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Determination of Effective Atomic Number of Rubber

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RINGKASAN

Kertas ini melaporkan suatu cara mudah untuk menentukan nombor atom berkesan bahan getah. Pekali pengecilan linear sinar gamma bagi getah telah diukur dengan menggunakan pengesan Si(Li) yang mempunyai peleraian tinggi bagi sinar gamma bertenaga rendah dan nombor atom berkesan telah ditentukan dengan nisbah fungsi pekali pengecilan sinar gamma pada tenaga yang berbeza. Kajian ini dapat memberi panduan untuk memahami mutu getah berdasarkan kepada kandungannya.

SUMMARY

This paper reports a simple technique to determine the effective atomic number of rubber materials. The gamma ray attenuation coefficient of rubber was measured with high energy resolution Si(Li) detector at low gamma ray energies and the effective atomic number was determined by the functional ratio of attenuation coefficients at different energies. This study could provide a guide to an understanding of the quality of rubber based on its composition.

INTRODUCTION

The concept of effective atomic number is not valid over a wide range of gamma ray energies (Jackson, 1982). Nevertheless, over a limited range of photon energies it is an important quantity which can be used in diagnostic study to analyse the atomic composition of composite materials. The simplest way to determine the effective atomic number is by the technique first describe by Spiers (1946) and later by Weber and Van der Berge (1969) based on the linear attenuations of X-rays in matter. Using a polychromatic X-ray beam they were able to measure the effective atomic numbers of some body tissues. The technique was further improved by Rutherford *et al.* (1976) using a computerised assisted tomography (CAT) EMI scanner developed by Hounsfield (1973) and were able to determine the atomic numbers and electron densities of brain tissues and tumours. In 1977, White noted that the effective atomic numbers are energy dependent and determined the effective atomic numbers of biological tissues and their substitutes at different energies.

A similar technique was employed for rubber materials, the effective numbers of which are expected to be very close to those of biological tissues. In this work, we used gamma rays of three different energies from an ^{241}Am gamma ray source to determine the linear attenuation coefficients of rubber sheets with different percentages of carbon content. The effective atomic number thus determined is dependent to some extent on the experimental arrangement as well as the parametrisation described through equations (4) and (5) below. Despite this, the choice of geometry of the experiments as well as the parameters is such that the effective atomic number thus determined is close to the properly weighted mean atomic number of the samples.

THEORY

The interaction of a gamma ray photon with matter is largely dependent on its ability to transfer energy in its path through matter. Following the interaction processes, the intensity

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of the gamma ray photons in a good geometry experiment is attenuated in accordance with the following relationship.

$$I = I_0 \exp.(-\mu x) \quad (1)$$

where I is the transmitted intensity, I_0 is the incident intensity, x is the absorber thickness and μ is the linear attenuation coefficient of the absorbing material. For a compound material, the attenuation coefficient is related to its atomic composition and is given by:

$$\mu = \Sigma\, \sigma_i\, N_i \quad (2)$$

where σ_i is the atomic cross-section for the removal of gamma ray photons from the beam by atoms of type i and N_i is the number of atoms of type i per unit volume.

In the low energy range (<100 keV), the attenuation is mainly due to photoelectric absorption in which the gamma ray photons interact largely with the innermost electrons of the atom and Compton scattering involving the outer electrons which can be considered as free electrons. The interaction also includes coherent scattering but in the energies considered here the effect of molecular binding can be neglected. Thus the total cross-section can be written as:

$$\sigma(Z_i, E) = \sigma_i^P(Z_i, E) + \sigma_c(E) Z_i + \delta_i(Z_i, E) \quad (3)$$

where $\sigma_i^P(Z_i, E)$ and $\sigma_c(E)$ are respectively the photoelectric and Compton cross-sections for gamma rays of energy E and $\delta_i(Z_i, E)$ is the contribution from coherent scattering.

The cross-sections in the gamma ray considered here can be expressed in the functional form of $\sigma = kE^{-m} Z^n$ which can be fitted to standard data for the region of energy and atomic number of interest. Using the compiled data by Veigele (1973) and optimizing for carbon, the resulting expressions are;

$$\sigma_i^P(Z_i, E) = 28.44\, E^{-3.30}\, Z_i^{4.47} \quad (4)$$

and

$$\delta_i(Z_i, E) = 3.18\, E^{-1.78}\, Z_i^{2.50} \quad (5)$$

The energy E is in keV. Thus equation (3) becomes

$$\mu(E) = 28.44E^{-3.30}\, \Sigma\, Z_i^{4.47}\, N_i + \sigma_c(E)\, \Sigma\, Z_i\, N_i + 3.18E^{-1.78}\, \Sigma\, Z_i^{2.50}\, N_i \quad (6)$$

For a composite material two parameters are defined (Spiers, 1946), namely the effective atomic number $\tilde{Z}$ and the effective number of atoms per unit volume $\tilde{N}$. The final equation can be rewritten as;

$$\mu(E) = 28.44E^{-3.30}\, \tilde{Z}^{4.47}\, \tilde{N} + \sigma_c(E)\, \tilde{Z}\, \tilde{N} + 3.18E^{-1.78}\, \tilde{Z}^{2.50}\, \tilde{N} \quad (7)$$

By making measurements of μ at three different energies, the effective electron density $\tilde{Z}\,\tilde{N}$ can then be evaluated.

