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The Effect of Adding Pure Calcium Carbonate and Eggshells on the Linear Absorption Coefficient of Beta Particles for Unsaturated Polyester Resin

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Abstract

The linear absorption coefficient of beta particles in unsaturated polyester resin is an essential factor in radiation protection and medical imaging. This research aims at determining the impact of adding two forms of calcium carbonate, namely, pure calcium carbonate and eggshells on the linear absorption coefficient of beta particles in unsaturated polyester resin. Calcium carbonate and eggshells were selected as fillers since they have the possibility to enhance the radiation shielding capability of the resin. It is also revealed that the incorporation of both calcium carbonate and eggshells can enhance the linear absorption coefficient of beta particles in the unsaturated polyester resin for radiation protection. Further, the incorporation of natural additives such as eggshells is a better option as compared to synthetic fillers. As a result of this study it has been established that the adding of calcium carbonate and eggshells does affect the linear absorption coefficient of beta particles in unsaturated polyester resin. These results have significant implications for the fabrication of materials with desired radiation shielding characteristics and therefore, future work in this field should be continued to elucidate the underlying phenomena and to enhance the effectiveness of these composites.

I. Introduction

Radioactivity is the phenomenon in which an atomic nucleus transforms and releases energy in form of radiation. This phenomenon was first discovered in 1896 by Henri Becquerel and later Pierre and Marie Curie who also added more understanding to it by discovering other radioactive elements such as polonium and radium. It is a natural process that takes place in several elements like uranium and thorium and can also be artificially produced in other substances. There are three main types of radioactive decay: alpha decay in which the nucleus emits an alpha particle, which is made up of two protons and two neutrons; beta decay characterized by the emission of beta particles, which are electrons or positrons; and gamma decay in which the nucleus changes to a lower energy state and emits high energy gamma

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photons. Radioactive decay is the process through which a radioactive substance loses its ability to emit radiation and the manner in which the rate of decay is described is through the radioactive decay half-life which is the time that taken for half of the radioactive atoms in a substance to decay. Radioactivity has numerous uses for instance it is used in the medical industry to diagnose and treat diseases, in production of energy by nuclear power stations, and it is used in various scientific fields to date objects and study natural occurrence (Krane, 1988; Lilley, 2013).

II. Absorption coefficient

The linear absorption coefficient and mass absorption coefficient refer to some of the most basic parameters in the area of material and physical sciences, whereby more specifically they denote the manner in which material is able to absorb a given radiation.

1. Linear Absorption Coefficient (μ): The linear absorption coefficient is the ratio of the number of photons absorbed per second in a material of thickness one to the incident beam intensity; it is represented by the symbol μ. It is a measure of the amount of reduction in intensity of the radiation when it passes through a given substance. There is a direct proportion of the linear absorption coefficient to the properties of the material and the energy of incident radiation. This is given in units of inverse length for instance in cm^{-1}. The mathematical expression for the decrease in intensity, I, of radiation as it passes through a material of thickness x is given by Beer-Lambert's law (Attix, 2004):

$$I = I_0 e^{-\mu x} \quad (1)$$

Where: I_0 is the initial intensity of the radiation.

2. Mass Absorption Coefficient (μ/ρ): Mass absorption coefficient is also defined by its symbol μ/ρ and has a similar quantitative connection with the linear absorption coefficient though the variable is the density (ρ) of the material that is being absorbed. This coefficient, expressed in decibels meters or centimeters per kilogram, allows giving a measure of absorption per unit mass of material, which makes it possible to compare the absorbing properties of two or more materials on a density basis, which I call density coefficient. The units of it are area per mass such as cm^2/g. Mass absorption coefficient is more useful when comparing materials with different densities or when the density of the material may vary with conditions for example temperature (Knoll, 2010). Both coefficients play a significant role in different fields such as computer tomography in medicine, radiation therapy, material analysis and nuclear physics as they help in quantifying the behavior of radiation with matter.

III. The Geiger-Müller (G-M) counter

The Geiger-Müller (G-M) counter is a radiation counter that is widely used in the detection and measurement of ionizing radiation. It is made up of the Geiger-Müller tube which is the measuring component and an electronic circuitry that comprises counting and indication system. The G-M tube contains a gas mixture of argon or Helium with halogen and has a central wire anode surrounded by a cathode. High voltage electrons pass through the gas and ionizes it thus producing positive ions and free electrons. The voltage applied between the anode and the cathode is sufficient to enable these free electrons acquire enough energy to ionize even more of the gas molecules thus resulting in charged particle's explosion. This leads to an actual sluice of current, which is documented by the counter's electronics and is equated to a pulse. The

Geiger-Müller counter is preferred due to several reasons; firstly, the ease of use, secondly, it is highly durable and finally, it is sensitive to all forms of radiation including alpha particles, beta particles and gamma rays. However, to get the energy of the detected radiation, additional filtration or calibrating should be applied, its response is saturated in high fields and radiation rates exceed its limits, therefore, it is not suitable for measuring very high rates of radiation (Knoll, 2010; Wiley. Leo, 1994).

