Assessment of radiation shielding efficiency in polymeric composites reinforced with natural fibres and multilayered nanoparticles

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Abstract. This study describes the development and assessment of natural, polymeric, and hybrid epoxy-based composites that are reinforced with jute mats or polyethylene sheets and contain 25 wt% lead and 25 wt% boron carbide nanoparticles. According to mechanical tests, polymeric composites performed exceptionally well in flexural strength (45.7 ± 1.2 MPa) and impact resistance (1.75 ± 0.26 kJ/m2), while natural composites had the best tensile strength (10.84 ± 1.8 MPa) and hardness (92 ± 1 HRR). Hybrid composites have offered the midway performance rather than the natural and polymeric composites. The radiation shielding efficiency have been evaluated and provided in SI air kerma values in Ir-192 gamma exposure. The natural composites (14.7 mGy) showed better attenuation when compared to polymeric (19.8 mGy) and hybrid composites (21.5 mGy) in comparison with reference CS plate (15.8 mGy). The results showed that the laminate structure is an important part of multifunctional composites. Polymeric composites make things stronger, while natural fibre systems make things harder and better at protecting them.

1 Introduction

Radiation shielding is the use of materials that can absorb or lower the energy of radiation to protect people and the environment from the harmful effects of ionising radiation. This technique is incredibly important in fields like healthcare, nuclear energy, and scientific research, where being exposed to radiation can be very bad for your health. Lead, concrete, and other types of composites are some of the most common materials used for shielding. What kind of radiation you want to stop and how much of it will help you choose the best material. Because of the higher density characteristic, Lead is used in medical field environment especially in X- ray rooms and has the higher effect in blocking the gamma radiation [1].

Concrete walls with higher thickness have been used in the nuclear powerplants and thereby it can protect the workers from the radiation from radioactive materials. To be safe in such environment, radiation shielding is needed to properly installed in the harmful

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environment. Thereby it can well protect the patients, workers, and the public from radiation contact, which drops the threat of receiving sick from radiation. Through the enhancement in the technology, investigators are always looking for methods to improve shielding materials and procedures. This means that areas with a lot of radiation have robust safety standards and procedures [2].

The four essential properties that affect how well composite materials can block and resist radiation are density, effective atomic number, thickness, and filler dispersion. Materials with higher density are often preferred as it can increases the shielding effect and thereby it can prevent the interaction. A higher effective atomic number (Zeff), like lead, makes it easier for the photoelectric and Compton effects to absorb γ-rays. Further, increasing the shielding thickness is also crucial in resisting the radiation and resulted in longer contact path. Boron carbide and other fillers are also adequate in blocking neutrons by holding them in a radiation field. In the context of polymer matrix in multifunctional composites the usage of nanoparticles is recommended with even distribution throughout the matrix. This prevents them from bonding together, which retains gaps from forming and ensures that the composite material absorbs the radiation consistently.

The focus on medical use has led to the development of more accurate shielding technologies that make treatments safer and more effective. There has also been a move towards materials that are safer and don't have lead in them. To keep the higher standards and to provide the safer environment the regulatory bodies are working harder and suggesting the updates in the radiation standards frequently. They ensure this by making sure that safety rules are both firm and helpful. To protect humans and the environment from ionising radiation, radiation shielding technologies need to improve. This is because industries like healthcare and space exploration need more protection from radiation. Research and development will need to focus on bigger technologies that are light, work well, and are beneficial for the environment in the future [3].

Keeping all the above said facts into consideration, the developments in the shielding against radiation the positive approach to keep individuals safe from the destructive effects of ionising radiation. Also, continuous attempts were made by the researchers to identify the finest materials for better shielding in the risks of radiation. During the initial stages, lead aprons in the hospitals were simply used as a protective west. The continuous developments in radiation shielding are well apparent in achieving the safety standards in thrust areas. Through the continuous attempts new materials, composites and nanomaterials, can be manufactured and tailored for the specific needs. These materials are making shielding solutions more helpful and effective. The role of smart manufacturing allows the researchers to make shielding systems that can be highly effective and respond to diverse conditions.

