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Heavy Concrete Attenuation Study as Radiation Shield in Proton Therapy Using Monte Carlo Simulation

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Abstract

This research was conducted to attenuation of various types of concrete as shielding materials against neutron and photon radiation emitted from a proton source with an energy range of 100 MeV - 230 MeV. The MCNP 6.2 code is used to analyze the interaction of radiation with shielding materials, specifically on linear energy deposition (MeV/g) from various shield thicknesses and the linear attenuation coefficient (μ) as well as the mass attenuation coefficient (μ/ρ) from different energy ranges. The materials analyzed include concrete with heavy aggregates such as hematite and galena, compared to Low Activation Concrete (LAC). The research results show that the values of μ and μ/ρ decrease as the energy used increases. In a high-energy proton source, the values of μ and μ/ρ tend to be smaller because protons have high momentum and can penetrate materials more efficiently. Heavy galena concrete has a higher linear attenuation coefficient value of 0.073116 cm^{-1} compared to heavy hematite concrete 0.049318 cm^{-1} and LAC 0.056358 cm^{-1}. The selection of shielding material must consider not only the thickness of the shield but also the density and composition of the material's elements that affect its high radiation absorption capacity. From the research, this type of concrete can be used as a reference for making effective heavy concrete shields in proton therapy.

Keywords: Heavy Concrete, Attenuation, Shielding, Proton Therapy, MCNP 6.2

Introduction

Proton therapy is an increasingly popular modality in radiation therapy techniques. Proton therapy utilizes high-energy protons to destroy cancer cells by delivering a high radiation dose precisely to the tumor and a minimal dose to the healthy organs surrounding the tumor. The use of high energy requires facilities specifically designed to ensure radiation safety for workers, the public, and the environment. Therefore, radiation shielding is a fundamental aspect that must be considered to ensure effectiveness and safety during the operation of proton therapy. The shielding aims to slow down and absorb neutrons into thermal energy to reduce the effective dose equivalent from the source to the environment.

Things to consider for radiation shielding are the type of radiation source, dose limits, and the design of the shielding. Until now, lead has been a popular material used as radiation shielding, but it has several significant drawbacks such as toxicity, low mechanical properties, and low stability [1]. Therefore, the development of materials for radiation shielding continues, and the use of concrete has become an effective choice due to its wide availability, low cost, good durability, extensive application in buildings, high density, and large atomic structure, which enables it to block gamma rays and neutrons [2]. The effectiveness of concrete as a shielding depends on the selection of the materials used, such as the addition of high-density aggregates, which will produce a type of heavy concrete that has better capabilities as a shielding compared to conventional concrete.

Heavy concrete is a composite material specifically made by combining heavyweight aggregates such as magnetite, hematite, and barite to achieve very high density [3]. Then, several types of synthetic aggregates, such as iron ore, are designed to optimize the radiation shielding capability of concrete, which ranges from 2400 kg/cm^3 to 4000 kg/cm^3 or higher [4]. Examining the development of Ultra High Performance Concrete (UHPC) using a combination of heavy aggregates such as magnetite, hematite, ilmenite, and barite, as well as the use of steel fibers, lead fibers, and basalt fibers [5]. The use of several nanomaterials NPPbO, TiO_2, Fe_2O_3, ZrO_2, and $ZnFe_2O_4$ to enhance the effectiveness of radiation shielding [6, 7].

As mentioned, many studies have been conducted to create shielding with high effectiveness. However, there is still little research on radiotherapy shielding has high-voltage proton sources. In Indonesia, proton therapy facilities are still not operational, so to assess the effectiveness of the device, MCNP 6.2 is used. Monte Carlo N Particle (MCNP) is a Monte Carlo-based software that can be used for simulating the transport of neutrons, photons, electrons, ions, and others [8]. The concrete simulated as radiation shielding includes Low Activation Concrete (LAC) with a density of 2.18 g/cm^3, heavy concrete with the addition of hematite aggregate having a density of 4.898 g/cm^3, and heavy concrete with the addition of galena having a density of 7.141 g/cm^3. The importance of this research lies in the use of materials that are relatively cheaper than lead, do not require additional shielding, and are more efficient in terms of space in the proton therapy center. In addition, the results of this research can be used for nuclear facilities or research laboratories.

