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A New Simple Method to Measure the X-ray Linear Attenuation Coefficients of Materials using Micro-Digital Radiography Machine

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Abstract

X-ray linear attenuation coefficients have various applications in X-ray science; this work has been done to calculate the linear attenuation coefficient values in an alternative method for Plastic, Plexiglas, Silicone Rubber and Paraffin wax materials. These materials were prepared in a step-wedge triangle with 3 mm thickness different. All samples were exposed to X-ray with 30 keV and 20 mA parameters using Micro-Digital Radiography. Multiple images were captured for each sample. Then it was averaged and calculated with grayscale values by using image process program. The linear attenuation coefficient value was achieved by plotting the log of the x-ray intensity against the varying in thickness. The result as following, Plastic ABS is 0.0284 cm^{-1}, Plexiglas is 0.0436 cm^{-1}, Silicone Rubber is 0.0873 cm^{-1} and Paraffin wax is 0.0237 cm^{-1}. Compared with the results of another researcher the values of (μ) obtained indicates that there is a good agreement, and the method is appropriate to be used as an alternative method for measuring the linear attenuation coefficient of materials.

Keywords : Linear Attenuation Coefficient, X-ray imaging, Micro-digital radiography

INTRODUCTION

X-ray linear attenuation coefficients for materials are required in almost all fields in which the interaction of X-rays with matter is studied [1]. As x-ray photons passes through a material sample, the probability that interactions will occur. These interactions can be absorption of the photons or scattering (change of the photon direction). This absorption and scattering process is called attenuation. Other photons travel completely through the object without interacting with any of the material's particles. The number of photons transmitted through a material depends on the thickness, density, composition of the material, and the energy of the photons [2] [5]. The photon travelling different distances within a material is based on their encounter. The probability of photons interacting, especially with the photoelectric effect was related to their energy [3]. Increasing photon energy generally decreases the probability of interactions and, therefore, increases penetration [2]. Usually, high-energy photons are more penetrating than low-energy photons. Since the probability of an encounter increases with the distance traveled, the number of photons reaching a specific point within the object sample decreases exponentially with distance traveled. The exponential shape of the curve is described by the application of Beer-Lamberts [6].

X-ray attenuation is also usable in other fields. For example, the linear attenuation coefficient of unknown materials when exposing it to an X-ray of a known energy can also help to distinguish the material, since each element has slightly different attenuation coefficients [7]. In addition, the grayscale values of the X-ray radiograph can be used in order to calculate the linear attenuation coefficients of a material sample [7]. This application is very helpful in disciplines such as materials science, where one may want to try to investigate a sample of material without damaging it completely.

THEORETICAL CONCEPT

The linear attenuation coefficient μ characterizes the fraction of the incident x-rays beam that is absorbed or scattered per unit's thickness of the materials. The measuring unit of linear attenuation coefficient is 1/cm [8]. This value of linear attenuation coefficient mostly depends on the energy of the incident X-ray beam and the atomic number of the absorber material. The x-ray linear attenuation coefficient of a material at a particular energy can be determined by a measurement of the incident and transmitted intensity of a monochromatic and collimated X-ray beam as it passes through a parallel-faced sample. The linear attenuation coefficient is defined by the relationship in Equation (1):

$$I = I_0 e^{-\mu x} \tag{1}$$

Where I = intensity of transmitted x-rays

I_0 = intensity of incident x-rays

μ = linear attenuation coefficient of the material

x = thickness of the material

Since the factors that affect the linear attenuation coefficients are beam energy and materials thickness, therefore the total attenuation is a function of x. then it can be expressed as follows:

$$ln\left(\frac{I_0}{I}\right) = \int \mu(x)dx \quad (2)$$

$\mu(x)$ is the linear attenuation coefficient as a function of position. Assuming that the sample is uniform in the beam path then, $\mu(x)$ should be a constant. So the equation (2) can be written as:

$$\mu x = ln\left(\frac{I_0}{I}\right) \quad (3)$$

By plotting the values of $\ln(I_0/I)$ against the thickness x, the linear attenuation coefficient μ can be calculated using the linear regression method.