Laterally with standard lead and concrete barriers, there is an increasing attention in polymer-based nanocomposites. These composites are preferred for its user-friendly nature, light weight and higher adoptability to the variety of environments

Scientists are looking into using polymers and high-density fillers to make composites that protect against radiation. For instance, epoxy composites with BiO_3 particles at the micro and nanoscale have been shown to be stronger against heat and mechanical stress, as well as better at blocking γ-rays. Polypropylene filled with BiO_3 nanoparticles has shown that metal oxide fillers work well in polymer matrices. This is because polypropylene does a good job of blocking gamma rays. The creation of PE–B_4C concrete systems for better neutron shielding in neutron attenuation shows that adding boron carbide can make systems based on hydrogen-rich polymers much better. Most of the research on jute fiber-based composites for structural use has been done in places where they are used to stop bullets or electromagnetic interference, not to protect against ionising radiation.

This study presents a dual nanoparticle system comprising lead and boron carbide, which enhances a hybrid laminate structure composed of jute mats and polyethylene sheets, thereby

advancing the field. This makes it possible to improve both mechanical strength and the ability to block many types of radiation (neutron and gamma) at the same time. This work also includes measurements of radiation shielding based on SI (air kerma, HVL, TVL) that are compared to steel. It also includes mechanical tests including tensile, flexural, impact, and hardness tests that use ASTM standards and statistical analysis.

2 Materials and methods

To ensure the validity and reproducibility of the study, the Materials and Methods chapter describes the precise tools and techniques utilised to carry out the investigation.

2.1 Natural composites

Natural fibre compounds from minerals, plants, or animals are essential in many fields, but mainly in textiles and composite materials. Some well-known examples are cotton, wool, hemp, and jute. Each of them has its own specific qualities, such being able to store moisture, breathe, and keep heat in. These fibres are strong, light, and make fabrics appear better, which makes them more comfortable and improves the quality of the product as a whole. Natural fibres are a highly essential resource today that people are more concerned about the environment. This is because they can be utilised in numerous ways, are helpful for the environment, and operate effectively [4]. Because jute mats are flexible, you may easily shape them into many different patterns. This means they can be utilised for many tasks, such shaping and reinforcing composite materials. Jute mats are also light and possess low bulk density makes the transportation and handling easier in all stages. The jute fibre density (1.3–1.4 g/cm³), makes the material as light to its extent [5].

2.2 Polymeric composites

Polymeric composites are contemporary materials that contain a polymer matrix with reinforcing elements, such as fibres or particles, that make them tougher, more flexible, and better at carrying heat and electricity. They are becoming more common in several areas, including aircraft, vehicles, sports equipment, and construction, because they are light, durable for their weight, and can be used in many different ways. Adding things like glass, carbon, or natural fibres to these composites can make things stiffer, more resistant to impact, and last longer, all while keeping them light. You can modify the type and arrangement of the reinforcing fibres to give them various mechanical and thermal properties. This provides engineers and manufacturers a lot of freedom to make things to customise in their own way. Polymeric composites are a great choice for many things since they are cheap, flexible, and function well [6].

Polyethylene is a kind of plastic that is made by putting together ethylene monomers. This material is very flexible and cheap, and it may be used for a number of things, such as packaging, construction, medical equipment, and industrial purposes. Some types of radiation, such gamma and X-rays of lower energy, can't get through polyethylene. It is quite resistant to a lot of things, which implies that the protective substance will last and stay strong [7].

2.3 Nano particles

Boron (10B) is the best material for shielding since it has a large cross section for neutrons at all energy levels. When boron combines with neutrons, it doesn't send off any extra radiation. Lithium and Helium are stable isotopes that come from this mechanism. Boron carbide is utilised to soak up nuclear radiation because it has a lot of boron atoms in it. Boron carbide can keep its shape and protect itself at high temperatures because it has a very high melting point, about 2,350°C (4,270°F) [8].

Lead may greatly reduce some types of radiation since it is dense and has a high atomic number. It performs a wonderful job of keeping gamma and x-rays out. Lead is good at blocking radiation because it has a very high density (11.34 g/cm³). Lead is good at blocking radiation, especially gamma rays and X-rays, because it has a high atomic mass. Lead can be used as a preferred alternate to stop gamma rays and X-rays [9].