Material and methods

Selection of Concrete and Target Material

Heavyweight concrete and Low Activation Concrete (LAC) were the materials employed in this investigation. Adapted from research [9] and modified for its use as a radiation barrier in proton treatment, the heavy concrete uses aggregates from two distinct minerals, namely hematite and galena. To attenuate radioactive rays and greatly raise their mass attenuation coefficient, radiation-resistant aggregates are required. Atomic number and high density, which have notable gamma absorption rates, are used to choose components for heavy concrete. Lightweight materials with a high ability to slow down neutrons, including hydrogen compounds and polypropylene fibers, can be added to neutron absorption cross-sections. Please see Table 1 for the material data utilized.

Table 1: Weight fraction of elements in percent (%) in concrete samples adapted from [9]

Sample	H	C	O	Na	Mg	Al	Si	S	K	Ca	Fe	I	Pb	Density (g/cm^3)
LAC	0.72	8.9	47.8	0.08	0.24	0.27	1.2	0	0.03	40.5	0.06	0	0	2.18
Heavy concrete galena	0.13	0.05	2.72	0	0.11	0.11	0.5	12.5	0	2.32	0.16	1.19	80.23	7.141
Heavy concrete hematit	0.185	0.068	30.716	0	0.147	0.156	0.692	0.087	0	3.228	63.060	1.661	0	4.898

Then the information is integrated into the input file for simulation with MCNP (Monte Carlo N-Particle) version 6.2.

Computational tools

The neutron and photon power density of the shielding was calculated using the MCNP 6.2 code. MCNP 6.2 is a toolkit that can be used to simulate the transport and interaction of particles within a material [10]. The MCNP code was developed by the Los Alamos National Laboratory (Los Alamos, NM, USA) and is widely used in nuclear physics, space research, medical physics, and other fields. Tally F6 is used to calculate the energy absorbed per unit mass that passes through heavy concrete and then mathematically used to calculate other parameters as follows.

Linear damping coefficient:

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

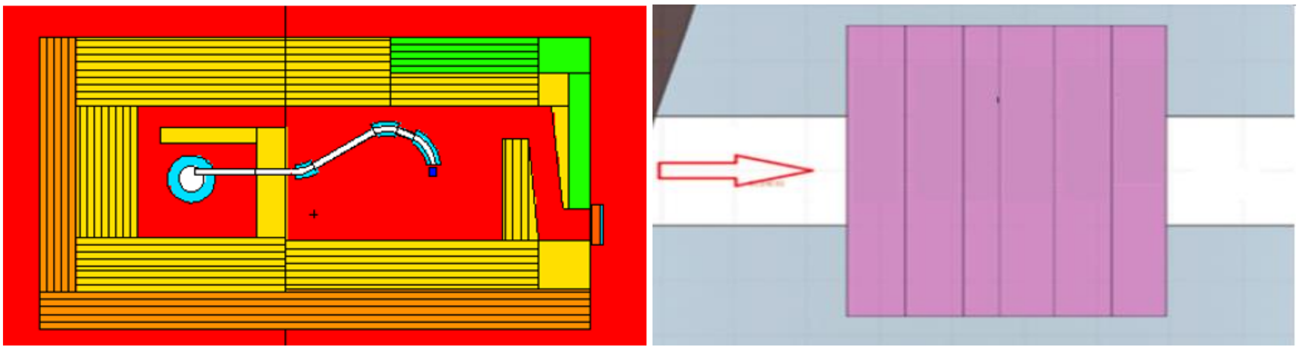
Where I and I_0 are the initial and final intensities of the radiation beam after passing through x thickness of the shielding material, μ is the linear attenuation coefficient [11].

Mass Attenuation Coefficient:

$$\mu m = \mu/\rho = \ln(Io/I)/\rho x$$

where ρ is the density (g/cm^3) of the shielding [10].