Based on the density of a material, linear attenuation coefficient μ is responsible for image contrast in medical radiography and industrial non-destructive testing. A precise measurements of linear attenuation coefficient require X-rays source, a sample, a detector, and collimation to refuse scattered radiation [9,10,11]. The application of Beer-Lambert's is ideally valid for monochromatic x-ray beam source. Since low energy x-ray beams are more adsorbed when it passes through materials than the higher energy X-ray beams, for polychromatic sources, it results in attenuation of a homogenous sample being not proportional to its thickness. This produces distortions and false density gradients due to the hardening of the beam. Hence, commercial radiography devices which uses x-ray sources are filtered out low energy x-rays to correct such artifacts [7].

EXPERIMENTAL DETAILS

The experimental system used to measure the linear attenuation coefficients is shown in Figure 1; consisting of a laboratory x-ray generator of a Molybdenum anode target as an x-ray radiation sources, a sample holder, water cooled process for heat transfer, and a fluorescence screen in a dark cabinet, along with a CMOS camera as the x-ray detector. The X-ray detector was coupled with an image digitizer in which it was controlled by customized software developed specifically for the radiography image acquisition. The distance from the X-ray tube to the sample is 150 mm arranged. The system named as X-ray Micro-Digital Radiography has been developed at the department of Physics in University of Gadjah Mada, Yogyakarta, Indonesia [12].

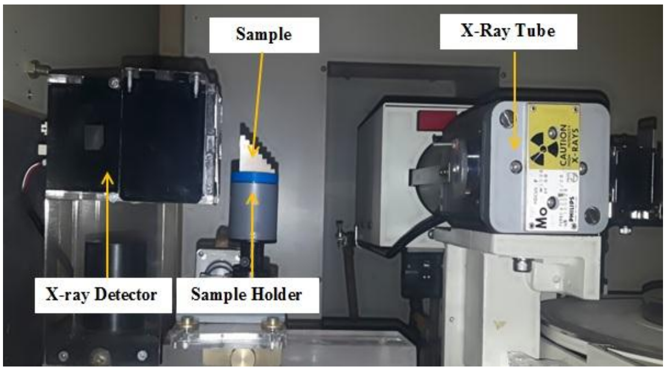

Figure 1: Experimental system arrangement setup

SAMPLE PREPARATION

The samples used to measure the linear attenuation coefficient were designed as step-wedge in a triangle shape. The dimension of the step wedge was 24 mm x 24 mm that consists of eight steps, each of which had 3 mm thickness difference between consecutive steps. According to the design, the radiograph image is expected as a series of degradations of intensities. From this image, the linear attenuation coefficient was determined from the gray scale values and plotted against the thickness of the sample. Detailed illustration of the design can be seen in Figure 2.

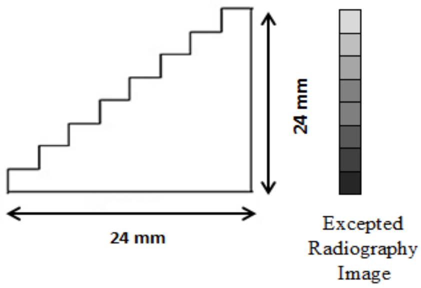

Figure 2: Sample design and expected Inverted Radiograph image

The experiment involved four kinds of different materials. Most of the selected materials used to create the experiment sample to calculate the linear attenuation coefficients values have been used as the tissue-equivalent material in dosimetry for diagnostic radiology. Table 1 illustrates the selected materials. Plexiglas (PMMA; Polymethyl methacrylate) offers easy handling and it has been reported as a tissue equivalent material [13,14]. Plastic as stated in the (AAPM) Report No.1, was used as a part of CT phantoms [15]. Paraffin has been studied to simulate the human-tissues in dosimetry for diagnostic radiology [14]. Different materials of the sample will result in slightly different linear attenuation coefficient value when exposed to the equal energy of the X-ray beam. Therefore, samples prepared in this process are expected to give variations of the linear attenuation coefficient value. Figure 3 shows the final product of the sample used in this research.