IV. Polymers

Polymers are large molecules produced from smaller and simpler molecules referred to as monomers and linked through a covalent bond to form a long chain. These materials possess a broad spectrum of essential physical and chemical characteristics and hence widely used in everyday life and industries. Polymers can be classified into two main categories: there are two categories of polymers; natural polymers these are the ones that occur naturally and these include cellulose, proteins and DNA, synthetic polymers these are the ones that are man-made, and they include plastics, nylon and synthetic rubber. While the strength, elasticity and durability are the characteristics which define the nature of the polymers, this is dependent on the monomers and the structure of the polymer chains (Young, 1987). Polymers may be further defined concerning their behavior at the temperature level and the types include thermoplastic polymers which become soft when they are heated and become solid when cooled while thermosetting polymers which become permanently hardened when they are heated. This classification is important to study for any use or processing them in different manufacturing technology. Polymers can be defined as the entire structure composed of repeating structural units known as monomers, and the polymer science and engineering is interdisciplinary that covers chemistry, physics and engineering to investigate and improve on the various properties of polymers for specialized uses (Gedde, 1995).

V. Unsaturated Polyester Resin (UPR)

Unsaturated Polyester Resin or UPR is a type of polymer which is extensively used in the composite's industry especially for the fabrication of fiberglass reinforced plastics. These resins are synthesized by the polycondensation reaction between unsaturated dibasic acids or their anhydrides with dials and incorporating a vinyl monomer such as styrene as illustrated in fig. (1). The final available product is a thermoses polymer which can be cross-linked from liquid stage to solid phase at the room temperature with the help of initiators and accelerators for starting and regulating the reactions respectively (Gupta et al., 2017).

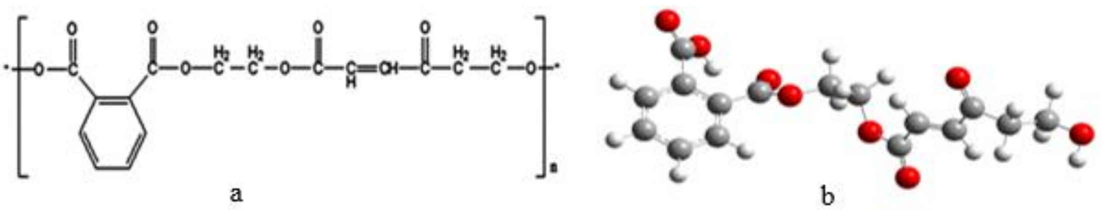

Figure (1): (a) The chemical structure of unsaturated polyester resin, (b) The three-dimensional chemical structure of unsaturated polyester resin, where the gray color represents carbon atoms, white represents hydrogen atoms, and red represents oxygen atoms.

These properties have the possibility to be chemically resistant, mechanically robust, long-lived, as well as being conveniently formable into intricate structures due to its nature, making it highly applicable across almost all industries. Such as automotive parts, marine and building construction, tanks and pipes, electrical component and others. The desirability and applicability of UPR can be further increased by further adapting the resin matrix through the addition of fillers, reinforcements or other substances depending on the desired application characteristics. One of the major characteristics of unsaturated polyester resins is the desaturation level and this is complemented by the added styrene monomer. It means that during the curing process which is triggered by free radicals produced by initiation, crosslinking reactions are possible. This indicates that the cross-link density can be manipulated in an attempt to prescribe the final characteristics of the cured resin in terms of hardness, flexibility, and heat resistance amongst others. This tunability of UPR is very advantageous concerning adaptability to the different industrial applications since they can be configured with varying density and performance without compromising so much on cost (Gupta et al., 2017).

VI. Base materials and reinforcement materials

Base materials and reinforcement materials are common components utilized in material science and engineering especially in composite material systems. Bases are also referred to as matrix materials, and they are found in the continuous phase doing the following: they act as a structural form and also assists in the distribution of mechanical loads to reinforcement materials. The base material can be a polymer, metal, ceramic or glass. A wide variety of polymers such as thermoses and thermoplastics are most frequently used matrices as they are easy to process and offer light weight, and good resistance to corrosion (Hull & Clyne, 1996). Reinforcement materials, on the other hand, are incorporated into the base material to improve properties like strength, rigidity, and wear or corrosion resistance. These can be in the form of fibers, particles or flake like structures. Fibers, consisting of glass, carbon and aramid, are the most preferred reinforcement type due to their high aspect ratio and excellent properties along the fiber's length. The type, size, fractions, position, and dispersion of the reinforcement material all impacts on the characteristic of the final composite material (Mallick, 2007). Thus, base materials set the general structural background and many other characteristics of a composite, and reinforcement materials are introduced to improve one or another mechanical or physical characteristic of a composite.

VII. Calcium carbonate and Eggshell

Calcium carbonate is a chemical compound which has the molecular formula of CaCO3 this material is white, and powder and it is the non-scented material as can be seen in the figure 2. It is present widely in rocks as two minerals, namely calcite and aragonite; it is the chief constituent of limestone which is composed of both the minerals and is the basic element of pearls and shells of some marine animals, snails, and eggs. Calcium carbonate is the principal constituent of agricultural lime and is formed when calcium ions in hard water combining with carbonate ions to form lime scale. In its natural state it is traditionally used to supplement one's diet for calcium intake or used as an antacid but when taken in large amounts it can be lethal. Calcium carbonate is mineral that is found in four main forms: chalk, limestone, marble and calcite. Geochemically, it is created through the accumulation of layers of small fossilized shells of snails and shellfish, corals and other marine creatures that take a very long time, millions of years to form. In commercially, it can be extracted from limestone or marble, and it finds application in construction industry for making cement and concretes.

Figure (2): Pure calcium carbonate.