2.4 Epoxy resins

Epoxy resins can stick better and it's easier to attach with boron carbide and natural fibres. This makes the composite stronger in both tension and compression, which makes the structure stronger. There are variety of ways to use the epoxy resin, which is a type of polymer. It is very valuable in composite materials since it sticks well, is strong, and lasts a long time. The curing process makes a network of cross-linked polymers that gives the resin the strength and heat resistance it needs [10].

The first version of the composite material is made of jute mat, lead, and boron carbide, which are held together by epoxy glue. The second kind of composite material is made up of a polythene sheet, lead, and boron carbide as fillers. Epoxy resin strengthens it. The third kind of composite material is made up of a jute mat and a polythene sheet, with lead and boron carbide as fillers. It is also strengthened with epoxy resin. Figure 1 demonstrates the steps that go into making three different samples [11].

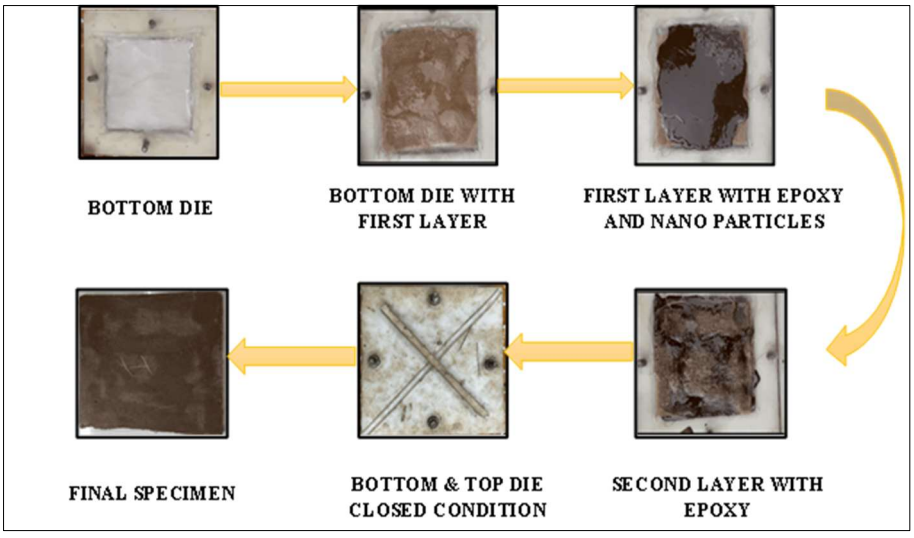

Fig. 1. Sample preparation by hand layup method.

Table 1. Material preparation.

SC*	Composite Type	SS*	Ply Count (Total)	BL*	TL*	Pb (wt %)	B_4C (wt%)	Epoxy (wt %)	FLT* (mm)
Sample 1	Natural Fiber Composite	[Jute / Matrix / Jute]	3 plies (2 Jute + 1 Matrix)	Jute Mat	Jute Mat	25	25	50	**5.1**
Sample 2	Polymeric Composite	[PE / Matrix / PE]	3 plies (2 PE + 1 Matrix)	PE Sheet	PE Sheet	25	25	50	**4.9**
Sample 3	Hybrid Composite	[Jute / Matrix / PE]	4 plies (1 Jute + 1 PE + 2 Matrix)	Jute Mat	PE Sheet	25	25	50	**5.3**

*SC – Sample Code, SS -Stacking Sequence, BL – Bottom Layer, TL – Top Layer, FLT – Final Laminate Thickness.

Lead and boron carbide (B4C) filler materials were added to the polymer matrix in the current investigation on a weight percentage (wt%) basis, each of which made up 25 wt%. While the polyethylene (PE) sheets were measured using a thickness of 0.20 mm and mass per unit area of 190 g/m2, the jute reinforcement was quantified using an areal density of 360 g/m² and a matching average thickness of 0.45 mm per mat. Table 1 shows the full reconciliation of the laminate composition, which includes the PE sheets, jute mats, filler particles, and polymer matrix. Depending on the type of composite, the laminates were manufactured using clearly defined stacking sequences.

Sample 1: Natural Fibre Composite: ply count: 3 plies (2 jute mats + 1 matrix layer), stacking sequence [Jute / Matrix / Jute].
Sample 2: Polymeric Composite: ply count: 3 plies (2 PE sheets + 1 matrix layer), stacking sequence [PE / Matrix / PE].
Sample 3: Hybrid Composite: ply count: 4 plies (1 jute mat + 1 PE sheet + 2 matrix layers), stacking sequence [Jute / Matrix / PE].

