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Conductive natural and waste rubbers composites-loaded with lead powder as environmental flexible gamma radiation shielding material

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Abstract

It is well known that materials with lead (Pb) content are very effective as protective materials against radiation. Natural rubber (NR) has been loaded with 30 phr of N220 black (critical concentration) as a conductive and reinforcing filler. These rubber matrices are loaded with different concentrations of Pb powder (up to 100 phr) as filler. Gamma attenuation study was carried out using 3" × 3" NaI (TI) (scintillation detector) gamma-ray spectrometer for (Cs-137), (Co-60), (Ba-133), and (Eu-152). The effect on the shielding property of Pb/NR composite was studied by varying the content of Pb and photon energy. It was found that the addition of Pb filler remarkably increases the linear attenuation coefficient (μ) of Pb/NR composites, especially for low photon energy. Linear attenuation coefficient experimental measures and theoretical calculations (using the XCOM code) were performed. It was noted that there is a reasonable agreement between measured and calculated results. In this paper, gamma-ray radiation shielding parameters are also studied for composites based on waste rubber. Its experimental results showed that Pb/W/NR composites have better γ shielding ability compared to Pb/NR ones at the Pb contents so, these are promising materials for fabricating protecting clothes against radiation in addition to their low cost and effective aid to get a clean environment.

1. Introduction

Gamma-ray represents a significant risk to the workers in the nuclear power industry and radioactive therapy due to its high penetration ability and destructive effect on the body cells, so, the protection from radiation has become necessary required. Polymer composites doped with fillers (metal or metal oxides) with high atomic number (Z) (tungsten (W), barium (Ba), lead (Pb), gadolinium (Gd), tin (Sn), and bismuth (Bi)) attracted the attention of many scientists for future applications in radiation shielding. They have unique properties such as reasonable cost, easy to process, lightweight, flexibility, good mechanical strength, and electrical properties [1–5]. Rubber is a polymer type that has the elastic characteristics and is derived from the tropical and subtropical latex sap known as natural rubber or manufactured from petroleum products, which is called synthetic rubber. It is necessary to combine the rubber with conductive additives such as carbon black, steel, metal, or metal oxide because it is an insulator material [6]. These conductive rubber composite materials have wide uses in electromagnetic interference shielding and many electronic and electrical applications [7, 8]. Some researchers have been studied rubber composites for the purposes of radiation protection. Lead with concentration up to 30 phr, paraffin wax of 60 phr, and boron carbide of 20 phr was loaded on natural rubber in...
order to study the attenuation of both gamma rays and neutrons [9]. NBR (Nitrile-Butadiene Rubber) mixed with a lead with different ratios of weight and the linear attenuation coefficient of gamma-rays that released by 241 Am (0.059 MeV), 152Eu(0.13 MeV), and 137 Cs (0.662 MeV) were determined [10]. Silicone rubbers/lead oxide composites were investigated for γ-radiation shielding properties [11]. Gamma-ray attenuation capability of Ethylene Propylene Diene Monomer (EPDM) rubber filled with 10%, 20%, and 30% (w/w) bismuth trioxide was studied [12]. In recent decades, researchers around the world have begun to think about waste materials, recycling, and using it for many purposes. In addition, the fact that the burning of these substances leads to the occurrence of many environmental problems. Waste rubber comes from three materials called rubber, textile fibers, and steel wires [13]. Usually reclaiming waste tire is carried out by combining waste tire rubber (WTR) to the virgin rubber [14], then these materials are recycled and involved in the manufacture of new materials such as plastic parts, asphalt, concrete, etc [15, 16]. The computations of the linear attenuation coefficient μ, λ (mean free path) and HVL for natural rubber blended with 15 wt% of recycled acrylonitrile-butadiene rubber (NBRs) added to NR. Then the blend mixed with metal wastes such as iron particulates, iron filing, and steel slag were investigated using NaI (TI) detector, 137 Cs, and 60 Co radioactive sources [16]. The results showed that NR/NBR is good shielding material. Aim et al [17] studied the attenuation of neutron and gamma-ray for high-density concrete mixed with waste rubber, barite, lead, and boron carbide powders using the MCNP computer code and verified by radiation attenuation experiments. The adjustment of 5% lead and 5% waste rubber into high-density concrete has been found to increase attenuations of both neutrons and gamma rays.

In the present work, twelve composites of Pb/NR and Pb/W/NR were prepared. Six samples of conductive NR loaded with different contents of Pb were fabricated. The experimental linear attenuation coefficients of gamma-rays emitted from the radioactive sources 152Eu, 133Ba, 137Cs, and 60Co were determined and compared with theoretical calculations that are obtained from the XCOM program. Five samples with different contents of waste rubber showed that W50 (50W/50NR) composite had the highest value of the linear attenuation coefficient. It is clear that 100 phr of Pb as optimum content were incorporated in W50 composite as it called 100W50. Finally, W50 and 100W50 were selected to obtain a flexible, lightweight, and low-cost substance that has the ability to attenuate gamma rays. At the same time, the exploitation of waste rubber has economic and environmental benefits, as it contributes to reducing the economic cost by saving the use of virgin rubbers.

2. Materials and methods

2.1. Materials

Natural Rubber (NR) (SMR-20, specific gravity 0.934 (g cm⁻³); ash content 1%) is donated from Transportation and Engineering Co., (TRENCO, Alexandria, Egypt). The carbon black used in this work is N220 (ISAF) from CARBON BLACK Co., Egypt. Lead fine powder (Pb) (specific gravity 11.3 (g cm⁻³) and other chemicals such as Sulphur, stearic acid, the paraffinic oil, and zinc oxide were used in commercial-grade without purification and locally manufactured by ADWIC Co. Egypt.

2.2. Composites preparation

The preparation of six different formulations of Pb/NR composites and six samples of Pb/W/NR were carried out according to ASTM D 3185—(99)(see tables 1 and 2). 10 phr of paraffinic oil is included in the rubber compound to reduce the shore hardness of the final composite, where it is considered as a plasticizer or softener material. All rubber ingredients have been combined using the two roll mill with dimensions as follows: outside diameter: 460 mm, working distance: 250 mm, rolling speed: 16 rpm, and gear ratio: 1.4 at a research laboratory of TRENCO company, Alexandria, Egypt. The two-roll mill has the facility of rolling temperature control. After milling, the sample sheet was collected from the mill, cut, and put into a steel mold of 0.3 cm thickness, 25 cm wide, and 20 cm height divided into four circles of 8.2 cm in diameter (samples of the standard test) which is needed for radiation protection properties testing. Then the rubber composites were vulcanized using a hot press at 143 ± 2 °C for 15 min with an applied pressure of 15 MPa.