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Table 1: Materials used to fabricate the sample

No	Materials scientific name
1	Plastic ABS(Acrylonitrile butadiene styrene)
2	Plexiglas PMMA (Poly(methyl methacrylate)
3	Silicone Rubber (polysiloxanes)
4	Paraffin wax (Paraffin wax petroleum)

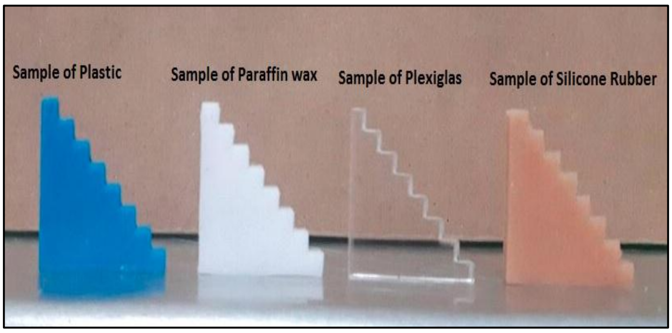

Figure 3: Manufactured samples

MEASUREMENT PROCEDURE

The measurement process began with the preparation of the Micro-Digital Radiography System, including setting the X-Ray energy to 30 keV and 20 mA. Placing the sample on the top of sample holder continued with capturing five radiography images for each sample by using the system. As an advantage the system was able to capture several images in a short period of time while assuming there are no significant changes in the sample being imaged [16]. The results of the radiography images for all samples are shown in Figure 4 then they were averaged into one image using image process. After averaging the five images of radiograph, an average image obtained used to calculate the gray scale values of the initial intensity (I_0) and the transmitted intensity (I_X) for each step in the sample by selected Region of Interest (RoI) where sample details presented as shown in Figure 5. In order to perform the measurement of the x-ray linear attenuation coefficients of the samples materials, the x-ray intensity (ln I_0/I) was determined from the grayscale values of the Region of Interest (RoI) and plotted against the thickness (x) of the sample. According to all samples which were scanned on the Micro-Digital Radiography the linear relationship was observed between log of x-ray intensity (ln I_0/I) and the thickness of x verifying the Beer-Lambert's law.