The effective atomic number had been given by Spears (1946), Cho *et al.* (1975) and White (1977) as

$$\tilde{Z} = (\Sigma_i\, \alpha_i\, Z_i^{n-1})^{\frac{1}{n-1}} \quad (8)$$

where α_i is the relative electron fraction of element i. Therefore, equation (7) can be expressed in the form of

$$\mu(E_i) = f(\tilde{Z}, E_i)\tilde{N} \quad (9)$$

The value of $\tilde{Z}$ could be obtained since the functional ratio of $\frac{\mu(E_2)}{\mu(E_2)}$ and $\frac{\mu(E_2)}{\mu(E_3)}$ would be satisfied only by one real value of $\tilde{Z}$.

EXPERIMENTAL PROCEDURE

The linear attenuation coefficients for four different types of rubber samples were determined separately by transmission measurements of a collimated ^{241}Am source at three energies 17.8 keV, 26.4 keV and 59.5 keV. The experimental arrangement employed a lithium drifted silicon Si(Li) detector, a preamplifier, an amplifier and a multichannel analyser (MCA) as shown in *Fig. 1.* The collimator was 5mm in diameter bored through a 5 cm × 5 cm × 6 cm lead block. The radiation source was deliberately chosen to be of low intensity, namely 1.43×10^6 Bq. The counting time of 5 minutes was used although this could easily be increased. In the intensity determination, the number of counts in the photopeak of the spectrum, was measured at a fixed geometry corresponding to the source-detector distance used in the efficiency determination of the detector. When there was no sample between the source and the detector, the intensity was taken as the initial intensity. The experiments were repeated for different thicknesses. The rubber samples were supplied by the Rubber Research Institute of Malaysia (RRI) and were in the form of sheet of thickness 0.240 ± 0.005 cm.

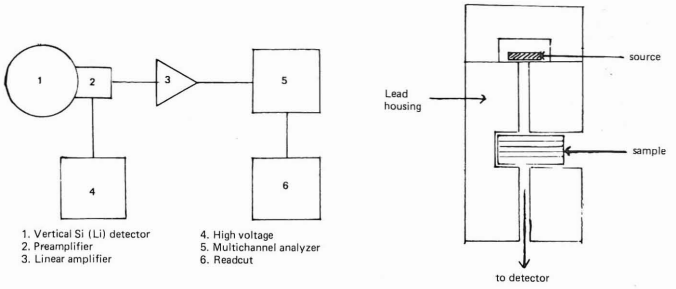

Fig. 1. Experimental set-up and sample holder.

RESULTS AND DISCUSSION

The linear attenuation coefficients at different energies and the effective atomic number of rubber samples were tabulated in Table 1. The calculations were performed on the ZENITH data system of the Physics Department, Universiti Pertanian Malaysia.

The effective atomic number of pure rubber was found to be 4.99 ± 0.04. Since the major elemental composition of pure rubber is carbon and hydrogen, the effective atomic number is expected to be less than that of carbon atom (Z = 6). By equation (8) and considering only the photoelectric absorption effect the calculated value was found to be 4.8. This value was based on cis-1-4-polyisoprene structure which contributes as much as 95 percent of natural rubber. The effective atomic number of sulphur vulcanised rubber is higher at the lower percentage of carbon content and approaches the atomic number of carbon as more carbon is added.

We were unable to make a direct comparison with previous results due to the absence of published reports of studies on rubber. All previous data were concentrated on biological materials and their substitues such as fats, muscles, bones, water and saline solution. The effective atomic

TABLE 1
The linear attenuation coefficients at different energies of gamma rays and the effective atomic numbers of rubber materials for different percentages of carbon content.

Sample	% Carbon	Energy (keV)	μ (cm^{-1})	$\tilde{Z}$
Pure rubber	0	17.7	0.388 ± 0.005	4.99
		26.4	0.188 ± 0.005	
		59.5	0.096 ± 0.001	
	25	17.7	0.794 ± 0.005	8.66
		26.4	0.348 ± 0.005	
		59.5	0.168 ± 0.005	
Sulphur Vulcanised Rubber	50	17.7	0.740 ± 0.005	7.05
		26.4	0.318 ± 0.005	
		59.5	0.136 ± 0.005	
	75	17.7	0.706 ± 0.005	6.62
		26.4	0.284 ± 0.005	
		59.5	0.116 ± 0.005	

number of fats was found to be 5.6 (Spiers, 1946), 6.0 (Rutherford *et al.*, 1976) and 5.95 (White, 1977). The higher effective atomic number of fats compared with that of pure rubber is possibly due to the presence of oxygen.

CONCLUSION

The effective atomic number of rubber has been measured using a collimated gamma ray transmission method. Because of its simplicity this technique offers a good non-destructive method in the measurement of effective atomic number of composite materials as an indication of their atomic compositions.

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