3. Instrumentation

3.1. Instrumentation for characterization

Evaluation of curing parameters can be determined by measuring ML (minimum torque), MH (maximum torque), Tsc (scorch time), and T90 (optimum cure time). The vulcanization parameters of the prepared composites were measured using rheometer type (MDR-2000; version 1.00, England) with a temperature range of 100 °C—200 °C according to ASTM D-5289.
Crosslink density measurements were calculated by the equilibrium swelling method using benzene at 25°C for 24 h to achieve the equilibrium swelling condition using samples with dimensions of 0.2 × 0.5 × 2 cm³. The crosslink density was determined using the Flory-Rehner equation [18].

Thermodynamics calculations were done by calculating the change in elastic Gibbs free energy which can be determined from the Flory-Huggins [18]. From the Statistical theory of rubber elasticity, the conformational entropy can be calculated.

The surface morphology structure (SEM) of the Pb/NR and Pb/W/NR composites were investigated by Analytical-SEM (type: JEOL, JSM-6360 LA, Japan with 15 kV voltages for secondary electron imaging). All investigated composites are coated with Au using an ion sputter coater (model: 11430, USA, combined with vacuum base unit or SPi module control, model: 11425, USA).

The mechanical measurements were done by measuring the tensile strength, modulus at 100%, and elongation at break for the Pb/NR and Pb/W/NR composites by using Monsanto tensiometer of capacity 10 kN according to ASTM D-412 at room temperature. The mechanical test has been done by cutting five individual dumbbell shape specimens from the vulcanized sheets for each sample.

The hardness measurements were performed by a Durometer in Shore A according to ASTM D-2240. Five measurements were taken, and the average values were reported.

The thermogravimetric analysis (TGA) of Pb/NR and Pb/W/NR composites were carried out using (Shimadzu TGA-50, Japan) analyzer at a heating rate of 10°C/min in nitrogen over a temperature ranging from room temperature to 750°C. From the TGA curves, thermal degradation characteristics were calculated.

The electrical measurements were carried out by measuring the dc electrical conductivity of composites using dc voltage/current generator, along with a precision digital electrometer (Keithley 616). AC electrical conductivity of composites was carried using an LCR meter (HIOKI IM 3536, Japan) connected to a computer.

### Table 1. Pb/NR composites ingredients.

| Ingredients (phr) | Pb0 | Pb20 | Pb40 | Pb60 | Pb80 | Pb100 |
|------------------|-----|------|------|------|------|-------|
| NR               | 100 | 100  | 100  | 100  | 100  | 100   |
| Waste rubber     | —   | —    | —    | —    | —    | —     |
| Stearic acid     | 2   | 2    | 2    | 2    | 2    | 2     |
| Carbon black     | 5   | 5    | 5    | 5    | 5    | 5     |
| (N220) 6PPD   | 30  | 30   | 30   | 30   | 30   | 30    |
| Paraffinic Oil   | 10  | 10   | 10   | 10   | 10   | 10    |
| Pb               | 0   | 20   | 40   | 60   | 80   | 100   |
| Sulfur           | 2   | 2    | 2    | 2    | 2    | 2     |
| CBS              | 2   | 2    | 2    | 2    | 2    | 2     |

### Table 2. Pb/W/NR composites ingredients.

| Ingredients (phr) | W10 | W20 | W30 | W40 | W50 | 100W50 |
|------------------|-----|-----|-----|-----|-----|--------|
| NR               | 90  | 80  | 70  | 60  | 50  | 50     |
| Waste rubber     | 10  | 20  | 30  | 40  | 50  | 50     |
| Stearic acid     | 2   | 2   | 2   | 2   | 2   | 2      |
| Zinc oxide       | 5   | 5   | 5   | 5   | 5   | 5      |
| (N220) 6PPD   | 30  | 30  | 30  | 30  | 30  | 30     |
| Paraffinic Oil   | 1   | 1   | 1   | 1   | 1   | 1      |
| Pb               | 0   | 0   | 0   | 0   | 0   | 100    |
| Sulfur           | 2   | 2   | 2   | 2   | 2   | 2      |
| CBS              | 2   | 2   | 2   | 2   | 2   | 2      |

* Part per hundred parts of rubber by weight.

7 N-(1,3-Dimethylbutyl)-N'-phenyl-p-phenylenediamine.

8 n-cyclohexyl-2-benzoazolesulfonamide.
interface to record data in a frequency range from 42 Hz up to 8 MHz. All measurements have been done using samples with an area of 1 cm² and about 0.3 cm thickness.

3.2. Instrumentation for gamma-ray shielding measurements

When gamma-ray having initial intensity (I₀) passes through shielding material with a thickness (x), its intensity will be attenuated according to exponential relation expressed by Lambert-Beer law [19]

\[ I = I_0 \exp(-\mu x) \]  

where \( I_0 \) and \( I \) are the initial and transmitted intensities of gamma-ray respectively and \( \mu \) is the linear attenuation coefficient which describes the extent to which the intensity of an energy beam is reduced as it passes through specific material and expressed in units of inverse length (cm⁻¹). The linear attenuation coefficient is reliant on the type of material (atomic number Z) and the energy of the radiation. By dividing \( \mu \) by the density \( \rho \) of the material, the mass attenuation coefficient \( (\mu_m \text{ (cm}^2 / \text{g})) \) could be evaluated. The density of the samples was measured experimentally at room temperature by the Archimedes rule [3] and the theoretical values of the density of the composites were also calculated [3]. Half Value Layer (HVL) is a parameter used to define the shielding properties and determine the thickness of the material that reduces the radiation intensity to half of its initial intensity and is given as follows

\[ \text{HVL} = \frac{\ln 2}{\mu} \]  

Gamma-ray attenuation properties of Pb/NR and Pb/W/NR composites were performed by calculating the linear attenuation coefficient \( \mu \) (cm⁻¹). The test was performed in the radiation physics laboratory, Faculty of Science Alexandria University, Egypt, using 3″ × 3″ NaI scintillation detector Canberra Model 802. The radioactive sources purchased from Physikalisch-Technische Bundesanstalt PTB were used to generate gamma rays in this study as shown in table 3. A homemade Plexiglas holder was used to measure all the radioactive sources at a distance of 508.67 mm from the detector surface. The choice of such a high distance between the surface of the detector and the radioactive source is due to several reasons such as obtains a parallel beam, reduces the impact of dead time, and ignores the effect of coincidence summing [20]. During the practical measurement, the samples were exposed to the radioactive source for a sufficient measuring time until the error is less than 1%.

