve represents the direct distance from transmitter to receiver; the parabolic curve represents the longer path of pulses following the boundary of a discontinuity. Both figures can be obtained from measurements in which the receiver moves from position 1 to position 7, whereas the transmitter is fixed.

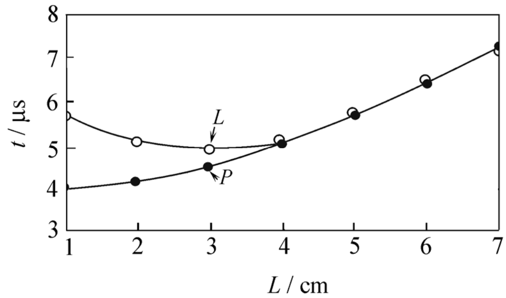

Fig. 8. Difference between the direct distance and the pulse travel distance.

There are two different curves in Fig. 8. The first one is the curve obtained from the measured pulse travel times (shown as L) between transmitter and receiver, the second one is the direct distance (shown as P) according to the receiver position from 1 to 5. There is a large difference between the two lines showing that the pulse travel path to the position of receiver 1 is interrupted by the discontinuity surface. Although the receiver moves along a line in equal increments from position 1 to 5, the gap between two lines narrows steadily. This behavior gives a very important clue about the boundary of the discontinuity surface. In the second region of the graph, from receiver position 5 to 7, the two lines meet. This behavior indicates that there is no discontinuity surface between the transmitter and receiver. This process defines the boundary in the longitudinal direction but not in the vertical. As shown in Fig. 9, the discontinuity can be at any position of h that is the vertical distance of the surface from the top of the block.

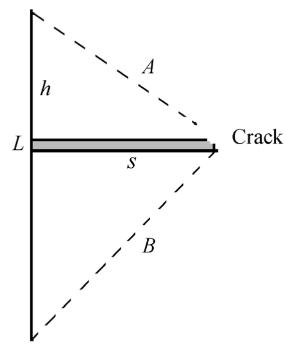

Fig. 9. Pulses moving around the crack.

Let's take s as the length of the crack, h is the vertical distance from the upper surface, $A+B$ is the path of a pulse traveling from the transmitter to the receiver, and L is the shortest distance between the two transducers. The pulse travels the distance $A+B$ instead of L.

$$Ls=A+B \tag{3}$$

Some simple linear algebra can be used to obtain h and s, giving the boundary location (S) of the discontinuity.

$$S=\sqrt{\frac{h^2-(L-h)^2}{2Ls}+\frac{Ls}{2}-h^2} \tag{4}$$

Eq. (4) is a function of the vertical distance h. In this formula, both s and h are unknown. The purpose of Eq. (4) above is to define h and s. In Eq. (4), if h changes from 0 to L and s is plotted, Fig. 10 can be obtained. In this process, the only measurements that can be obtained are the directly measured L and A+B that is estimated from the linear equation (Eq. (2)) for the homogenous material.

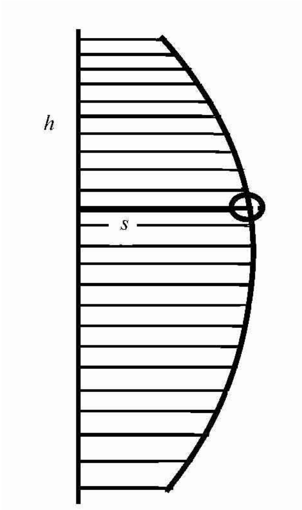

Fig. 10. Curve that shows possible paths obtained from a single measurement.

When the receiver moves to position 2 in Fig. 7, the same measurements are made to plot a second curve. Both figures are combined to obtain an intersection point that gives the correct position of the boundary, and h and s can be determined (Fig. 11).

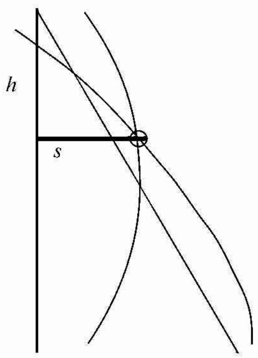

Fig. 11. Combined curves giving *h* and *s*.

Obtaining h and s is very important because if the receiver moves in four different directions, then four different h and s can be obtained in different directions. The receiver moves in such a way that the different h and s taken together enable us to find the exact boundary shape of the discontinuity in 3D.