The average thickness of each jute mat is 0.45 mm, and its area weight is 360 g/m². Sheets of polyethylene (PE) weigh 190 g/m² and are 0.20 mm thick every sheet. All samples used epoxy as their polymeric matrix, with fillers added at 25 weight percent lead and 25 weight percent B4C (in relation to the polymer matrix); as a result, the matrix fraction is 50 weight percent epoxy. The reinforcement layers were impregnated with the matrix-filler combination, and all samples were hot-pressed under the same pressure and temperature conditions.

A calibrated micrometre was used to measure the final laminate thicknesses at five different points, and the results were averaged. Samples 1, 2, and 3 had mean final thicknesses of 5.1 mm, 4.9 mm, and 5.3 mm, respectively. These architectural and thickness values are reflected in the specimens used for the tensile, flexural, impact, hardness, and

radiation shielding tests, which were cut from these consolidated laminates. The specimens were prepared according to ASTM standards.

The boron carbide (B4C) nanoparticles utilised in this investigation had an average particle size of 80–100 nm and a distribution range between 60 and 150 nm. A three-step mixing process was used to ensure homogeneous dispersion within the polymer matrix: (i) B_4C nanoparticles were first mechanically sheared in ethanol at 1000 rpm for 30 minutes; (ii) the suspension was probe sonicated at 200 W for 20 minutes to break down soft agglomerates; (iii) the solvent was evaporated, and the nanoparticles were added to the polymer matrix while being continuously stirred at 120 °C. The chosen dispersion methodology has been well documented in the literature to reduce nanoparticle agglomeration and encourage uniform distribution within polymer matrices, despite the fact that no direct microstructural imaging (such as SEM) was carried out in this investigation.

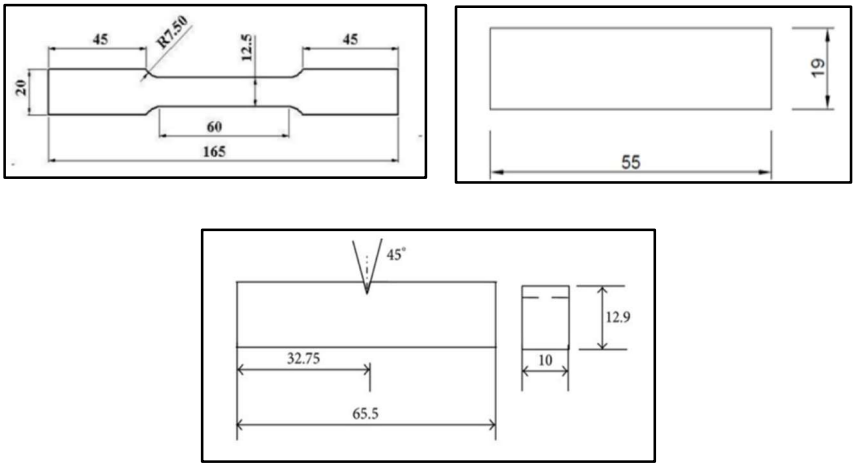

Fig. 2. Mechanical test specimens' dimensions.

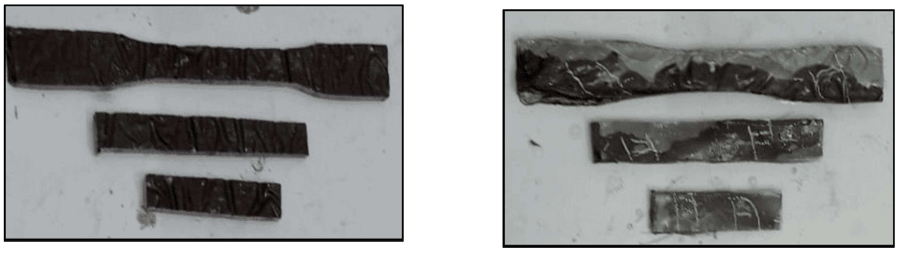

Fig. 3. Polymeric and hybrid composite specimens for mechanical testing.