It is worthy to mention that the interesting peak area in each spectrum and each run was calculated by Genie 2000 software made by Canberra. The fitting of each peak was done using a Gaussian shape for the NaI detector spectra. Lightweight is the most advantages of polymer composite materials and the parameter which describes this characteristic is called heaviness where it was calculated relative to the lead [19].

4. Results and discussion

4.1. Curing parameters of Pb/NR and Pb/W/NR Composites

The cure properties of Pb/NR Pb and Pb/W/NR composites are shown in table 4. From these data, it can be seen that the incorporation of Pb increases the minimum torque (ML), maximum torque (MH) while decreases the scorch time (Tsc) and optimum cure time (T90). In addition, the same behaviors were observed in Pb/W/NR due to the increase of waste rubber.

| Radioactive source | Photon Energy (keV) | Activity(kBq) on 1 June 2009 | Half Life-time \((T_{1/2})\) (Days) |
|-------------------|-------------------|-----------------------------|----------------------------------|
| Co-60             | 1173.2            | 212.1 ± 1.5                 | 1925.31                          |
|                   | 1332.5            |                             |                                  |
| Cs-137            | 661.6             | 385.0 ± 4.0                 | 11004.98                         |
| Ba-133            | 356.01            | 275.3 ± 2.8                 | 3847.91                          |
| Eu-152            | 121.8             | 290.0 ± 4.0                 | 4943.29                          |

244.7
344.3
964
1085
1408

Table 3. Photon energies, activity, and half-life time for all used radioactive sources.
It is already reported that MH and $\Delta M$ are dependent on the crosslinking density of Pb/NR composites. It is noticed that the degree of crosslinking increased by increasing Pb content. This was due to the fact that this metallic filler acts as a co-activator during the chemical vulcanization process, causes better connections between the molecular chains of rubber and sulfur, which leads to an increase in cross-linking density and higher torque differences [21]. ML is a measure of the stiffness and viscosity of vulcanized compounds; it is clear that ML increased by increasing Pb content. By increasing the lead content, the flow rate in the rubber increases, due to the large difference between the lead density and that of natural rubber. The density of Pb (11.3 g cm$^{-3}$) is much higher than the density of NR vulcanizates (0.92 g cm$^{-3}$), which requires an increase in the flow, which leads to increase viscosity and the torque. The decreasing trend of both Tsc and T90 may be attributed to the good acceleration of crosslinking reaction. This is also due to the existence of proteins content and other substances such as lipids which could act as natural accelerators for the vulcanization process [22]. In other words, the incorporation of Pb in the Pb/NR composites causes an increase in the rate of vulcanization. This is because of the increase of reactive sites on the rubber molecules for the crosslinking reaction. Pb filler could be regarded as co-activators during the chemical vulcanization process, which leads to a lowering of the curing time of the composites. For Pb/W/NR composites, the cured waste rubber acted like filler so ML, MH, and $\Delta M$ increased but T90 and Tsc are decreased by increasing the waste content. The increase in ML, MH, and $\Delta M$ due to waste rubber does not move into the matrix quickly so that the rise of waste loadings will decrease flow and thus increase torque. Also, the highly aggregated and convoluted composition of waste rubber powder involves a void space in which the rubber matrix is trapped thus raising the effective waste volume fraction of rubber [23]. By comparing the values of curing parameters for Pb0, W50, Pb100, and 100W50, it was observed that W50 and 100W50 had higher values of curing parameters than Pb0 and Pb100. It is expected that the crosslinking density of samples W50 and 100W50 are higher than those of samples Pb0 and Pb100.

4.2. Physico-chemical properties of Pb/NR and Pb/W/NR composites

4.2.1. Crosslinking density and thermodynamic parameters calculations

Crosslink density values of Pb/NR and Pb/W/NR composites were estimated using benzene as shown in table 5. For Pb/NR composites, it is obvious that the crosslink density of the Pb/NR composites increased with increasing Pb powder content. This could be attributed to the existence of the Pb powder which increased the degree of crosslinking and it is illustrated by differences in torque which increased by increasing the Pb content so, the crosslinking density becomes too high. The same behavior was observed in Pb/W/NR composites where the crosslink density of the Pb/W/NR composites increased with increasing waste powder content. It was in good agreement with the results of MH and $\Delta M$ which increased by increasing the waste content. Thermodynamic parameters estimated for Pb/NR and Pb/W/NR composites are also given in table 5. It is obvious to say that the thermodynamically stable system is formed when $\Delta G < 0$. It is clear that Gibbs’s free energy values became more negative by increasing Pb content in Pb/NR composites and by increasing waste content in Pb/W/NR composites. In addition, entropy values also increase as the content of Pb and waste rubber increase. It was noticed that W50 and 100W50 had higher values of the cross-linking density, $\Delta G$ and $\Delta S$ than Pb0 and Pb100, respectively. The waste rubber increased values of cross-linking density and $\Delta G$, so it is expected that TGA analysis of W50 and 100W50 composites are more thermally stable than Pb0 and Pb100 composites.

### Table 4. Vulcanization characteristics of Pb/NR and Pb/W/NR composites.

| Sample Name | ML (dNm) | MH (dNm) | $\Delta M$ (MH-ML) (dNm) | Tsc (min) | T90 (min) |
|-------------|-----------|----------|--------------------------|-----------|-----------|
| Pb0         | 0.33      | 15.61    | 15.28                    | 1.73      | 12.68     |
| Pb20        | 0.44      | 15.91    | 15.47                    | 1.58      | 12.52     |
| Pb40        | 0.47      | 17.92    | 17.45                    | 1.50      | 12.31     |
| Pb60        | 0.48      | 18.55    | 18.07                    | 1.50      | 12.2      |
| Pb80        | 0.48      | 18.72    | 18.24                    | 1.42      | 11.98     |
| Pb100       | 0.49      | 20.09    | 19.6                     | 1.393     | 11.80     |
| W10         | 0.70      | 17.88    | 17.18                    | 1.90      | 15.8      |
| W20         | 0.73      | 18.33    | 17.60                    | 1.68      | 15.62     |
| W30         | 0.77      | 19.96    | 19.19                    | 1.61      | 15.40     |
| W40         | 0.85      | 20.50    | 19.65                    | 1.58      | 15.10     |
| W50         | 0.96      | 21.2     | 20.24                    | 1.47      | 14.86     |
| 100W50      | 1.03      | 23.97    | 22.94                    | 1.41      | 14.20     |
4.3. Scanning electron microscope (SEM)