Finding the h and s values is a time consuming process, so a computer program has been written to analyze the measurements and plot the entire finding. For a better understanding, Fig. 12 must be explained first.

Considering Fig. 12, the values that can be obtained from measurements are as follows.

L_1: the direct distance from transmitter to the receiver at position 1;

L_2: the direct distance from transmitter to the receiver at position 2;

S_1: the length of pulse traveling path for the receiver at position 1;

S_2: the length of pulse traveling path for the receiver at position 2;

Art: the distance between the receivers at position 1 and 2.

With an iteration of Eq. (4) for both measurements on the same plane, only one point equals h and s. The problem is to find this point that is the boundary of the discontinuity surface.

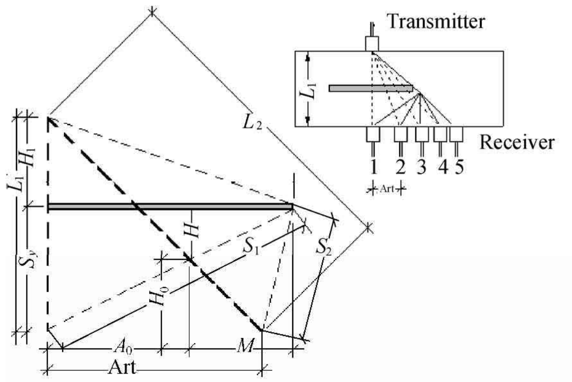

Fig. 12. Pulse traveling paths for both receiver positions.

To verify the model explained in previous section, a cubic homogenous marble block with a certain cut inside was prepared. The dimensions of the block and cut are shown in Fig. 13.

The transmitter is placed on the top of the block 12 cm away from the left side and 13 cm away from the front face. The receiver was moved along the front face of the block in a 2.5 cm×2.5 cm grid pattern (Fig. 14).

Before the pulse traveling times are taken, direct measurements were used to obtain the standard linear equation for the homogenous marble block:

$$T=0.877L+7.287\ (\mu s) \tag{5}$$

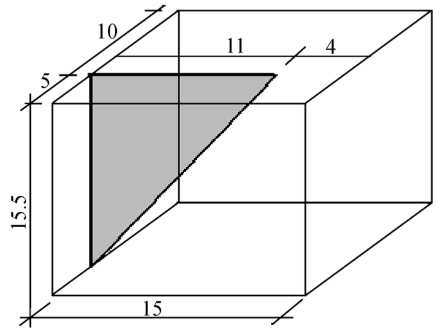

Fig. 13. Block model dimension (unit: cm).

Table 1 shows the measured times for 9 different receiver positions according to Fig. 14.

Table 1 is made up of 4 sections. The first one is the direct measurement taken from the instrument. By using the linear behavior of the homogenous block given in Eq. (5), standard traveling times are calculated for the case where no cut exists in the path of the probes. These calculated times are given in the second section of Table 1. The exact distances are measured and given in the third section. The last section is the calculated pulse path length obtained from the measured traveling time as discussed previously. Receiver position (1, 1) has the highest measured traveling time, showing the pulse travels the longest path to reach the receiver (according to the first section in Table 1). This indicates that a crack exists between the two transducers. When the receiver is moved to position (3, 3), there is no difference between the measured traveling time and the standard traveling time, indicating there is no obstacle between the two transducers. The measured traveling times and distances between the transmitter and receiver are input to the computer so that all other values can be calculated to find the exact place of the cut. The crack position located by the computer is given in Fig. 15.

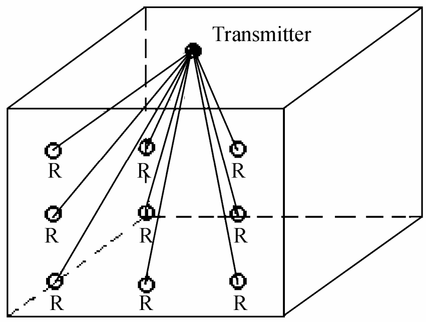

Fig. 14. Positions of transmitter and receiver.