The sample dimensions for various mechanical tests are presented in Figure 2, with measurements in millimetres. Figure 3 represents the polymeric composite and hybrid composite samples intended for mechanical testing.

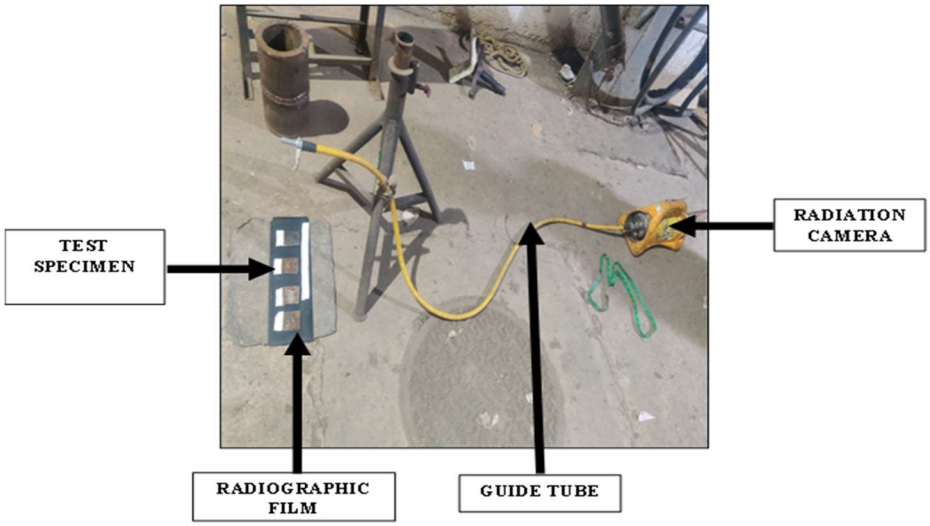

Fig. 4. Set up of radiographic testing using gamma rays.

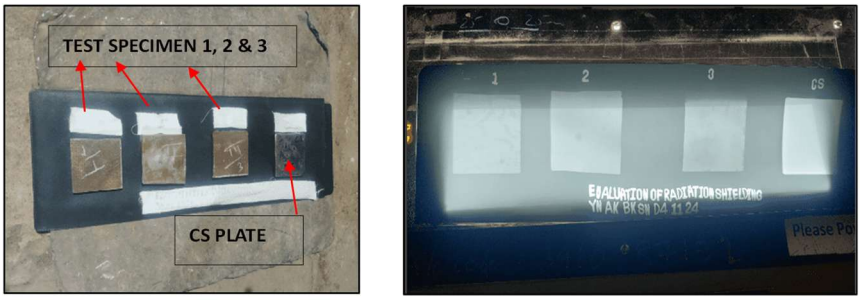

Fig. 5. Composite samples and cs plate for radiation testing and radiographic film after developing process.

Figure 4 illustrates the configuration of radiographic testing utilising gamma rays, including all requisite components. Figure 5 illustrates the composite test specimens and CS plate designated for radiation testing. It also illustrates the radiography film of various test specimens following development for optical density evaluations.

3 Results and discussions

To evaluate the mechanical strength of the samples, the following tests were conducted. Ultimate tensile strength was assessed using tensile testing, flexural strength was determined via flexural testing, impact energy was quantified using impact testing, and hardness was evaluated through hardness testing. All assessments were conducted in accordance with ASTM standards [12].

In order to guarantee reproducibility and comparability, mechanical characterisation was carried out in compliance with accepted test procedures. A universal testing machine was used to perform tensile tests in accordance with ASTM D638 (Type I specimens) at a crosshead speed of 5 $mm \cdot min^{-1}$; the specimen dimensions meet the Type I geometry requirements of the standard. With a span-to-depth ratio of 16:1, flexural properties were assessed in three-point bending in accordance with ASTM D790. Impact resistance is expressed in $J \cdot m^{-1}$ and was evaluated using the Izod notched impact method (ASTM D256).

The Rockwell M scale, which is appropriate for polymeric composites, was used to assess hardness in accordance with ASTM D785. Prior to testing, all specimens were conditioned for 48 hours at 23 ± 2 °C and 50 ± 5% relative humidity. Five specimens were assessed for every test and material group. The values that are reported are the mean ± SD.