It also has application in many industries, for instance, in the production of plastics, paints and paper. In the environmental sector, calcium carbonate has its usage in the water and soil treatment activities where it acts as an agent to counteract for the acidity. In the pharmaceutical and especially the food industry calcium carbonate is used as a calcium supplement and as an antacid since the substance is alkaline in nature and will counteract stomach acid. But its consumption must be controlled (National Center for Biotechnology Information, 2021).
While, eggshell is the outer layer of the egg which is mainly composed of calcium carbonate which accounts for nearly 95% of its weight and rest of 5% is constituted by proteins and other organic materials. Eggshells belongs to biodegradable waste materials that have been the subject of research for use as fertilizer, source of calcium for animal feed, bioplastics and construction materials among others. Due to high calcium carbonate content, eggshells are a source that can be recycled and reused in so many ways these include industrial and environmental purposes. (King'ori, 2011; Rovenský et al., 2003; Wong.M, 1984).

VIII. Methodology

The study was conducted to investigate the effect of adding pure calcium carbonate and eggshells to unsaturated polyester resin on the linear absorption coefficient of beta particles. The manual molding method was used to prepare the study samples, which numbered thirty-nine (39) samples, (3) samples for each ratio and each category, and (3) pure non-reinforced samples. The samples were prepared by mixing unsaturated polyester resin and the hardening agent in a ratio of 1:3, where they were thoroughly mixed manually. Different concentrations of calcium carbonate and eggshells were added in the following weight percentages (0.5%, 1%, 1.5%, 2%, 2.5%, and 3%), resulting in (18) samples reinforced with calcium carbonate and (18) samples reinforced with eggshells at the aforementioned ratios and the linear absorption coefficient was measured using a Geiger-Müller counter.

Figure (3): Samples of impure polyester reinforced with pure calcium carbonate and eggshells.

IX. Measurements and data recording

The Geiger-Muller counter is set to a time of (sec60), without using the radioactive source, in order to measure the background radiation ($R_{b.g}$), as shown in Fig. (4a). Then, the beta radioactive source is placed as shown in Fig. (4b), without any absorbing material, where the amount of radiation count for the source (the original intensity of the radioactive source R_0) is measured. Samples of different thicknesses (6 mm,6.3 mm,6.7 mm,12 mm, 13 mm, 19mm) are then placed between the Geiger tube and the radioactive source, as shown in Fig. (5), and the counter reading (count rate, in the presence of the absorbing material R) is taken, and the previous steps are repeated for all samples with different weight ratios.

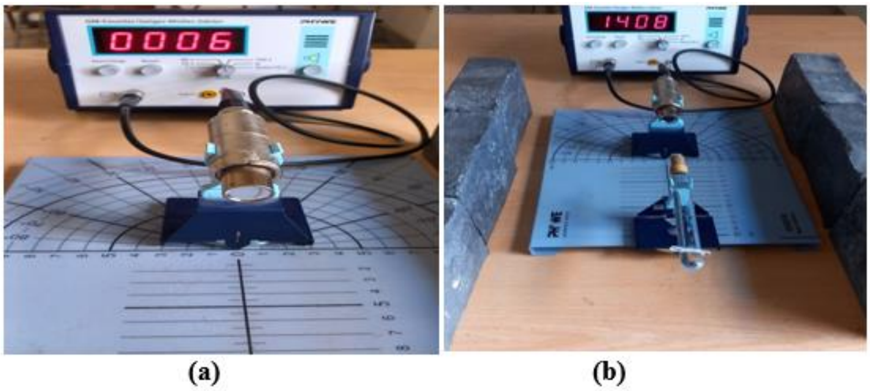

Figure (4): (a) the background radiation, (b) the original intensity of the radioactive source $^{90}_{37}Sr$

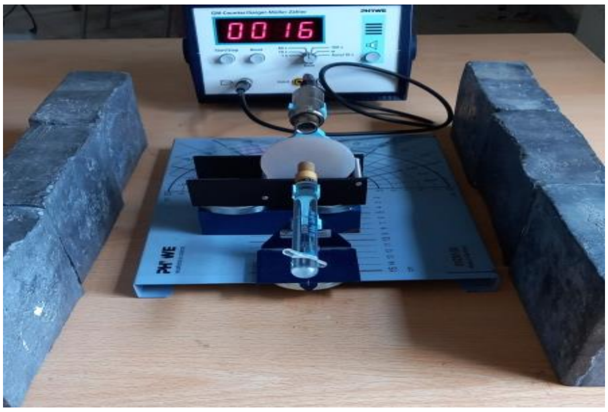

Figure (5): Count Rate in the presence of the absorbing material.

The counter reading in the presence of the absorbing material (R) and in the absence of it (R_0) is corrected by subtracting the background radiation value $R_{b.g}$ from the count rate for each, which represents in this case the true count rate ($R - R_{b.g}$). A relationship is plotted between the logarithms of the net true count rate as a function of the thickness of the material (sample), from which the value of the linear absorption coefficient is calculated practically.
Table [1] shows the counting rate using pure saturated polyester samples as a function of material thickness. Table [2] shows the counting rate using saturated polyester samples reinforced with pure calcium carbonate at different weight ratios as a function of material thickness. Table [3] shows the counting rate using saturated polyester samples reinforced with eggshells at different weight ratios as a function of material thickness. Table [4] shows the linear absorption coefficient for beta rays for polyester samples reinforced with pure calcium carbonate and eggshells at different weight ratios.