SEM was used as a complementary tool to get a better understanding of how the lead micron can affect the compatibility of NR and blend of W/NR. It can also show the change in the morphology of NR matrices as a result of adding a waste rubber. Figure 1 displays images of SEM of Pb/NR composites. Figure 1(a) represents a micrograph of Pb0 and it seemed to be a smooth and clear profile. Generally, uniform dispersion of Pb in NR matrices was observed in figures 1(b)–(f), but the filler tends to form agglomerates at higher loadings. By increasing the lead content, the agglomerates become clearer and more complicated. Figures 1(g)–(i) shows SEM of Pb/W/NR composites. In figure 1(g), the fractured surface of the blend contains 10 phr loading of waste (W10) reveals that the phase separation is more clearly observable. Figure 1(h) shows high reinforcement compounds of 50 phr waste (W50) which increased faults and crack a sand number of pull-out holes ascribed to a higher mix shearing effect when blending the waste rubber in the NR matrix which worsens interfacial adhesion. In this case, NR particles do not have a percentage appropriate to surround the waste particles and

| Table 5. Physico-chemical parameters of Pb/NR and Pb/W/NR composites. |
|-----------------|-----------------|-----------------|
| Sample Name    | Crosslinking density (10^-4) | ΔG (J mol^-1) | ΔS (J mol^-1 K^-1) |
| Pb0            | 2.47            | -83.07         | 0.278            |
| Pb20           | 3.06            | -105.3         | 0.353            |
| Pb40           | 3.16            | -108.85        | 0.365            |
| Pb60           | 3.23            | -112.05        | 0.376            |
| Pb80           | 3.39            | -117.90        | 0.395            |
| Pb100          | 3.42            | -119.05        | 0.399            |
| W10            | 28.61           | -1437.00       | 4.82             |
| W20            | 33.51           | -1698.10       | 5.70             |
| W30            | 33.98           | -1723.32       | 5.78             |
| W40            | 40.36           | -2064.28       | 6.93             |
| W50            | 46.92           | -2416.15       | 8.11             |
| 100W50         | 52.46           | -2713.44       | 9.11             |

Figure 1. SEM micrograph of (a) Pb0, (b) Pb20, (c) Pb40, (d) Pb60, (e) Pb80, (f) Pb100, (g) W10, (h) W50 and (i) 100W50 composites.
render the joint tough, with large cracks and pores occurring in the contour. On the other side, there are larger opportunities for agglomeration of waste particles; this agglomerate behaves as a large particle. Figure 1(i) represents an SEM image of 100W50 and it seems a relatively rough and uneven fractured surface. This may be due to the interaction between Pb particles and the rubber blend in addition to Pb’s ability to perform clear aggregations.

4.4. Mechanical measurements of Pb/NR and Pb/W/NR composites

The mechanical properties of Pb/NR and Pb/W/NR composites with different Pb and waste contents are shown in Table 6. For Pb/NR composites, by increasing Pb content tensile strength, modulus at 300%, and elongation at break decreased while hardness increased. The decreasing trend may be due to poor interfacial compatibility of filler and the lack of uniform distribution of Pb in the rubber matrix and filler–filler interactions with a high tendency to form aggregations, which weaken the bonding strength between the filler and the rubber. Also, it damages the continuous structure of the composites. At the same time, the movement of molecular chains is limited by the increase of powder filler due to the interaction between filler and rubber molecular chains, which also contributes to the decrease of elongation at break [21]. The hardness values of Pb/NR increased, as Pb content increases, due to the high rigidity of Pb metal powder in NR composites and the increase in torque differences. The same behavior was observed in Pb/W/NR composites whereby increasing waste content, the mechanical parameters decreased but hardness increased. By comparing TS, M300%, and Eb% of Pb0, W50, Pb100, and 100W50 composites, it is observed that the composites that contain waste rubber (W50 and 100W50) had lower values than those contain NR only (Pb0 and Pb100). This decreasing trend may be due to the low bonding force between the waste rubber and NR. As a result, the sample loses its elasticity and became a little bit brittle especially for large amounts of waste rubber. This means that the poor interfacial compatibility between waste and NR caused low mechanical properties. This decrease was expected due to the cracks and number of pull-out holes that showed in the SEM investigation of W50 and 100W50 composites. The hardness values of Pb/W/NR composites are higher than that of Pb/NR composites due to the high crosslinking density of Pb/W/NR composites compared to Pb/NR composites.

4.5. Thermo–gravimetric analysis (TGA)

The thermal properties of Pb/NR, W10, W50, and 100W50 composites are characterized by the TGA instrument. Figure 2 represents TGA data of Pb0, W50, Pb100, and 100W50, respectively. According to TGA results, the thermal degradation of Pb0, W50, Pb100, and 100W50 composites could occur through three stages. The thermal behavior in the first degradation stage of the composites may be due to volatile compounds. The second degradation stage referred to the rubber pyrolysis. The remaining polymer mass shows a complete thermal degradation, due to both carbonization and volatilization processes, at the third degradation stage. Temperature and weight loss characteristics of each stage of Pb/NR and W/NR composites, Tonset and T50 are illustrated in Table 7. The mid-weight temperature is defined as the temperature at which half weight loss of the sample is detected and Tonset is the temperature of onset decomposition, these are useful properties to identify the thermal stability of the material. The higher the values of T50 and Tonset, the higher is the thermal stability of the composites [24]. According to TGA results that tabulated in Table 7, T50 and Tonset values increased with increasing Pb content. Also, W50 and 100W50 composites showed thermal stability higher than those contain

| Sample name | Tensile strength (MPa) | Modulus at 300% (MPa) | Elongation at break Eb (%) | Hardness (Shore A) |
|-------------|------------------------|-----------------------|---------------------------|-------------------|
| Pb0         | 29                     | 9.2                   | 564                       | 61.5              |
| Pb20        | 26                     | 10                    | 544                       | 62.6              |
| Pb40        | 23.7                   | 8.9                   | 528                       | 63.4              |
| Pb60        | 20.04                  | 7.2                   | 505                       | 65.7              |
| Pb80        | 18.9                   | 6.77                  | 491                       | 66.9              |
| Pb100       | 17.48                  | 6.29                  | 480                       | 68.3              |
| W10         | 20.5                   | 8.7                   | 534                       | 65.5              |
| W20         | 16.3                   | 10.9                  | 419                       | 67.0              |
| W30         | 14.47                  | 9.4                   | 410                       | 68.5              |
| W40         | 11.5                   | 8.0                   | 272                       | 70.0              |
| W50         | 11.1                   | 6.5                   | 241                       | 72.0              |
| 100W50      | 9.8                    | 5.3                   | 210                       | 76.0              |
NR only (Pb0 and 100W50). This may be due to the higher thermal stability of waste rubber compared to pure NR. In addition, the crosslinking density is an important factor affecting the thermal stability of vulcanized rubber. Higher crosslink density leads to better thermal stability because of the higher values of activation energy needed for thermal decomposition of vulcanizates [25]. Thus, waste rubber improved the thermal stability of the blends because of the presence of crosslinking. It can be said that Pb/W/NR has more thermal stability than Pb/NR composites. Finally, 100W50 composite has the highest thermal stability.