3.1 Tensile test results

Using three different samples of each type, the ultimate tensile strength was measured. The average values were 10.84 MPa for natural fibre composites, 5.07 MPa for polymeric composites, and 3.44 MPa for hybrid composites. Figure 6 displays the different numbers that were being looked at throughout the tensile test. The natural composite specimen exhibited the highest ultimate tensile strength, measuring 12.56 MPa. Hybrid composites exhibited diminished tensile strength in comparison to natural fibre composites, presumably due to variations in fiber-matrix adhesion and mechanical incompatibility among fibres. Microstructural flaws, fibre clustering, and unequal stress distribution make load carrying even less effective. The anticipated synergistic impact of hybridisation was not realised.

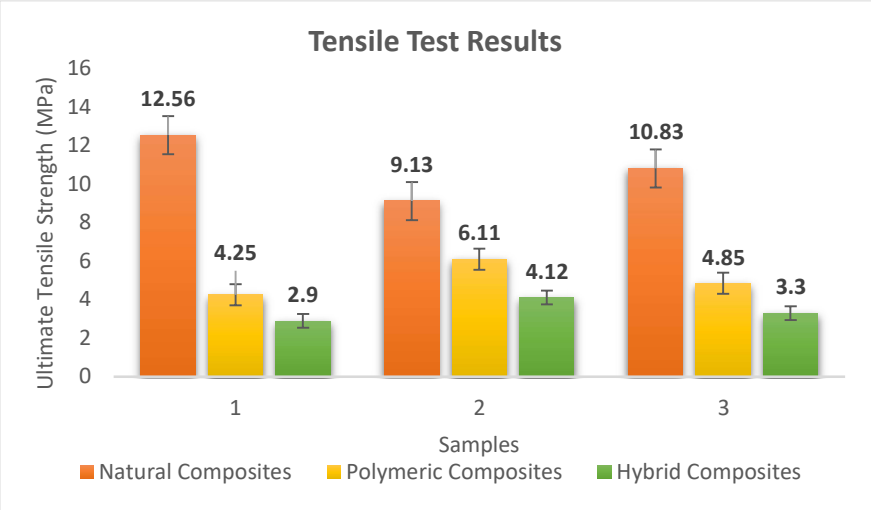

Fig. 6. Tensile test results.

3.2 Flexural test results

The flexural strength of composites tells you how well they can handle bending forces. This is a key way to quantify stiffness, durability, and how well the fibres and matrix work together when the structure is under stress. We measured the flexural strength, and the average values were 40.3 MPa for natural fibre composites, 45.7 MPa for polymeric composites, and 20.5 MPa for hybrid composites. The flexural test measured varied values, which are shown in Figure 7. The polymeric composite sample exhibited the maximum flexural strength, which was 46.5 MPa.

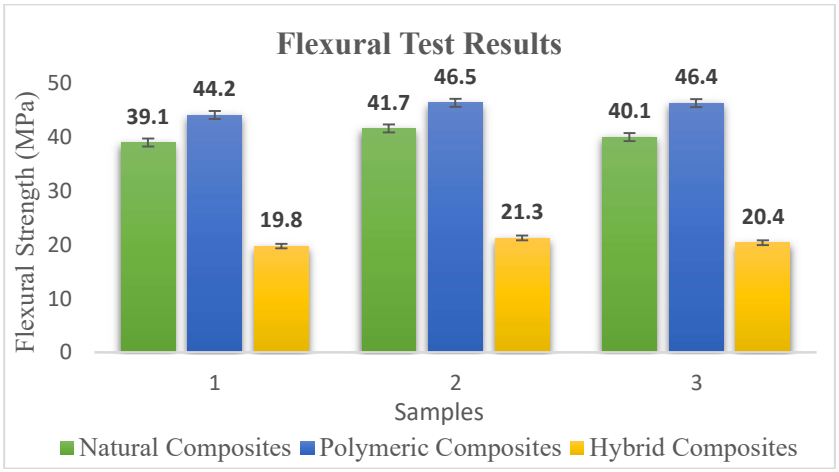

Fig. 7. Flexural test results.