Table [1]: the counting rate using pure saturated polyester samples as a function of material thickness.

weight percentage %		0%	
Material thickness (x)mm	Background Counting Rate ($R_{B.G}$)(Count/sec)	Correction Counting rate ($R-R_{B.G.}$)(Count/sec)	Correction Counting rate Ln ($R-R_{B.G.}$)
0	0.167	23.322	3.149
6		0.317	-1.150
6.3		0.167	-1.792
6.7		0.217	-1.529
12		0.028	-3.584
13		0.083	-2.485
19		0.072	-2.628

Table [2]: the counting rate using saturated polyester samples reinforced with pure calcium carbonate at different weight ratios as a function of material thickness.

weight percentage %		0.5%		1%	
Material thickness (x)mm	Background Counting Rate($R_{B.G}$) (Count/sec)	Correction Counting rate (R-$R_{B.G.}$) (Count/sec)	Correction Counting rate Ln (R-$R_{B.G.}$)	Correction Counting rate (R-$R_{B.G.}$) (Count/sec)	Correction Counting rate Ln (R-$R_{B.G.}$)
0	0.167	23.322	3.149	23.322	3.149
6		0.122	-2.102	0.111	-2.197
6.3		0.183	-1.696	0.100	-2.303
6.7		0.117	-2.148	0.083	-2.485
12		0.100	-2.303	0.072	-2.628
13		0.067	-2.708	0.083	-2.485
19		0.089	-2.420	0.094	-2.360
weight percentage %		1.5%		2%	
Material thickness (x)mm	Background Counting Rate($R_{B.G}$) (Count/sec)	Correction Counting rate (R-$R_{B.G.}$) (Count/sec)	Correction Counting rate Ln (R-$R_{B.G.}$)	Correction Counting rate (R-$R_{B.G.}$) (Count/sec)	Correction Counting rate Ln (R-$R_{B.G.}$)
0	0.167	23.322	3.149	23.322	3.149
6		0.133	-2.015	0.183	-1.696
6.3		0.122	-2.102	0.139	-1.974
6.7		0.094	-2.360	0.100	-2.303
12		0.100	-2.303	0.156	-1.861
13		0.117	-2.148	0.122	-2.102
19		0.111	-2.197	0.117	-2.148
weight percentage %		2.5%		3%	
Material thickness (x)mm	Background Counting Rate($R_{B.G}$) (Count/sec)	Correction Counting rate (R-$R_{B.G.}$) (Count/sec)	Correction Counting rate Ln (R-$R_{B.G.}$)	Correction Counting rate (R-$R_{B.G.}$) (Count/sec)	Correction Counting rate Ln (R-$R_{B.G.}$)
0	0.167	23.322	3.149	23.322	3.149
6		0.083	-2.489	0.089	-2.424
6.3		0.111	-2.200	0.089	-2.424
6.7		0.094	-2.363	0.061	-2.801
12		0.144	-1.937	0.077	-2.558
13		0.116	-2.151	0.094	-2.363
19		0.127	-2.060	0.144	-1.937

Table [3]: the counting rate using saturated polyester samples reinforced with eggshells at different weight ratios as a function of material thickness.

weight percentage %		0.5%		1%	
Material thickness (x)mm	Background Counting Rate($R_{B.G}$) (Count/sec)	Correction Counting rate ($R-R_{B.G.}$) (Count/sec)	Correction Counting rate Ln ($R-R_{B.G.}$)	Correction Counting rate ($R-R_{B.G.}$) (Count/sec)	Correction Counting rate Ln ($R-R_{B.G.}$)
0	0.167	23.322	3.149	23.322	3.149
6		0.094	-2.360	0.128	-2.057
6.3		0.228	-1.479	0.150	-1.897
6.7		0.056	-2.890	0.139	-1.974
12		0.089	-2.420	0.061	-2.795
13		0.072	-2.628	0.106	-2.249
19		0.089	-2.420	0.083	-2.485
weight percentage %		1.5%		2%	
Material thickness (x)mm	Background Counting Rate($R_{B.G}$) (Count/sec)	Correction Counting rate ($R-R_{B.G.}$) (Count/sec)	Correction Counting rate Ln ($R-R_{B.G.}$)	Correction Counting rate ($R-R_{B.G.}$) (Count/sec)	Correction Counting rate Ln ($R-R_{B.G.}$)
0	0.167	23.322	3.149	23.322	3.149
6		0.078	-2.554	0.117	-2.148
6.3		0.089	-2.420	0.094	-2.360
6.7		0.094	-2.360	0.094	-2.360
12		0.028	-3.584	0.056	-2.890
13		0.050	-2.996	0.100	-2.303
19		0.061	-2.795	0.061	-2.795
weight percentage %		2.5%		3%	
Material thickness (x)mm	Background Counting Rate($R_{B.G}$) (Count/sec)	Correction Counting rate ($R-R_{B.G.}$) (Count/sec)	Correction Counting rate Ln ($R-R_{B.G.}$)	Correction Counting rate ($R-R_{B.G.}$) (Count/sec)	Correction Counting rate Ln ($R-R_{B.G.}$)
0	0.167	23.322	3.149	23.322	3.149
6		0.106	-2.249	0.089	-2.420
6.3		0.083	-2.485	0.117	-2.148
6.7		0.133	-2.015	0.033	-3.401
12		0.050	-2.996	0.039	-3.247
13		0.078	-2.554	0.083	-2.485
19		0.056	-2.890	0.089	-2.420

Table [4]: the linear absorption coefficient for beta rays for polyester samples reinforced with pure calcium carbonate and eggshells at different weight ratios.