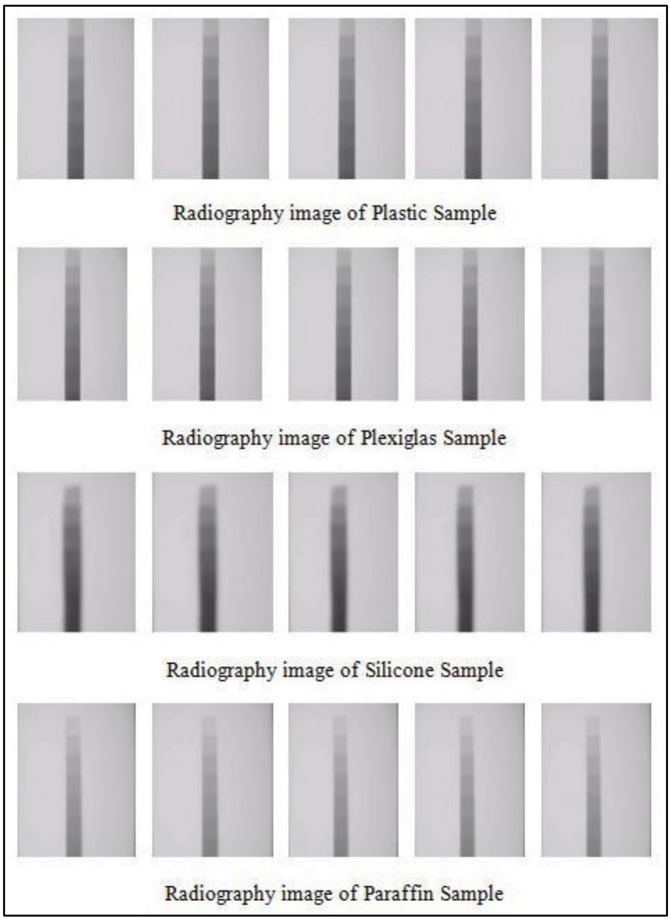

Figure 4: Radiography images of all samples

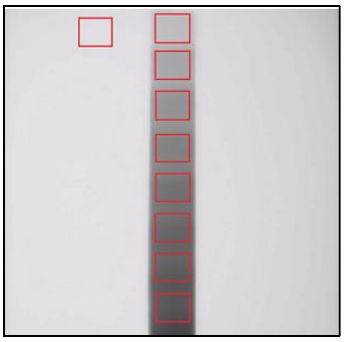

Figure 5: Calculation of the gray scale of the average image intensity

RESULT AND DISCUSSION

In the present study, linear attenuation coefficient measurements were performed on four materials using an X-ray Micro Digital Radiography system, the experiment results show that the radiation intensity can be weakened after the interaction between x-ray radiations with object sample of known thickness. As sample thickness is essential for the calculation of the X-ray attenuation, It should be done with accurate measurements geometries. The samples thicknesses were made as a step-wedge triangle that consists of eight steps. Each step had 3 mm thickness difference. The average of radiography images obtained for each material sample is shown in Figure 5. Table 2 shows the comparison value of (ln I_0/I) for all thicknesses and materials. It illustrates that as x increases the value of (ln I_0/I) will increase. This indicates that the logarithmic value of intensities ratio has a linear relationship with object thickness which can be referred from the equation 3.

Table 2: The linear attenuation coefficients measurement for the all samples

No	X (mm)	In $(^{I_0}/_I)$			
		ABS	Plexiglass	Silicone Rubber	Paraffin wax
1	3	0,125585	0,107906	0,653668	0,055038
2	6	0,197863	0,239553	1,190850	0,111430
3	9	0,274493	0,381586	1,696780	0,178663
4	12	0,352832	0,515161	1,982410	0,248734
5	15	0,439524	0,649044	2,206560	0,321479
6	18	0,538561	0,791708	2,355097	0,381485
7	21	0,650773	0,911493	2,432104	0,459604
8	24	0,697325	1,001126	2,594044	0,561500

After plotting the data for each material sample and extracting the linear relationship by using the linear regression method, a clear relationship was found between $(\ln I_0/I)$ and the thickness of the material sample. Figure 6 to Figure 9 shows the four different graphs were generated, and in each graph, the slope of the line was found to be relatively close to the accepted value for the linear attenuation coefficient at the given energy of the x-ray beam. This verifies that the proposed method is valid to be used as alternative method for measuring the linear attenuation coefficient of materials.

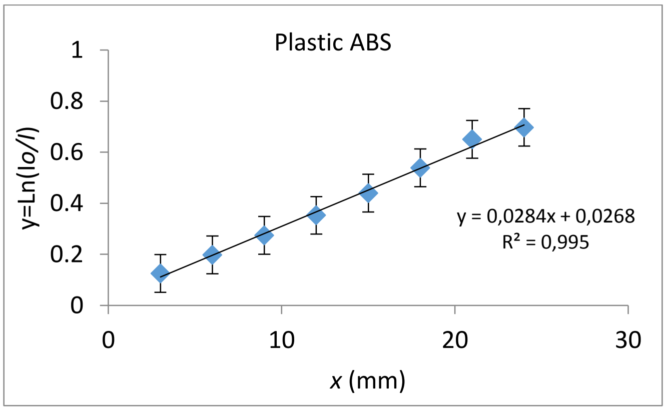

Figure 6: Plots of In$(^{I_0}/_I)$ vs. thickness x for plastic (ABS)