3.3 Impact test results

In low-velocity impact testing, the impact energy of a composite material shows how well it can absorb stress without breaking or delaminating. This is mostly based on how strong the fiber-matrix adhesion is and how well the material can spread energy. The impact energy was measured, and the average values were 0.85 kJ/m² for natural fibre composites, 1.75 kJ/m² for polymeric composites, and 1.14 kJ/m² for hybrid composites. The impact test measured different values, as you can see in Figure 8. The polymeric composite sample had the highest impact energy, which was 1.75 kJ/m^2. Polymeric composites were better at withstanding impacts because their strong, flexible matrix spreads and absorbs energy well. Strong bonding between the fibre and the matrix, as well as even spacing of the fibres, help move loads. On the other hand, things like fibre pull-out and matrix yielding help spread energy. These properties work together to make the impact performance better than that of natural and hybrid composites.

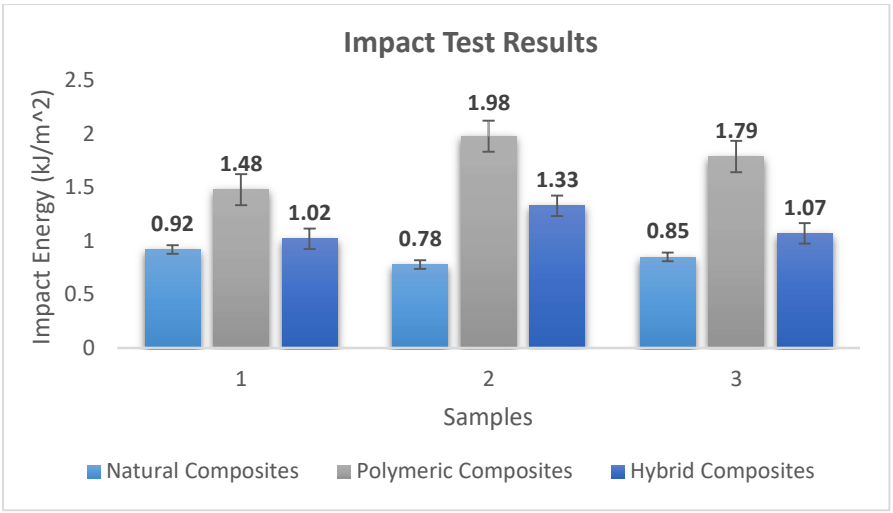

Fig. 8. Impact test results.

3.4 Hardness test results

The hardness value of each specimen has been measured in different locations and the average values across the samples have been provided in this section. The pictures have error bars that shows the difference in the measurements, and also gives a better idea about the hardness property of the composites. The hardness was measured, and the average values were 92 HRR for natural fibre composites, 90 HRR for polymer composites, and 85 HRR for hybrid composites. Figure 9 displays the different numbers that were recorded during the hardness test. These numbers don't fluctuate too much. The natural composite sample had the maximum hardness value, which was 93 HRR.

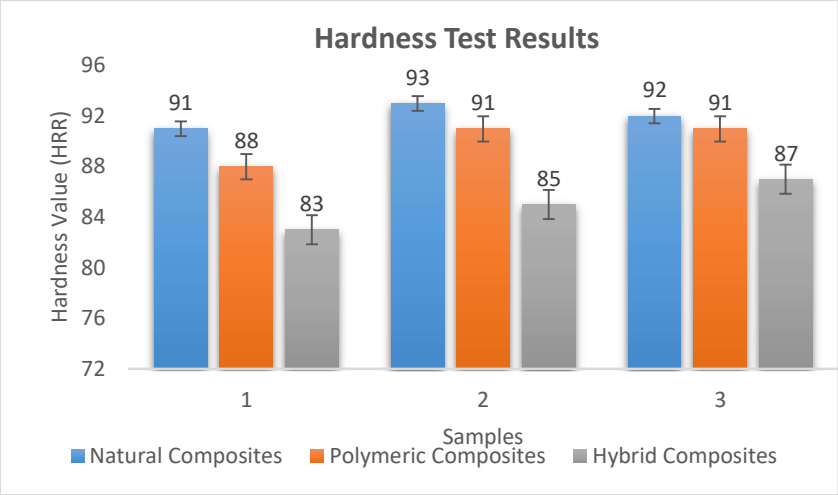

Fig. 9. Hardness test results.

