Effect of Porosity on the Elastic Properties of Materials

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Abstract: The elastic properties is an important aspect in determining the potential application of a material. Hence, this study was carried out to determine the effect of porosity on the elastic properties of materials. The ultrasonic pulse-echo immersion technique was employed in this study to determine five elastic properties of materials; Young's modulus, shear modulus, bulk modulus, longitudinal modulus and Lam constant. The nonporous and porous polymethyl methacrylate were used as samples to differentiate the elastic properties of nonporous and porous sample. The result indicated that the elastic properties of porous sample are less than the elastic properties of non-porous sample. It can be concluded that the existence of porosity in a material decreases its elastic properties.

Keywords: porosity; elastic properties; pulse-echo immersion technique

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http://dx.doi.org/10.12962/j24604682.v20i3.20656

I. INTRODUCTION

The material properties of materials are the crucial aspect in determining their potential applications in various industries. Previous studies employed various tests such as tensile test [1 - 4], shear test [5 - 11] and indentation test [12 - 16] to measure the elastic properties of materials. However, these tests has limitation in term of sample destruction. Therefore, the non-destructive testing, such as ultrasonic testing can be employed as an alternative to determine the material properties of materials [17 - 21].

Pores are fine holes found in a material. Previous studies have utilized the ultrasonic through *transmission technique* (TT) to measure the material properties of porous materials such as bone [22-25], composites [26, 27], muscle [28, 29] and ceramics [30, 31]. However, TT requires to use the coupling materials such as synthetic rubber [32] and hydrogel [33] to couple the transducer and the tested sample. The use of viscous coupling materials pose significant challenges to study the material properties of porous materials as they can block the pores, leading to the inaccurate measurement values. Therefore, previous studies utilized water as the propagation medium to replace the coupling materials to characterize the elastic properties of porous materials [34, 35].

The use of water as a propagation medium has its own set of challenges for TT as the requirement of water temperature measurement is needed as the calibration procedure before the measurement of material properties took place [36, 37]. Thus, previous studies took an initiative to employ the ultrasonic *pulse-echo immersion technique* (PEIT) to eliminate the calibration procedure [38, 39]. The PEIT also offers advantages in term of the use of single ultrasonic transducer as transmitter and receiver to measure the material properties of the tested sample [40, 41].

The existence of pores in a material significantly influences its application in specific fields [42]. Hence, the elastic properties measurement is required to understand and predict the behavior of engineering materials. However, most previous researches utilized the PEIT to determine the acoustic properties of materials; longitudinal velocity [30], [43] and attenuation coefficient [39]. Therefore, this study was performed to measure five elastic properties of nonporous and porous materials; Young's modulus (E), shear modulus (G), bulk modulus (K), longitudinal modulus (L), and Lam constant (λ) using the PEIT and polymethyl methacrylate (PMMA) as samples. Then, the values of elastic properties of nonporous materials are compared with porous materials to determine the effect of porosity on the elastic properties of materials.

II. METHOD

A. Sample Preparation

The sample of this study is made of PMMA sheet. PMMA was commonly selected as a sample in ultrasonic testing [26], [43 - 50] due to its consistent acoustic properties over a small range of ambient temperatures [51 - 53] and its mechanical properties that remain unaffected by heat changes [54]. For this study, a PMMA sheet was cut into 2 rectangular blocks with $16.00 \times 8.00 \times 0.3$ cm^3 dimensions using a laser cutter as shown in Fig. 1 (a) and Fig. 1 (b). After that, a pore for porous PMMA sample [Fig. 1 (b)] was made by drilling a hole with 1.88 mm diameter and 1.02 mm depth at the bottom side of the sample using an acrylic drill bit. The density (ρ), of both samples is 1180 kg m^{-3}, and their Poisson's ratio (ν), value is 0.339 [46].

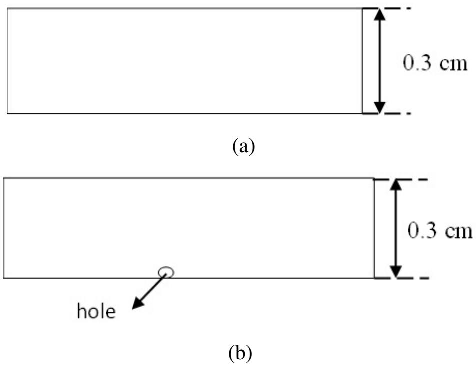

FIG. 1: Side view of (a) nonporous sample, and (b) porous sample.

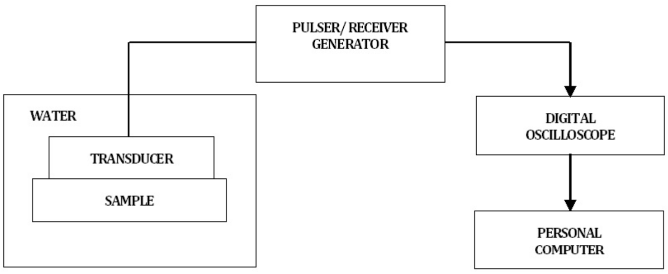

FIG. 2: Material characterization system.