The model of proton therapy is illustrated in Fig 1 with a proton source and a 2D geometric arrangement. The source in the simulation is proton particles emitted from an accelerator with an energy range of 100 MeV - 230 MeV. In this case, each heavy concrete has a thickness of 50 cm and an additional thickness variation of up to 100 cm to calculate the linear energy deposition value.



a) b)

Fig 1: Research Geometry, (a) adaptation of the proton therapy model using MCNP [12], and (b) Shielding layer geometry.

Results and discussion

Heavy concrete shields are designed to reduce neutron and gamma radiation at the proton therapy center. Therefore, it involves calculations of linear energy deposition, linear attenuation coefficient, and mass attenuation coefficient. The calculations were obtained from the MCNP 6.2 simulation conducted with a low uncertainty error of 3% for LAC and heavy concrete. In assessing the effectiveness of radiation-absorbing materials, linear energy deposition is one of the important parameters. The value of linear energy deposition indicates the amount of energy absorbed per unit mass by the material due to the interaction between radiation particles and the constituent material particles of the shield. In this study, the linear energy deposition was calculated from three concrete samples, namely LAC, galena heavy concrete, and hematite heavy concrete, with different shield thickness variations. How the thickness used affects the amount of energy absorbed can be seen in Fig 2.

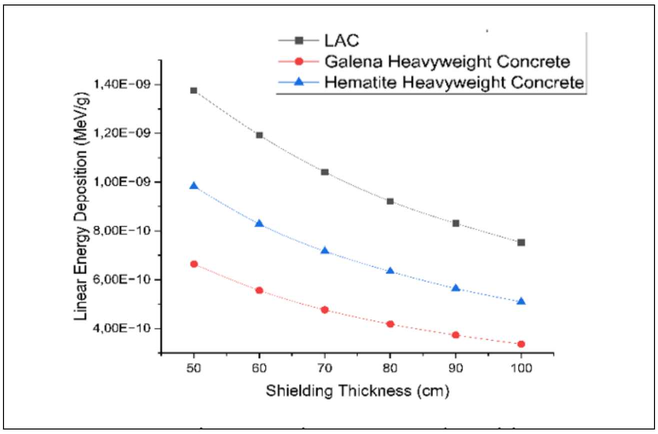


Fig 2: Linear energy deposition

Based on the graph in Fig 2, shows the comparison between shield thickness and linear energy deposition. LAC has a higher linear energy deposition value of MeV at a thickness of 50 cm compared to heavy galena concrete MeV and hematite MeV for all thickness sizes. Meanwhile, overall, the linear energy deposition value decreases as the thickness of the shield increases for all types of concrete. The high values obtained indicate that the material used is capable of absorbing most of the radiation energy. Based on this, galena heavy concrete becomes a more effective material for reducing neutron and gamma radiation as a shield that can be applied in proton therapy.

Fig 3 shows the data on the linear attenuation coefficient (μ) measured with the proton source modality for all the concrete samples with different energy ranges. One important way to judge how well the shield works is to look at the value of the linear attenuation coefficient, which shows how well the material blocks neutron and photon radiation per unit length. The greater the value of the linear attenuation coefficient, the more effective the concrete is in reducing the energy of radiation passing through the material.