3.5 Radiation test results

The Radiation density is the amount of energy that a composite material absorbs or transmits when it is exposed to electromagnetic radiation. It also tells you how stable the material is at high temperatures, how it breaks down, and how well it can block radiation. We used an Ir-192 gamma source (average photon energy ≈ 380 keV, SSD = 50 cm, SOD = 45 cm) to test the radiation shielding effectiveness of three composite specimens and compare them to a conventional carbon steel (CS) reference. As demonstrated in Figure 10, the natural composite specimen (density = 1.7 g/cm³) had the most attenuation of the three. The hybrid composite (density = 2.5 g/cm³) and polymeric composite (density = 2.27 g/cm³) had a lot less attenuation.

The Beer-Lambert relation was used to find the linear attenuation coefficients (μ) from the observed exposure data. This was done to make shielding performance by thickness more consistent. After that, the half-value layer (HVL) and tenth-value layer (TVL) values were calculated. The results demonstrate that the natural composite was better at minimising sound because it had the lowest HVL (0.92 cm) and TVL (3.05 cm). This is different from the polymeric composites (HVL = 1.15 cm; TVL = 3.83 cm) and the hybrid composites (HVL = 1.21 cm; TVL = 4.02 cm). All three composites proved that they might be employed as lightweight shielding solutions when compared to CS. Their shielding performance was competitive, but their densities were far lower.

The findings showed that the natural fibre composite (1.7 R - 14.9 mGy) had the best shielding of all the produced laminates. It even let through less radiation than the CS plate

reference (2.0 R - 17.5 mGy). The polymeric composite (2.27 R - 19.9 mGy) and the hybrid composite (2.5 R - 21.9 mGy) both let through more radiation than the CS plate and the natural composite. This means that they don't do as good of a job of blocking radiation.

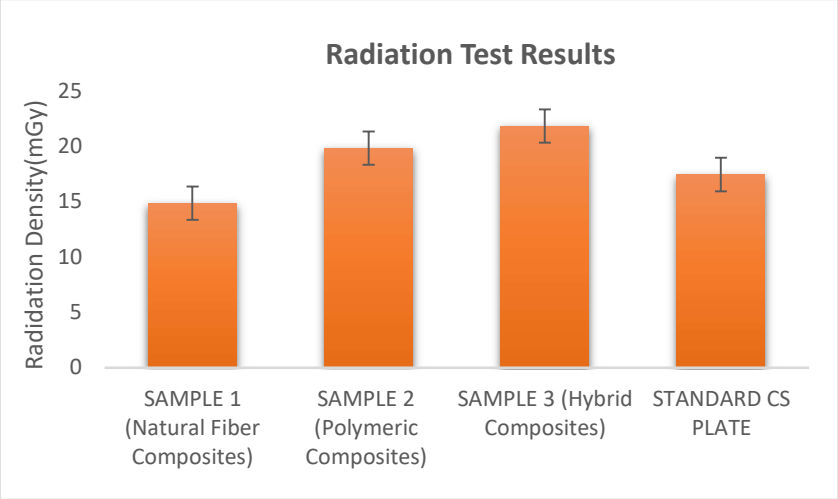

Fig. 10. Radiation test results.

4 Conclusion

The Natural Fibre Composite got the best tensile strength (10.84 MPa) and the highest flexural strength (40.3 MPa) in the mechanical test. The Polymeric Composite, on the other hand, was better at withstanding impacts, with a rating of 1.75 kJ/m². The hardness test showed that natural composites had a hardness of 92 HRR, polymeric composites had a hardness of 90 HRR, and hybrid composites had a hardness of 85 HRR. The radiation test with the assessment of shielding effect resulted that the natural fibre composites with lead nanoparticles are highly effective in radiation exposure. The Natural Fibre Composite (1.7 R ~ 14.9 mGy) was the utmost preference at blocking radiation. It let through even less radiation than the CS plate (2.0 R = 17.5 mGy). The Polymeric Composite (2.27 R = 19.9 mGy) and the Hybrid Composite (2.5 R ≈ 21.9 mGy) allow more radiation, which means they weren't as good at blocking it. The results show that natural fibre composites are strong and better at blocking radiation. This makes them great for aviation, medical imaging, and light structural systems. Future study will concentrate on improving nanoparticle ratios and corroborating results via computational simulations.

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