percentage %	Eggshells	pure calcium carbonate
	Linear absorption factor (μ)mm^{-1}	Linear absorption factor (μ)mm^{-1}
0%	0.2791	0.2791
0.5%	0.2311	0.2393
1%	0.2405	0.225
1.5%	0.261	0.214
2%	0.2458	0.211
2.5%	0.2564	0.196
3%	0.2256	0.196

X. Results & Discussion

The results of this study indicate that the addition of calcium carbonate and eggshells to unsaturated polyester resin can significantly affect the linear absorption coefficient of beta particles. From the results we obtained, the relationship between the logarithm (base 10) of the counting rate Ln(R-R_{bg}) and the thickness of the absorbing material X (mm) was graphically represented as shown in the following figures: (6), (7), (8), (9), (10), (11) and (12). Data fitting was conducted for the data shown in tables [1], [2] and [3], and the slope of the straight line for each graph was found, which represents the linear absorption coefficient of beta rays on the samples used in the research as shown in figure (13).

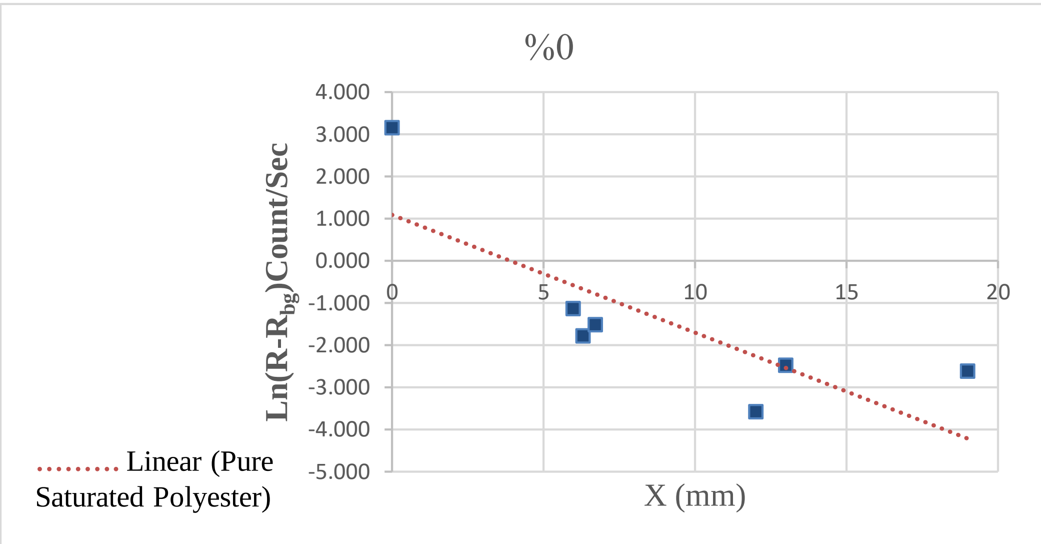

Figure (6): The relationship between Ln(R-R_{bg}) and the thickness of the absorbing material X (mm) for pure saturated polyester samples.

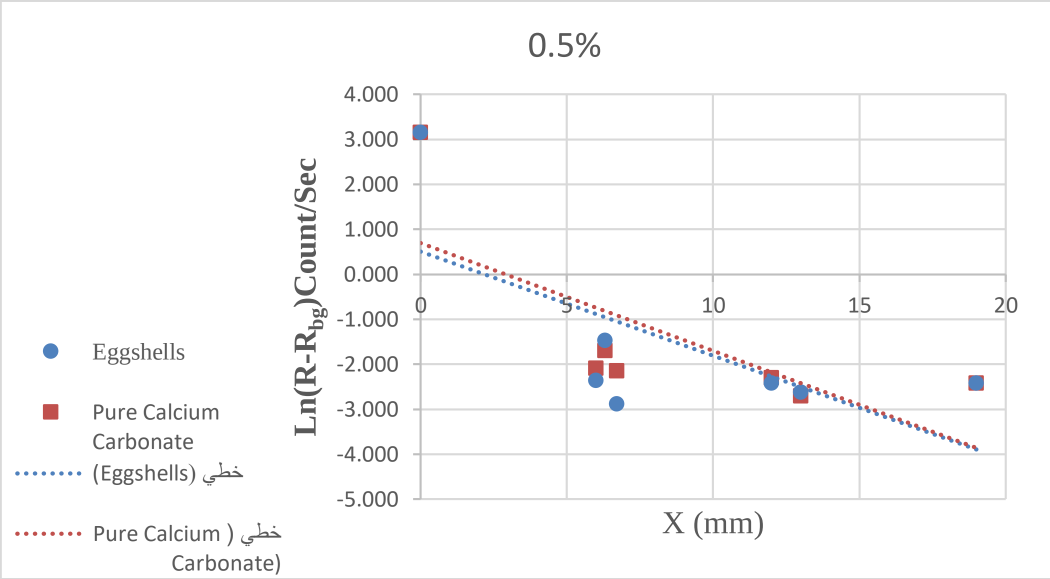

Figure (7): The relationship between Ln(R-R_{bg}) and the thickness of the absorbing material X (mm) for saturated polyester samples reinforced with eggshells and pure calcium carbonate at weight ratio of 0.5%.