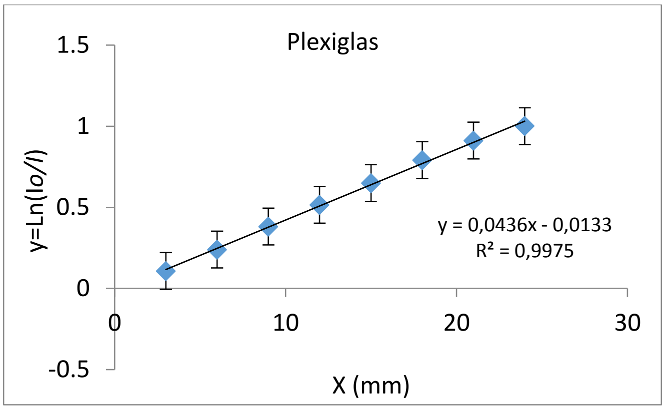

Figure 7: Plots of ln$(^{I_0}/_I)$) vs. thickness x for Plexiglas

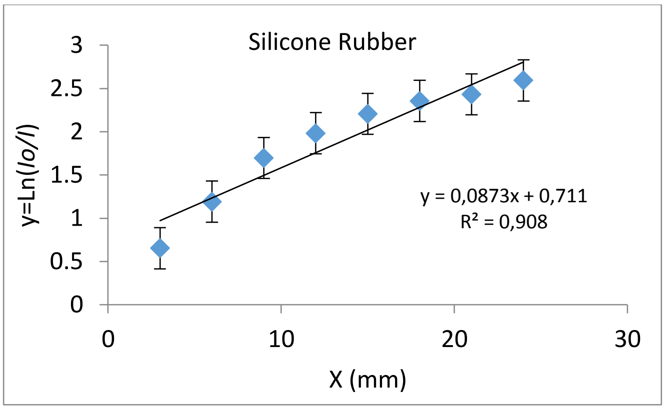

Figure 8: Plots of In$(^{I_0}/_I)$) vs. thickness x for Silicone Rubber

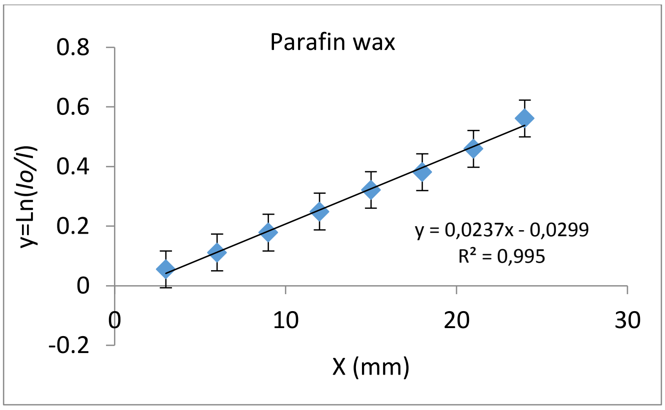

Figure 9: Plots of In$(^{I_0}/_I)$) vs. thickness x for Paraffin wax

From the plots on Figure 6 to 9, the result of the linear regression method is straight forward showing the linear attenuation coefficient value. Table 3 presented the linear attenuation coefficient values for each material using the linear regression method. The linear attenuation coefficient value is converted to cm^{-1} for convenient comparison with the standard value.

Table 3: Linear attenuation coefficient value of each material

No	Material	μ (cm^{-1})	R Square
1	Paraffin	0,0237±0.0007	0,995
2	Plastic ABS	0,0284±0.0008	0,995
3	Plexiglas	0,0436±0.0009	0,997
4	Silicone Rubber	0,0873±0.0113	0,908

Compared to the published results from the literature [17] and the value obtained from the National Institute of Standards and Technology [18] the measured values of the linear attenuation coefficient using the proposed method of measurement were found to be close to the accepted value for the linear attenuation coefficient.

CONCLUSIONS

The x-ray linear attenuation coefficient values of Plastic ABS, Plexiglas, Silicone Rubber and Paraffin wax materials have been measured using Micro-Digital Radiography Machine in a new method. The linear attenuation coefficient values of materials can be measured experimentally by exposing the materials with x-ray for different thicknesses and taking their digital radiographs. The results show that the μ for Paraffin is 0.0237 cm^{-1} which is the smallest value of linear attenuation coefficient at 30 keV and 20 mA X-ray exposure, while the largest one is the μ of Silicone Rubber at a value of 0.0873 cm^{-1}. The other materials are Plastic ABS with μ of 0.0284 cm^{-1} and Plexiglas with μ of 0.0436 cm^{-1}. From the presented results, it can be concluded that the proposed method used in this work were more accurate than the conventional methods, and the results obtained in this experiment shows the potential of choosing the materials to create a phantom which can be used to measure the image quality of the x-ray imaging system.