Table 1. Measurement results

Receive position	Measured traveling time / μs			Standard traveling time / μs			Distance between the transmitter and the receiver / cm			Calculated pulse path length / cm		
	1	2	3	1	2	3	1	2	3	1	2	3
1	27	23	23	20	21	23	15	16	18	18	22	18
2	25	23	24	21	22	24	16	17	19	20	17	18
3	25	24	25	23	24	25	19	21	20	20	19	21

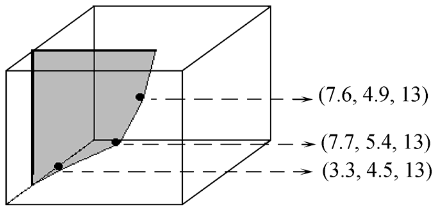

Fig. 15. Computed location of the crack.

6. Conclusion

The importance of determining whether marble blocks contain a discontinuity such as a void, crack, and cave has been presented in this work. It is also important to notice that any abnormalities in marble blocks must be found by using a simple method and without causing any damage to the main body. The method commonly used to test the quality of concrete is perfectly well suited to testing marble blocks because of its simplicity. First, experiments performed in the laboratory on a simulated block gave promising results that support the possibility of using such a technique on marble blocks. One must bear in mind that a prepared concrete block is more homogenous than natural stone. Direct measurements give a better understanding of the structure of any block, allowing the boundary of a discontinuity surface in the body to be located clearly. Nevertheless, direct measurements become very hard to apply in the field depending on the number of free faces. To develop a measurement technique that is useful in the field, semi-direct and indirect measurements have been taken on a block obtained from a marble factory. A mathematical model was applied to the block but the results showed that fixing the transmitter in a single position does not give an accurate picture of the body if there is a complicated discontinuity structure. Although it is possible to find the exact positions of discontinuities by moving the transmitter, the number of measurements increases in logarithmic scale with the number of transmitter locations. However, statistical analysis could be a way to identify complex defect structures reliably, instead of finding their exact location.

References

[1] W.R. Davis and R. Brough, Ultrasonic techniques in ceramic research and testing, *Ultrasonics*, 10(1972), No.3, p.118.

[2] S.G. Davis and S.J. Martin, *The Quality of Concrete and Its Variation in Structures*, Cement and Concrete Association, 1973.

[3] R.H. Elvery, Non-destructive testing of concrete and its relationship to specifications, *Concrete*, 5(1971). No.4. p.122.

[4] A. Saad and Abo-Qudais, Effect of concrete mixing parameters on propagation of ultrasonic waves, *Constr. Build. Mater.*, 19(2005), p.257.

[5] M. Dereman, R. Omar, A.G. Harun, and M.P. Ismail, Young's modulus of carbon from self-adhesive carbon grain of oil palm bunches, *J. Mater. Sci. Lett.*, 17(1998), p.2050.

[6] H. Tsuda, Ultrasound and damage detection in CFRP using fiber bragg grating sensor, *Compos. Sci. Technol.*, 66(2006), p.676.

[7] F. Zhang, S. Krishnaswamy, D. Fei, D. Rebinsky, and B. Feng, Ultrasonic characterization of mechanical properties of Cr- and W- doped diamond like carbon hard coatings, *Thin Solid Films*, 503(2006), p.250.

[8] R. Jones, The non-destructive testing of concrete, *Mag. Concr. Res.*, 2(1949), p.67.

[9] R. Jones, *Non-destructive Testing of Concrete*, Cambridge Press, 1962.

[10] R. Jones and E.N. Gatfield, Testing concrete by an ultrasonic pulse technique, *Road Research Laboratory, Technical Paper No. 34*, H.M.S.O., London, 1955.

[11] M.S. King, M.R. Stauffer, and B.I. Pandit, Quality of rock masses by acoustic borehole logging, [in] *Proceedings 3rd International Congress Engineering Geology*, Madrid, 1978, p.156.

[12] B.M. New, Ultrasonic wave propagation in discontinuous rock, *Transport & Road Research Laboratory, Department of the Environmental, TRRL Laboratory Report 720*, London, 1985.

[13] H.N. Tomsett, Site testing of concrete, *Br. J. Non Destr. Test.*, 18(1976), p.82.

[14] D.S. Parasnis, *Principles of Applied Geophysics*, 4th Ed., Chapman & Hall, London, 1994, p.402.