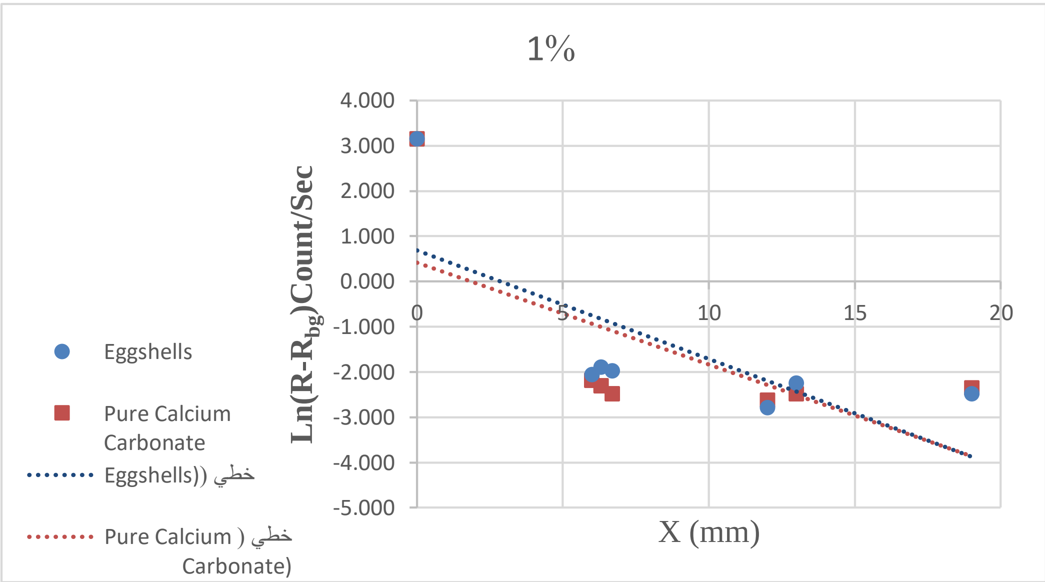

Figure (8): The relationship between Ln(R-R_{bg}) and the thickness of the absorbing material X (mm) for saturated polyester samples reinforced with eggshells and pure calcium carbonate at weight ratio of 1%.

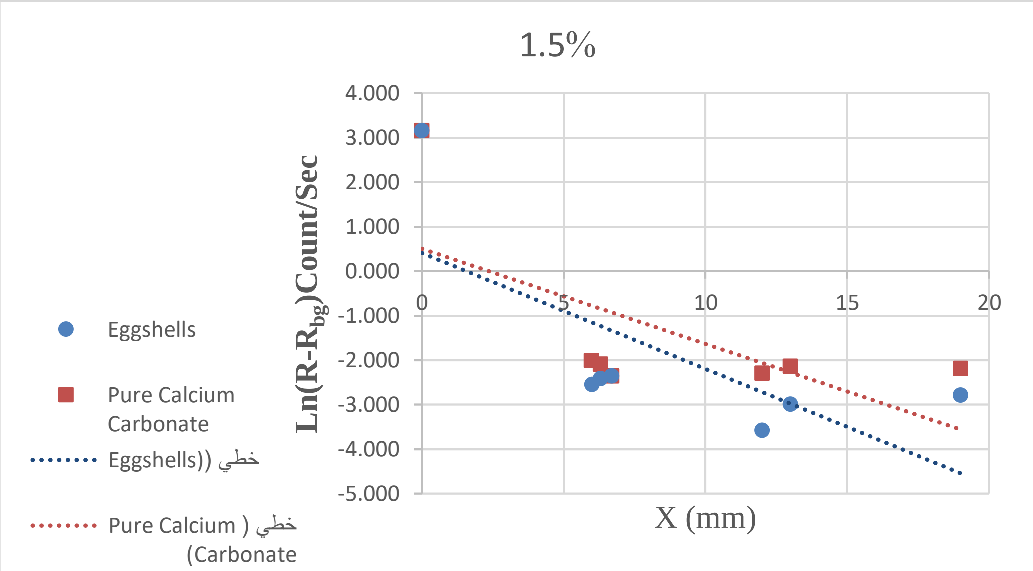

Figure (9): The relationship between Ln(R-R_{bg}) and the thickness of the absorbing material X (mm) for saturated polyester samples reinforced with eggshells and pure calcium carbonate at weight ratio of 1.5%.

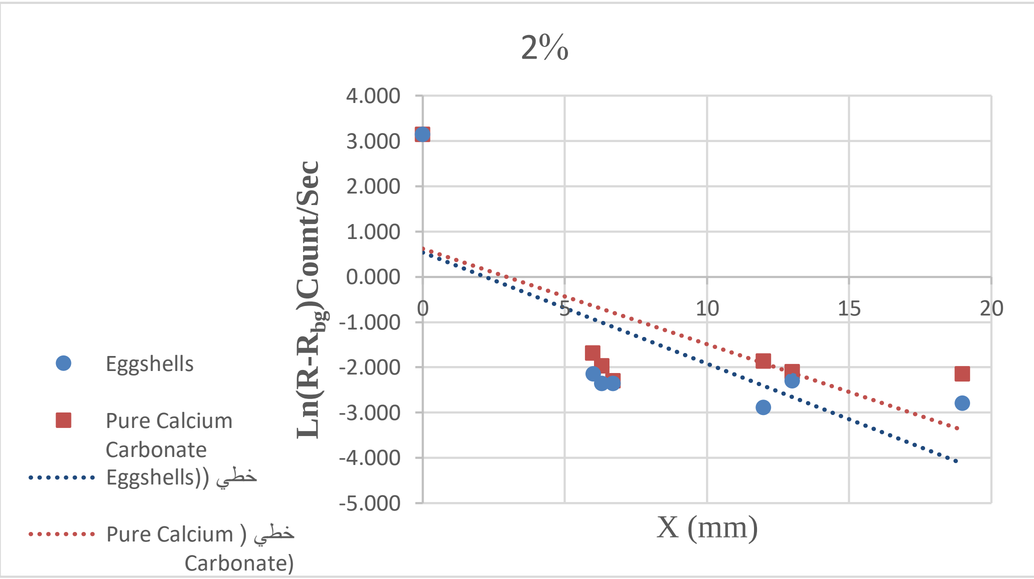

Figure (10): The relationship between Ln(R-R_{bg}) and the thickness of the absorbing material X (mm) for saturated polyester samples reinforced with eggshells and pure calcium carbonate at weight ratio of 2%.