4.6. Electrical properties of Pb/NR and Pb/W/NR composites

4.6.1. DC conductivity ($\sigma_{dc}$) of Pb/NR and W/NR composites

The variation of dc conductivity ($\sigma_{dc}$) with different Pb and W contents composites are showed in table 8. It is clear that $\sigma_{dc}$ of Pb/NR composites increased with increasing Pb content. This owed to the high electrical conductivity of Pb which is about $1.52 \times 10^6$ S m$^{-1}$, while NR has low electrical conductivity ($\sigma_{NR} < 10^{-14}$ S m$^{-1}$) [26]. In Pb/W/NR composites and by increasing waste content, $\sigma_{dc}$ increased. The reason for this increase may be due to the fact that the waste rubber acts as doping material which helps to facilitate the movement of electrons and increases electrical conductivity through hopping mechanics. In addition, another factor that may contribute to the increase of $\sigma_{dc}$ is the possibility to find carbon with probable content in the waste rubber. Carbon black is a conductive filler, has the ability to improve the conductivity of insulation.

### Table 7. Temperature and weight loss characteristics of Pb/NR and Pb/W/NR composites.

| Sample Name | 1st degradation stage | 2nd degradation stage | 3rd degradation stage | $T_{onset}$, °C | $T_{50}$, °C |
|-------------|-----------------------|-----------------------|-----------------------|----------------|-------------|
| Pb0         | 22–207 (0.68%)        | 207–450 (13%)         | 450–750 (13%)         | 207            | 328.5       |
| Pb20        | 28–300 (7.5%)         | 300–460 (9.7%)        | 460–750 (9.7%)        | 300            | 380         |
| Pb40        | 28–319 (7.8%)         | 319–464 (8.3%)        | 464–750 (8.3%)        | 319            | 391.5       |
| Pb60        | 24–320 (5.8%)         | 320–467 (2%)          | 467–600 (2%)          | 320            | 393.5       |
| Pb80        | 19–342 (6.2%)         | 342–487 (3%)          | 487–600 (3%)          | 342            | 414.5       |
| Pb100       | 30–363 (7.6%)         | 350–489 (11.7%)       | 489–800 (11.7%)       | 350            | 419.5       |
| W10         | 23.7–230 (5.65%)      | 230–621 (0.55%)       | 621–800 (0.55%)       | 220            | 425.5       |
| W50         | 31.8–280 (10.6%)      | 280–583 (1.2%)        | 583–800 (1.2%)        | 255            | 431         |
| 100W50      | 25–356 (9.3%)         | 356–555 (0.2%)        | 555–800 (0.2%)        | 356            | 456         |

[Figure 2. TGA curves of (a) Pb0 and W50 and (b) Pb100 and 100W50 composites.]

[Table 7. Temperature and weight loss characteristics of Pb/NR and Pb/W/NR composites.]
materials. By comparing $\sigma_{dc}$ values of Pb0, W50, Pb100, and 100W50, it was noticed that the composites that had waste rubber (W50 and 100W50) had higher values of $\sigma_{dc}$ compared to composites that had NR only (Pb0 and Pb100). It means that replacing 50 phr of NR with waste rubber improved dc conductivity; 100W50 composite had the highest value of $\sigma_{dc}$ due to the presence of both waste and Pb.

### 4.6.2. AC conductivity ($\sigma_{ac}$) of Pb/NR and Pb/W/NR composites

Figure 3 shows the $\sigma_{ac}$ of Pb0, W50, Pb100, and 100W50 as a function of frequency at room temperature. By increasing the frequency, the passing current increases which resulted in an increase in $\sigma_{ac}$ of the composites. In addition, the curves of W50 and 100W50 show higher values of $\sigma_{ac}$ than those of Pb0 and Pb100 composites. This shows the effect of waste rubber, which resulted in an increase of $\sigma_{ac}$. This means that the waste rubber acted as conducting filler caused the formation of a highly conducting space-charge layer along the normal conductor–insulator (W and NR) interface. Pb/W/NR composites have higher $\sigma_{ac}$ than Pb/NR composites.

#### 4.7. Gamma rays attenuation results

##### 4.7.1. Investigation of the gamma radiation shielding properties of Pb/NR composites

The experimental results showed that the linear attenuation coefficient increased by increasing Pb content due to the increase in the density of the composites. It is clear that the linear attenuation coefficient is a density-dependent factor. Table 9 lists the values of measured, theoretical densities, measured linear attenuation coefficient ($\mu$, cm$^{-1}$), theoretical linear attenuation coefficient (which determined from XCOM program), the mass attenuation coefficient ($\mu_m$, cm$^2$g$^{-1}$), and the discrepancy ($\Delta\%$) in the measured values of linear attenuation coefficient which was estimated to be 0.06: 2.77% and calculated using the following equation.

| Sample | $\sigma_{dc}$ (Sm$^{-1}$) |
|--------|--------------------------|
| Pb0    | $5.06 \times 10^{-6}$    |
| Pb20   | $6.53 \times 10^{-6}$ |
| Pb40   | $8.72 \times 10^{-6}$ |
| Pb60   | $1.07 \times 10^{-5}$ |
| Pb80   | $1.31 \times 10^{-5}$ |
| Pb100  | $1.55 \times 10^{-5}$ |
| W10    | $6.98 \times 10^{-5}$ |
| W20    | $9.58 \times 10^{-5}$ |
| W30    | $1.05 \times 10^{-4}$ |
| W40    | $1.1 \times 10^{-4}$ |
| W50    | $1.2 \times 10^{-4}$ |
| 100W50 | $3.82 \times 10^{-4}$ |

Figure 3. The variation of ac electrical conductivity as a function of the frequency of (a) Pb0, W50, and (b) Pb100, 100W50 composites.
Table 9. Values of measured and calculated densities, measured and theoretical linear attenuation coefficient, HVL, the mass attenuation coefficient, and Δ% of Pb/NR composites.