B. Material Characterization System

A material characterization system was developed based on the PEIT which employs the tap water as the propagation medium. An ultrasonic pulser/receiver (Olympus Panametrics NDT model 5072PR) generates an electrical pulse and sends it to an ultrasonic transducer (Olympus Panametric NDT 10MHz) to convert the electrical pulse into the ultrasonic pulse. The pulse propagates in the sample and reflects at the back interface of the sample. The reflected pulse was received by the transducer and converted back to the electrical pulse. The received pulse was displayed on a digital oscilloscope (LeCroy Wave Surfer 42 MX-s 400 MHz 5 GS/s) and analyzed by a custom-developed program that was installed on the personal computer as shown in Fig. 2.

C. Elastic Properties

There are five elastic properties of a material to be determined in this study; E, G, K, L, and . The values of E, G, K, L and of a material are calculated from the value of , longitudinal velocity, vL and , as shown in Eq. (1) [55], Eq. (2) [56], Eq. (3) [57], Eq. (4) [56] and Eq. (5) [57].

$$E = \frac{\nu_L^2 \rho (1+\nu)(1-2\nu)}{1-\nu} \quad (1)$$

$$G = \frac{E}{2(1-2\nu)} \quad (2)$$

$$K = \frac{E}{3(1-2\nu)} \quad (3)$$

$$L = \rho \nu_L^2 \quad (4)$$

$$\lambda = L - 2G \quad (5)$$

The value of ν_L of a material is calculated from its thickness, d, and pulse transit time, Δt, as shown in Eq. (6) [57].

$$\nu = \frac{2d}{\Delta t}\lambda = L - 2G \quad (6)$$

The value of t was determined from the displayed signal on the digital oscilloscope as shown in Fig. 3.

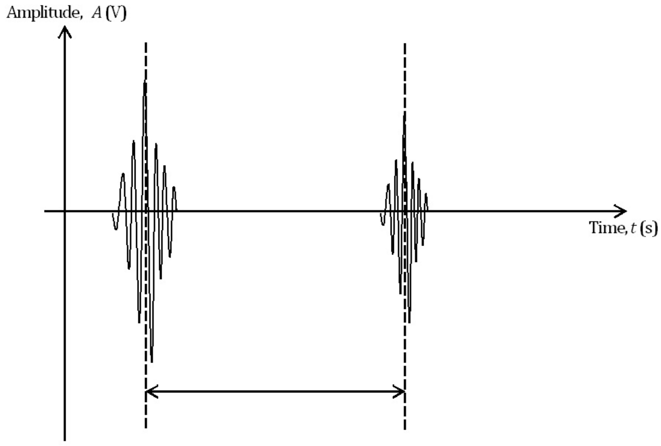

FIG. 3: An example of a signal when ultrasound propagates through a sample.

III. RESULTS AND DISCUSSION

Table I shows the comparison between the elastic properties of non-porous and porous PMMA. According to Table 1, the values of E, G, K, L and of non-porous PMMA are 6.21 GPa, 2.32 GPa, 6.42 GPa, 9.52 GPa and 4.88 GPa, respectively. Meanwhile, the values of E, G, K, L and of porous PMMA are 5.75 GPa, 2.14 GPa, 5.95 GPa, 8.82 GPa and 4.52 GPa, respectively. It indicated that the presence of pore decreases the values of E, G, K, L and of a material. The presence of pore decreases the density of a material [58, 59]. Since the elastic properties of a sample depends on its density, the elastic properties of a porous material is less than the elastic properties of a nonporous sample. However, the volume of pore (2.83×10^{-3} cm^3) in this study is much smaller compared to the volume of sample (38.4 cm^3). Therefore, the density of the porous sample is similar to the density of the nonporous sample (1180 kg m^{-3}).

TABLE I: Elastic properties of non-porous and porous PMMA.

Elastic Properties	Non-porous PMMA	Porous PMMA
E (GPa)	6.21	5.75
G (GPa)	2.32	2.14
K (GPa)	6.42	5.95
L (GPa)	9.52	8.82
(GPa)	4.88	4.52

The decreasing elastic properties of the material in this study could also be due to the change in velocity of an ultrasonic pulse as it encounters a pore in its propagation path. As the pulse strikes the front interface of the pore, it will experience the reflection and transmission phenomena [51, 60, 61]. A fraction of the pulse will reflect back to its original path and the remainder will transmit in the pore until it strikes the back interface of pore. Hence, the time taken for the pulse travel in the porous sample will be longer than in the non-porous sample. Therefore, the velocity of the pulse will be decreased as it travels in the porous material [45, 52 - 54, 62], [63]. Subsequently, the elastic properties of the material will be decreased with the presence of pore.

IV. CONCLUSION

In this study, the effect of porosity on the elastic properties of the material was successfully determined using the PEIT. The results showed the porosity decreases the elastic properties of materials. However, this study only focuses on the effect of porosity on the elastic properties of the material. Therefore, a further research is needed to determine the effect of the degree of porosity on the elastic properties of the samples.

Acknowledgments

The authors would like to acknowledge Mahmud Yunus Batusangkar State Islamic University, Indonesia, for the financial support through the SP DIPA-025-04.2.424069/2023 scholarship. The authors would also like to thank the Applied Optics Laboratory, Department of Physics, Faculty of Science and Mathematics, Sultan Idris Education University, Malaysia, for the facilities support.

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