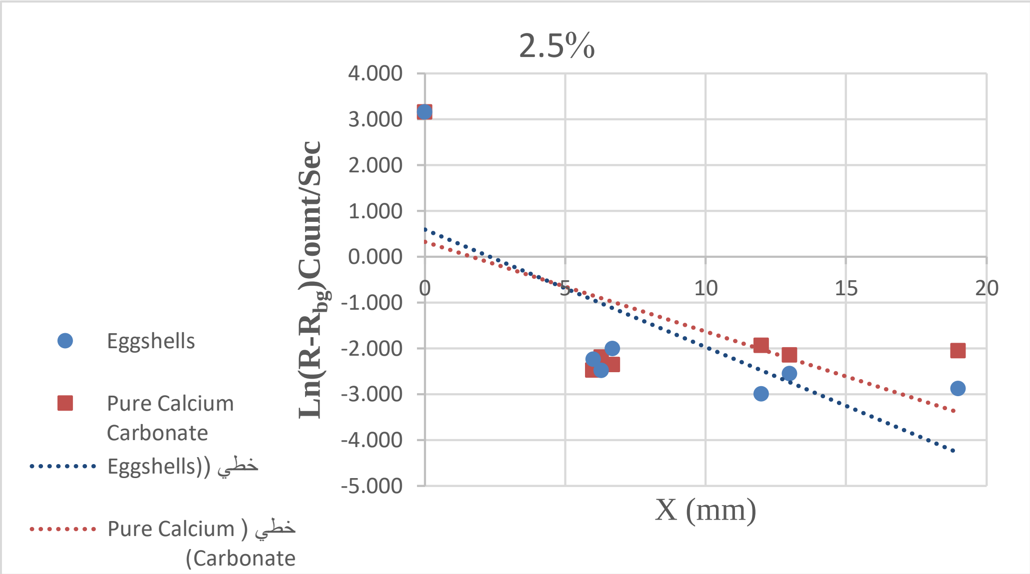

Figure (11): The relationship between $Ln(R-R_{bg})$ and the thickness of the absorbing material X (mm) for saturated polyester samples reinforced with eggshells and pure calcium carbonate at weight ratio of 2.5%.

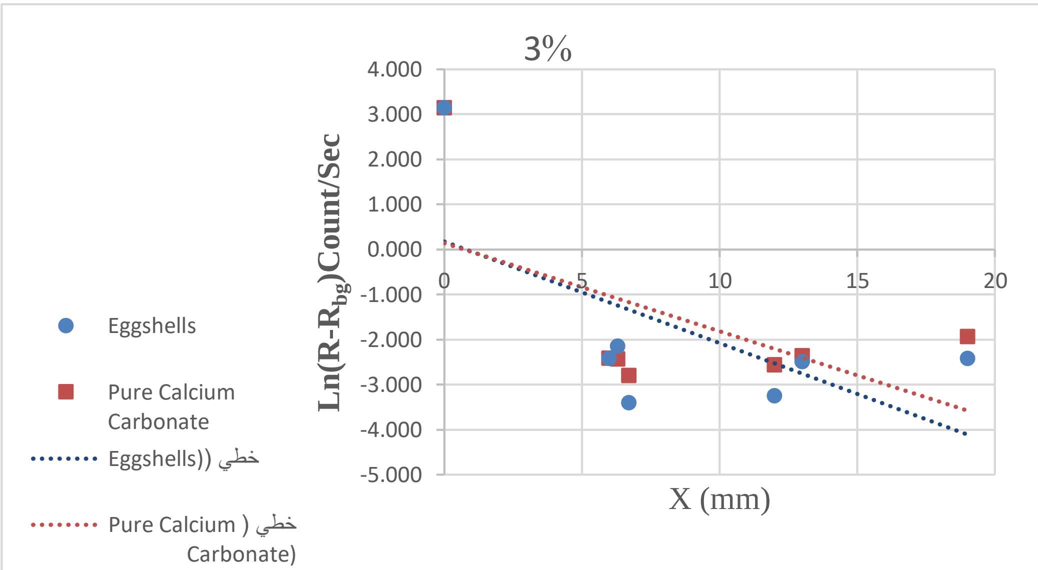

Figure (12): The relationship between $Ln(R-R_{bg})$ and the thickness of the absorbing material X (mm) for saturated polyester samples reinforced with eggshells and pure calcium carbonate at weight ratio of 3%.