| Sample name | Energy (keV) | Linear attenuation coefficient $\mu_x$ (cm$^{-1}$) | Measured XCOM | $\Delta$% | Measured mass ATTENUATION coefficient $\mu_{att}$ (cm$^2$g$^{-1}$) | HVL (cm) | Measured density (g cm$^{-3}$) | Calculated density (g cm$^{-3}$) |
|-------------|-------------|--------------------------------------------------|---------------|--------|--------------------------------------------------|---------|-------------------------------|-------------------------------|
| Pb0         | 121.8       | 0.168 ± 0.013 | 0.167          | 0.42%  | 0.139                                            | 4.126   | 1.073 ± 0.01                  | 1.059                         |
|             | 244.7       | 0.133 ± 0.011 | 0.132          | 0.60%  | 0.126                                            | 5.212   | 2.52                          |
|             | 344.3       | 0.117 ± 0.008 | 0.117          | 0.60%  | 0.111                                            | 5.909   | 2.43                          |
|             | 356.01      | 0.112 ± 0.009 | 0.115          | −2.72% | 0.106                                            | 6.189   | 2.56                          |
|             | 661.6       | 0.091 ± 0.005 | 0.089          | 1.98%  | 0.086                                            | 7.634   | 3.05                          |
|             | 964.13      | 0.075 ± 0.012 | 0.075          | 0.53%  | 0.071                                            | 9.242   | 3.65                          |
|             | 1085        | 0.07 ± 0.006  | 0.070          | −0.57% | 0.066                                            | 10.046  | 4.07                          |
|             | 1173.2      | 0.067 ± 0.007 | 0.068          | −0.06% | 0.064                                            | 10.239  | 4.16                          |
|             | 1332.5      | 0.063 ± 0.009 | 0.063          | −0.63% | 0.059                                            | 11.002  | 4.32                          |
|             | 1408        | 0.061 ± 0.004 | 0.062          | −0.98% | 0.058                                            | 11.363  | 4.51                          |
| Pb20        | 121.8       | 0.613 ± 0.017 | 0.610          | 0.53%  | 0.518                                            | 1.131   | 1.22 ± 0.026                  | 1.184                         |
|             | 244.7       | 0.209 ± 0.003 | 0.211          | −0.89% | 0.176                                            | 3.318   | 3.70                          |
|             | 344.3       | 0.155 ± 0.007 | 0.154          | 0.58%  | 0.131                                            | 4.472   | 4.52                          |
|             | 356.01      | 0.149 ± 0.006 | 0.150          | −0.67% | 0.126                                            | 4.649   | 5.07                          |
|             | 661.6       | 0.103 ± 0.002 | 0.103          | 0.00%  | 0.087                                            | 6.723   | 6.99                          |
|             | 964.13      | 0.084 ± 0.007 | 0.083          | 1.19%  | 0.071                                            | 8.222   | 9.53                          |
|             | 1085        | 0.077 ± 0.006 | 0.078          | −0.77% | 0.066                                            | 8.921   | 10.32                         |
|             | 1173.2      | 0.076 ± 0.001 | 0.075          | 0.62%  | 0.064                                            | 9.132   | 10.88                         |
|             | 1332.5      | 0.070 ± 0.004 | 0.070          | −0.57% | 0.059                                            | 9.902   | 11.87                         |
|             | 1408        | 0.068 ± 0.002 | 0.068          | 0.67%  | 0.058                                            | 10.089  | 12.00                         |
| Pb40        | 121.8       | 1.060 ± 0.045 | 1.042          | 1.92%  | 0.813                                            | 0.653   | 1.36 ± 0.041                  | 1.306                         |
|             | 244.7       | 0.291 ± 0.017 | 0.287          | 1.24%  | 0.223                                            | 2.382   | 3.68                          |
|             | 344.3       | 0.189 ± 0.022 | 0.191          | −0.58% | 0.145                                            | 3.650   | 5.15                          |
|             | 356.01      | 0.185 ± 0.009 | 0.184          | 0.54%  | 0.142                                            | 3.737   | 5.50                          |
|             | 661.6       | 0.116 ± 0.001 | 0.117          | −0.27% | 0.089                                            | 5.940   | 7.22                          |
|             | 964.13      | 0.094 ± 0.006 | 0.092          | 2.13%  | 0.072                                            | 7.374   | 8.82                          |
|             | 1085        | 0.086 ± 0.003 | 0.086          | 0.12%  | 0.066                                            | 8.050   | 9.69                          |
|             | 1173.2      | 0.082 ± 0.003 | 0.082          | −0.48% | 0.063                                            | 8.402   | 10.39                         |
|             | 1332.5      | 0.076 ± 0.001 | 0.077          | −1.32% | 0.058                                            | 9.120   | 11.47                         |
|             | 1408        | 0.074 ± 0.005 | 0.074          | −0.68% | 0.057                                            | 9.367   | 11.92                         |
| Pb60        | 121.8       | 1.490 ± 0.022 | 1.481          | 0.60%  | 1.046                                            | 0.466   | 1.47 ± 0.034                  | 1.425                         |
|             | 244.7       | 0.368 ± 0.023 | 0.365          | 0.82%  | 0.258                                            | 1.884   | 2.88                          |
|             | 344.3       | 0.225 ± 0.019 | 0.2274         | −1.07% | 0.158                                            | 3.081   | 4.44                          |
|             | 356.01      | 0.221 ± 0.006 | 0.218          | 1.54%  | 0.155                                            | 3.131   | 4.55                          |
Table 9. (Continued.)