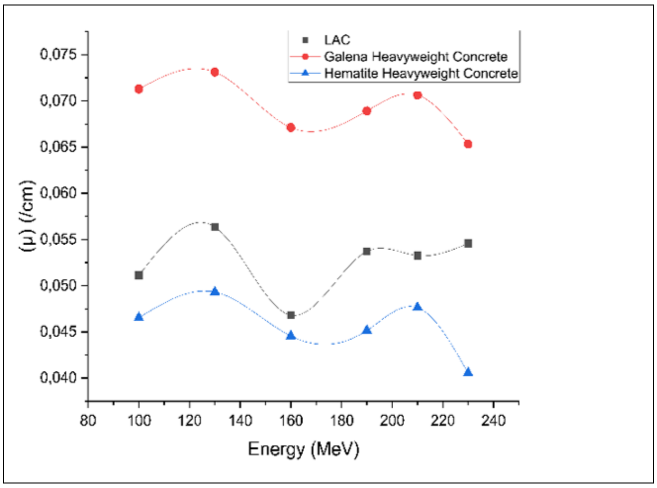


Fig 3: Linear attenuation coefficients

Based on the graph, shows the relationship between energy range and linear attenuation coefficient for three materials, namely LAC (black box), heavy galena concrete (red circle), and heavy hematite concrete (blue triangle). From the graph, heavy galena concrete has the highest μ value of 0.041294 cm^{-1} at 100 MeV energy, indicating that heavy galena concrete is more effective as a shield in attenuating photons and neutrons from a proton source. Furthermore, the linear attenuation coefficient value of galena heavy concrete is higher across all energy ranges compared to LAC and hematite heavy concrete. The value of μ describes the attenuation of radiation intensity in the material, where the higher the value of μ, the better the material absorbs radiation.

The effectiveness of galena heavy concrete is also influenced by the lead (Pb) content, which has a high density and atomic number. The pattern of the μ graph decreases with increasing energy due to the lower probability of interaction between particles at high energy. Additionally, there are fluctuations caused by the interaction between particles and the atomic nuclei that make up concrete, and a temporary increase in the value of μ can occur due to specific interactions with heavy elements in the concrete. For heavy galena concrete, the reduction in attenuation can also be influenced by hydrogen atoms in the concrete structure, which have the ability to slow down most of the incoming fast neutrons. In addition, substances such as water and polypropylene fibers can quickly slow down neutrons to thermal neutrons shortly after entering the shield, thereby enhancing the neutron absorption cross-section [9].

The density of concrete containing different aggregates and the linear attenuation coefficient (μ) calculated for all types of concrete mixtures affect the mass attenuation coefficient value of concrete [11]. The mass attenuation coefficient values are displayed for all concrete samples within a certain energy range in Fig 4.

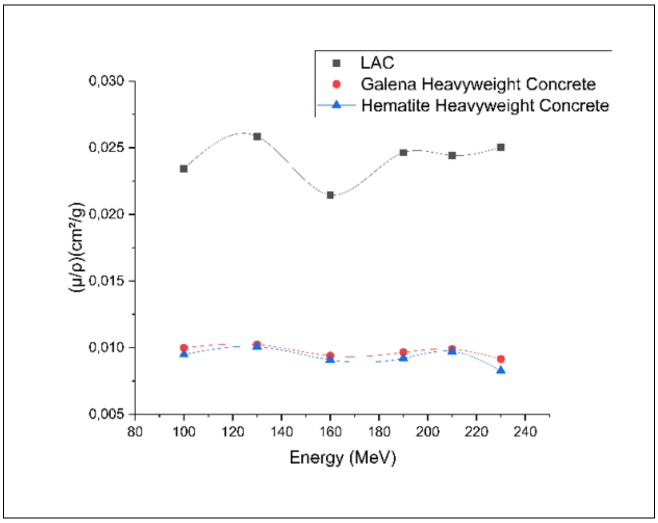


Fig 4: Mass attenuation coefficient

Looking at the data presented in Fig 4, shows the influence of the energy range on the μ/ρ value for all concrete samples. LAC has a higher mass attenuation coefficient of 0.017484 cm^2/g compared to galena heavy concrete and hematite heavy concrete, which have nearly the same value, and all values tend to fluctuate with the increase in the energy used. From the results, LAC is considered more effective in capturing photons, while galena heavy concrete and hematite heavy concrete are more effective in capturing neutrons due to the presence of Fe and Pb, which have better capabilities in slowing down and absorbing neutrons compared to conventional concrete. The μ/ρ value tends to be higher because the dominant interactions are the photoelectric effect and Compton scattering [9].

Conclusion

Based on the research results, the use of several types of concrete with varying thicknesses affects the linear energy deposition value, and the proton energy range used influences the μ and μ/ρ values of the shielding material in attenuating neutron and gamma radiation. From this, the use of LAC is better in absorbing photons, and heavy concrete with hematite and galena aggregates shows better attenuation in absorbing neutron radiation from proton sources. This research provides a reference for radiation shielding design, particularly in protection applications at proton therapy facilities or environments with high radiation exposure. Further studies can conduct experimental evaluations to further validate the simulation results.

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