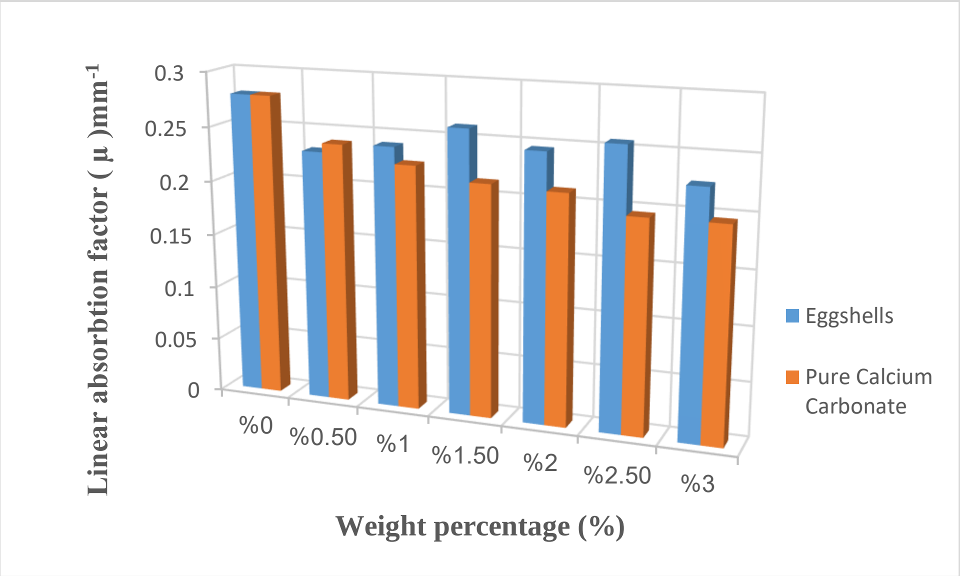

Figure (13): The linear absorption coefficient of beta rays for samples of unsaturated polyester reinforced with pure calcium carbonate and eggshells with different weight ratios.

The study into the linear absorption coefficients of beta rays in polyester samples enhanced with pure calcium carbonate and eggshells at various weight ratios produced notable results. In samples reinforced with pure calcium carbonate, the linear absorption coefficients demonstrated a declining trend with increasing weight percentage of the additive. Specifically, the coefficient measured 0.2791 mm^{-1} for the sample without calcium carbonate, decreasing to 0.196 mm^{-1} at 2.5%, and remaining stable at this level up to 3%. This reflects a reduction of approximately 29.7% in the linear absorption coefficient as the weight percentage of calcium carbonate increased from 0% to 2.5%.

Conversely, the samples reinforced with eggshells displayed a more variable pattern. The linear absorption coefficient began at 0.2791 mm^{-1} for the 0% eggshell sample and fluctuated across the different weight percentages, reaching a maximum of 0.261 mm^{-1} at 1.5% and a minimum of 0.2256 mm^{-1} at 3%. Notably, the absorption coefficient demonstrated an initial increase at 0.5% (0.2311 mm^{-1}) and 1% (0.2405 mm^{-1}), followed by a decrease at higher concentrations, indicating a more complex interaction of the eggshell additive with the polyester matrix. Overall, the results highlight the differing effects of calcium carbonate and eggshells on the linear absorption of beta rays in reinforced polyester composites.

XI. **Conclusions**

1. That as the contents of calcium carbonate and eggshells increase so do the linear absorption coefficients indicating that the two materials could be used to prevent or at least reduce beta radiation.
2. The absorption properties of the composites were found to increase with increase in the ratio of using eggshells as a calcium source instead of pure calcium carbonate, which thus prove that waste such as eggshells have the potential of enhancing the performance of polymer based composites.

3. as for reinforcement options, both selected reinforcements are proved to be viable – pure calcium carbonate and eggshells – besides, each of them provides various benefits.

XII. Recommendations

It is advised that subsequent research should be made on the linear absorption coefficients of gamma rays on the composites used in this research and should compare with the values achieved in the present work. We also suggest investigating their optical and mechanical properties in an effort to confirm the applicability of the eggshells instead of serving pure calcium carbonate as low-cost fillers for the composites which widely vary applications in commerce.

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تأثير إضافة كربونات الكالسيوم النقية وقشور البيض على مُعامل الإمتصاص الخطي لجسيمات بيتا لراتنج البولي استر- غير المشبع

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الملخص

يُعتبر معامل الامتصاص الخطي لجسيمات بيتا في راتنج البوليستر غير المشبع عاملاً أساسياً في حماية الإشعاع والتصوير الطبي. تهدف هذه الدراسة إلى تحديد تأثير إضافة شكلين من كربونات الكالسيوم، وهما كربونات الكالسيوم النقية وقشور البيض، على معامل الامتصاص الخطي لجسيمات بيتا في راتنج البوليستر غير المشبع. تم اختيار كربونات الكالسيوم وقشور البيض كمواد مالئة نظرًا لإمكانية تعزيز قدرة الراتنج على الحماية من الإشعاع. كما تم الكشف عن أن دمج كربونات الكالسيوم وقشور البيض يمكن أن يُحسن معامل الامتصاص الخطي لجسيمات بيتا في راتنج البوليستر غير المشبع لحماية الإشعاع. علاوة على ذلك، يُعتبر دمج الإضافات الطبيعية مثل قشور البيض خيارًا أفضل مقارنةً بالمواد المالئة الاصطناعية. ونتيجة لهذه الدراسة، تم إثبات أن إضافة كربونات الكالسيوم وقشور البيض يؤثر على معامل الامتصاص الخطي لجسيمات بيتا في راتنج البوليستر غير المشبع. لهذه النتائج تداعيات مهمة على تصنيع المواد ذات الخصائص المرغوبة في الحماية من الإشعاع، وبالتالي يجب الاستمرار في العمل المستقبلي في هذا المجال لتوضيح الظواهر الأساسية ولتعزيز فعالية هذه المركبات.

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