| Sample name | Energy (keV) | Measured XCOM | Δ%  | Measured mass ATTENUATION coefficient $\mu_m$ (cm²g⁻¹) | HVL (cm) | Measured density (g cm⁻³) | Calculated density (g cm⁻³) |
|-------------|--------------|---------------|-----|---------------------------------|---------|---------------------|-----------------------------|
| Pb80        | 661.6        | 0.131 ± 0.004 | 0.1303 | 0.53%                          | 0.092   | 5.291               |                            |
|             | 964.13       | 0.099 ± 0.01  | 0.100 | −1.13%                         | 0.069   | 7.010               |                            |
|             | 1085         | 0.093 ± 0.007 | 0.0935 | −0.75%                         | 0.065   | 7.469               |                            |
|             | 1173.2       | 0.09 ± 0.003  | 0.0893 | 0.78%                          | 0.063   | 7.702               |                            |
|             | 1332.5       | 0.083 ± 0.002 | 0.0831 | −0.12%                         | 0.058   | 8.351               |                            |
|             | 1408         | 0.081 ± 0.003 | 0.081 | −0.53%                         | 0.057   | 8.603               |                            |
| Pb100       | 121.8        | 1.850 ± 0.041 | 1.875 | −1.57%                         | 1.198   | 0.375               | 1.59 ± 0.036 1.541         |
|             | 244.7        | 0.438 ± 0.022 | 0.436 | 0.75%                          | 0.285   | 1.580               |                            |
|             | 344.3        | 0.260 ± 0.011 | 0.262 | −0.58%                         | 0.169   | 2.666               |                            |
|             | 356.01       | 0.255 ± 0.006 | 0.251 | 1.72%                          | 0.166   | 2.687               |                            |
|             | 661.6        | 0.140 ± 0.001 | 0.143 | −2.21%                         | 0.091   | 4.940               |                            |
|             | 964.13       | 0.107 ± 0.003 | 0.108 | −1.05%                         | 0.069   | 6.485               |                            |
|             | 1085         | 0.098 ± 0.013 | 0.101 | −2.02%                         | 0.064   | 7.001               |                            |
|             | 1173.2       | 0.097 ± 0.001 | 0.096 | 0.62%                          | 0.063   | 7.161               |                            |
|             | 1332.5       | 0.089 ± 0.004 | 0.089 | 0.11%                          | 0.058   | 7.745               |                            |
|             | 1408         | 0.088 ± 0.004 | 0.087 | 1.14%                          | 0.057   | 7.877               |                            |
| Pb100       | 121.8        | 2.26 ± 0.027  | 2.276 | −0.53%                         | 1.369   | 0.307               | 1.68 ± 0.018 1.654         |
|             | 244.7        | 0.502 ± 0.033 | 0.507 | −0.94%                         | 0.304   | 1.380               |                            |
|             | 344.3        | 0.289 ± 0.01  | 0.296 | −2.28%                         | 0.175   | 2.398               |                            |
|             | 356.01       | 0.31 ± 0.01   | 0.297 | 1.88%                          | 0.183   | 2.287               |                            |
|             | 661.6        | 0.156 ± 0.003 | 0.156 | −0.13%                         | 0.094   | 4.443               |                            |
|             | 964.13       | 0.117 ± 0.005 | 0.116 | 0.60%                          | 0.071   | 5.919               |                            |
|             | 1085         | 0.110 ± 0.007 | 0.108 | 1.82%                          | 0.066   | 6.301               |                            |
|             | 1173.2       | 0.102 ± 0.004 | 0.103 | −0.98%                         | 0.062   | 6.809               |                            |
|             | 1332.5       | 0.095 ± 0.003 | 0.095 | −0.26%                         | 0.058   | 7.287               |                            |
|             | 1408         | 0.092 ± 0.004 | 0.093 | 0.22%                          | 0.056   | 7.469               |                            |
It is obvious from table 9 that the mass attenuation coefficient ($\mu_m$, cm$^2$g$^{-1}$) increased with increasing Pb content. This means that the high Z fillers improve the attenuation of gamma radiation [27]. HVL is other shielding parameters which could be calculated from equation (2), it was observed that its values decrease by increasing Pb content. In other words, the lowering in HVL values means an enhancement in the shielding properties of the composite. The variations of $\mu$ with photon energy for all samples are shown in figure 4. These variations are due to the existence of three different interactions for gamma rays with the polymeric composites. It is clear that the linear attenuation coefficients were decreased with increasing the photon energy and in turn, according to the above-mentioned relation, HVL was increased. Photoelectric absorption is the main interaction process for low energy gamma-ray $\sim 15$ keV to several hundred keV [28]. Its probability depends on $(Z^3/E^3)$ [29, 30], where Z is the atomic number of the filler (Z for Pb $= 82$) and E is photon energy (as seen in table 3). In addition, the probability of photoelectric effect depends on binding energy, so K-electron is the most effective and plays a great role in the increase of attenuation due to photoelectric absorption [31]. According to that, the Pb-K edge is responsible for increasing the attenuation coefficient values at a low energy gamma-ray. The K shell binding energy of Pb is about 88 keV [32] and this illustrates the highest value of $\mu$ around this energy. Compton scattering is the predominant interaction in the intermediate energy from 0.5 MeV to several MeV, while for high energy region greater than the pair production process, it becomes dominant [28, 31]. In this region, the photon energy must be greater than $E_c \gtrsim 1.02$ MeV, the probability of interaction is very small at this value and increases very slowly, and then around 5 MeV and more, it takes a high chance to occur.

4.7.2. Investigation of the gamma radiation shielding properties of W/NR composites

To simplify the measurements and to reduce the number of runs, it was important to determine the optimum content of the added waste rubber and Pb to NR. Therefore, some experimental trials have been done to choose the suitable content of waste rubber that must be used to obtain a blend of W/NR as a protective material, which achieves the required purposes that are obtaining a flexible, lightweight, low-cost substance and has the ability to attenuate gamma rays. These trials began by replacing 10 phr of NR with waste rubber and this percentage increased until it reached 50 phr. Five samples with different content of waste rubber (W10, W20, W30, W40, and W50) were prepared as gamma-ray shielding materials as clear in table 2. The shielding ability for the five samples was investigated by measuring the linear attenuation coefficient using 137 Cs radioactive sources as a test. In order to choose the best blend as $\gamma$-shielding material then, the optimum Pb content (100 phr) is incorporated. Figure 5 shows the variation of linear attenuation coefficient with waste content.

From figure 5, it is clear that by increasing the waste content, the linear attenuation coefficient increased. This means that replacing a portion of virgin natural rubber with waste rubber enhanced the shielding properties at photon energy 661.6 keV and this behavior could be existing in all gamma-ray energies from 121.8 to 1408 keV. Based on the results obtained in this figure, it is observed that W50 recorded the best values of the linear attenuation coefficient. Therefore, W50 was selected and then 100 phr of Pb is added to this mixture blend to obtain 100W50 composite. The selection of Pb content to be 100 phr based on achieving the highest linear

$$\Delta\% = \frac{\mu_{\text{measured}} - \mu_{\text{XCOM}}}{\mu_{\text{measured}}} \times 100 \quad (3)$$

![Figure 4. The variation of linear attenuation coefficient with a photon energy of Pb/NR composites.](image-url)
to Pb0 and Pb100 composites for the same content of Pb was observed. The values of δ as a result of replacing 50 phr of NR in sample Pb0 by 50 phr of waste rubber in sample W50 were 6.9% at energy ranges from 121.8 to 1408 keV. These values showed the effect of waste rubber on the increase of fi.

4.7.3. Comparison between gamma radiation shielding properties of Pb/NR and Pb/W/NR composites

To find out the effect of waste rubber on the Pb/NR properties as a radiation shielding material, we offer a comparison between the measured linear attenuation coefficient values of Pb0, W50, Pb100, and 100W50 composites at (121.8, 244.7, 344.3, 356.01, 661.6, 964, 1085, 1173.2, 1332.5 and 1408 keV). The relative increase rate δ% values between μ of Pb/W/NR composites (μ\textsubscript{W/NR}) and μ of Pb/NR composites (μ\textsubscript{NR}) can be calculated using the following

\[ \delta \% = \frac{\mu_{W/NR} - \mu_{NR}}{\mu_{W/NR}} \times 100 \% \]  

The comparison between the measured values of μ of Pb0, W50, Pb100, 100W50 composites at Pb contents (0 and 100 phr), and relative increase rate δ% at different γ-ray energies are presented in table 10.