REFERENCES

[1] Hubbell, J. H., 1999. Review of photon interaction cross-section data in the medical and biological context. Phys. Med. Biol. 44, 1–22.

[2] James, R. Connolly., 2012.The Interaction of X-rays with Matter and Radiation Safety\ Introduction to X-Ray Powder Diffraction, EPS400-002.

[3] Saxby, B, Dale L., 2008. Investigation of the relationship between linear attenuation coefficients and CT Hounsfield units using radionuclides for SPECT. Science Direct Applied Radiation and Isotopes 1206–1212.

[4] Johns, H. E., Cunningham, J.R., 1984. The physics of radiology. 4th edition. Charles C. Thomas, Springfield, Illinois,U.S.A.

[5] Perry Sprawls., 1995. The Physical Principles of Medical Imaging, 2nd Ed. Department of Radiology Emory University School of Medicine Atlanta, GA, USA.

[6] Jackson, D. F, Hawkes, D.J., 1981. X-ray attenuation coefficients of elements and mixtures. Physics Reports. 70 (3):169–233

[7] Shivangi, K, Carol, J., 2015. Method to Determine the Density of Foods using X-ray Imaging Journal of food Engineering.1;159: 36–41.

[8] Madhusudhan, A. S., 2015. Determination of Effective Atomic Number and Electron Density of Wrought Aluminum Alloy 7010 for Multi-Energetic Photons, International Journal of Advanced Science and Technology Vol.81, pp.25-34

[9] Falcone, P. M, Baiano, A, Zanini, F, Mancini L, Tromba G, Dreossi D,. 2005. Three-dimensional Quantitative Analysis of Bread Crumb by X-ray Micro tomography. Journal of Food Science.70:E265–E272.

[10] Creagh, D. C., Hubbell, J.H., 1987. Problems with the measurement of X-ray attenuation coefficients. I: Silicon. Report on the international union of crystallography X-ray attenuation project. Acta. Cryst. A43, 102–112.

[11] Creagh, D. C., Hubbell, J. H., 1990. Problems associated with the measurement of X-ray attenuation coefficients. II. Carbon. Report on the international union of crystallography X-ray attenuation project. Acta. Cryst. A 46, 402–408.

[12] Suparta, G. B., Louk, A. C., Sam, N. H., and Wiguna, G.A,. 2013. “Quality Performance of Customized and Low Cost X-ray Micro-Digital Radiography System”, published in Sirisoonthorn, S.(Editors), 2014. Proc. SPIE 9234, International conference on Experimental Mechanics 2103 and Twelfth Asian Conference on Experimental Mechanics, 9234(7 pages)

[13] Boone, J., & Zhou, H., 2008. Monte Carlo evaluation of CTDI in infinitely long cylinders of water, polyethylene and PMMA with diameters from 10 mm to 500mm. Medical Physics, 2424-2431.

[14] Ferreira, C., Ximenes Filho, R., & Vieira, J., 2010. Evaluation of tissue-equivalent materials to be used as human brain tissue substitute in dosimetry for diagnostic radiology. Nuclear Intruments and Methods in Physics Research B 268, 2515-2521.

[15] American Association of Physicists in Medicine (AAPM) Report No. 1. 1977. Phantoms for performance evaluation and quality assurance of CT scanners. New York: Am Inst Phys

[16] Louk, A. C., Suparta, G. B., and Hidayah, N., 2014. "Image Processing for Multiple Micro- Radiography Images", Adv Mater Res 896, pp. 676–680

[17] Midgley, S. M., 2005. Measurements of the X-Ray Linear Attenuation Coefficient for Low Atomic Number Materials at Energies 32-66 and 140 keV. Radiation Physics and Chemistry, 72, 525-535.

[18] Hubbell, J. H., Seltzer, S. M., 1995. Tables of X-Ray Mass Attenuation coefficients and Mass Energy-Absorption Coefficients 1keV to 20MeV for Elements z=1 to 92 and 48 Additional Substances of Dosimetric Interest.