As listed in table 10, a significant increase in the values of μ of the W50 and 100W50 composites with respect to Pb0 and Pb100 composites for the same content of Pb was observed. The values of δ% are ranged from 0.7 to 6.9% at energy ranges from 121.8 to 1408 keV. These values showed the effect of waste rubber on the increase of μ as a result of replacing 50 phr of NR in sample Pb0 by 50 phr of waste rubber in sample W50 where the values of δ% are ranged from 5.6 to 24.6% in the same energy range (121.8–1408 keV). From figure 6, it is clear that μ values decreased with increasing the photon energy due to the probability of the three main interactions of photons with the matter as mentioned previously. It is also evident that the curves of 100W50 and W50

Figure 5. The variation between measured linear attenuation coefficient with waste rubber content for \(^{137}\text{Cs}\) (0.662 MeV).

| Energy (keV) | Pb0       | W50       | %     | Pb100      | 100PbW50  | %     |
|-------------|-----------|-----------|-------|------------|-----------|-------|
|             | μ\textsubscript{0 phr} (cm\(^{-1}\)) | μ\textsubscript{0 phr} (cm\(^{-1}\)) | δ%    | μ\textsubscript{0 phr} (cm\(^{-1}\)) | μ\textsubscript{0 phr} (cm\(^{-1}\)) | δ%    |
| 121.8       | 0.168 ± 0.013 | 0.169 ± 0.009 | 0.71% | 2.26 ± 0.027 | 2.45 ± 0.067 | 7.755% |
| 244.7       | 0.133 ± 0.011 | 0.136 ± 0.008 | 2.21% | 0.502 ± 0.033 | 0.352 ± 0.020 | 5.639% |
| 344.3       | 0.117 ± 0.008 | 0.119 ± 0.003 | 1.681% | 0.289 ± 0.010 | 0.320 ± 0.006 | 9.688% |
| 356.01      | 0.112 ± 0.009 | 0.118 ± 0.003 | 5.085% | 0.30 ± 0.010 | 0.316 ± 0.004 | 5.063% |
| 661.6       | 0.091 ± 0.005 | 0.095 ± 0.003 | 4.211% | 0.156 ± 0.003 | 0.187 ± 0.001 | 16.578% |
| 964         | 0.075 ± 0.012 | 0.079 ± 0.003 | 5.063% | 0.117 ± 0.005 | 0.149 ± 0.006 | 21.477% |
| 1085        | 0.070 ± 0.006 | 0.075 ± 0.004 | 6.667% | 0.110 ± 0.007 | 0.135 ± 0.005 | 18.519% |
| 1173.2      | 0.067 ± 0.007 | 0.072 ± 0.002 | 6.944% | 0.102 ± 0.004 | 0.133 ± 0.004 | 23.308% |
| 1332.5      | 0.063 ± 0.009 | 0.066 ± 0.002 | 4.545% | 0.095 ± 0.003 | 0.126 ± 0.004 | 24.603% |
| 1408        | 0.061 ± 0.004 | 0.065 ± 0.003 | 6.154% | 0.092 ± 0.004 | 0.112 ± 0.005 | 17.857% |

The variation of the linear attenuation coefficient values, but it is difficult to increase waste contains more than 50 phr.
composites that contain waste rubber are higher than its coordinates but contains NR only. 100W50 composite had the highest values of linear attenuation coefficients.

In order to examine the effectiveness of the prepared composites as shielding materials, the ratio of HVL of Pb0, W50, Pb100, and 100PbW50 composites to HVL values of pure Pb at different γ-ray energies is presented in Table 11. It is clear that 0.28 cm of 100W50 composite is equivalent to 0.019 cm of lead shield at 121.8 keV, which is 14.89 times the thickness of lead. However, at the higher energy of 1408.01 keV, 6.19 cm of this composite is equivalent to 1.16 cm of lead, which is only 5.31 times the thickness of lead. Therefore, this composite that contains 50 phr waste rubbers and 100 phr of Pb as lightweight material is promising to be used as an absorber for low energy photons and could be used as an alternative for lead shielding.

### 4.8. Density and Heaviness measurements of Pb/NR and Pb/W/NR composites

Table 12 shows the measured densities and heaviness % of Pb0, W50, Pb100, and 100PbW50 composites. According to these results, the replacement of 50 phr of NR with 50 phr of waste rubber increased the density of the composites and this may be referred to as the good shielding efficiency of W50 and 100W50 composites. As well, waste rubber increased the heaviness % of the W50 and 100W50 composites compared to Pb0 and Pb100. Figure 7 exposes the variation of heaviness % of the investigated samples with lead as standard. The heaviness % of 100W50 composite is 17.34%. This means that this composite is lightweight and low-cost shielding material against γ-rays.
5. Conclusion

In this study, Pb/NR and Pb/W/NR composites were prepared as gamma-ray absorbing materials included some characterization methods. The morphological structure of Pb/NR composites was studied using SEM and confirmed that bulk Pb possessed irregular size, shape and tends to form agglomerates at higher loadings in NR matrices. Micrographs of Pb/W/NR composites showed cracks and a number of pull-out holes. Increasing Pb content in Pb/NR composites increased ML, MH, crosslinking density, thermodynamic parameters (ΔG and ΔS), thermal stability, density, heaviness, hardness, and electrical conductivity. While it decreased Tsc, T90, Ts, M300%, and Eb % of Pb/NR composites. Many parameters of shielding have been investigated, such as linear, mass attenuation coefficients, and HVL. The gamma attenuation results indicate that the linear attenuation coefficient increases as the lead content increased. A reasonable agreement between the measured and calculated linear attenuation coefficients have been achieved. The comparison between Pb/NR and Pb/W/NR composites showed that Pb/W/NR composites enhanced the electrical, thermal stability, and the ability to attenuate gamma rays. In addition, these composites had higher values of curing parameters, crosslinking density, thermodynamic parameters, hardness, densities, and heaviness but with low mechanical parameters, values compared to Pb/NR composites. The obtained results demonstrated that the composites of Pb/W/NR are the most promising alternative materials for γ-ray shielding applications. Also, introducing more contents of lead and waste rubber as fillers inside the composite will produce a good shielding material but on the other hand, this will affect the stability of the composite and much future work should be done to solve the problem of stability.

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