Monte carlo simulation of innovative neutron and photon shielding material composing of high density concrete, waste rubber, lead and boron carbide

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Abstract. High-density concrete exhibits high strength and can perform an important role of gamma ray attenuation. In order to upgrade this material’s radiation-shielding performance, hydrogen-rich material can be incorporated. Waste rubber from vehicles has high hydrogen content which is the prominent characteristic to attenuate neutron. The objective of this work was to evaluate the radiation-shielding properties of this composite material against neutron and photon radiations. Monte Carlo transport simulation was conducted to simulate radiation through the composite material. Am-241/Be was utilized for neutron source and Co-60 for photon source. Parameters of the study included volume percentages of waste rubber, lead and boron carbide and thickness of the shielding material. These designs were also fabricated and the radiation shielding properties were experimentally evaluated. The best neutron and gamma ray shielding material was determined to be high-density concrete mixed with 5 vol% crumb rubber and 5 vol% lead powder. This shielding material increased the neutron attenuation by 64% and photon attenuation by 68% compared to ordinary concrete. Also, increasing the waste rubber content to greater than 5% resulted in a decrease in the radiation attenuation. This innovative composite radiation shielding material not only benefits nuclear science and engineering applications, but also helps solve the environmental issue of waste rubber.

1. Introduction
Crumb rubber is a material that is easy to find and inexpensive. It is made by recycling used automobile tires into powder. The recycling process helps reduce waste and the environmental problem. Used rubber has been utilized in many engineering works. For example, researchers in ref. [1] added used automobile tire to concrete and studied the strength of the compound. It was found that as the rubber aggregate percentage increased, the compressive strength decreased. Researchers in ref. [2] found that by adding a small amount of crumb rubber to concrete, the tensile splitting strength increased by 7% because the powder bonded with cement better than sand.

Today, there are many utilizations of radiation in medical, research and other fields. Safety in working with radiation must be emphasized, especially with neutron and gamma radiation which have high penetrating power. Thus, a shielding material capable of shielding both neutron and gamma ray should be designed. An example of a radiation source emitting both neutron and gamma ray is the high-energy gamma ray emitted from a synchrotron light source with the superconducting wiggler installed in the storage ring. Neutron radiation can be emitted when high-energy gamma ray interacted with the beryllium target, a process called photonuclear reaction [3].
Concrete has been widely used as gamma ray and, in certain applications, as neutron shielding material. Rubber is a hydrocarbon material composing mainly of carbon and hydrogen, which are effective neutron moderators. Moderating fast neutron into thermal one increases the chance of being absorbed [4], thus enhancing the neutron shielding efficiency of the shielding material. The objective of the present research is to design and study the neutron and gamma ray shielding efficiency of the shielding material composing of high-density concrete and waste rubber. Lead and boron carbide are also added to increase the shielding efficiency. The MCNP simulation as well as radiation attenuation experiments were performed to determine efficiency of the designed shielding materials.

2. Materials and Methods

2.1. Material Selection and Analysis
Concrete has been widely used as gamma ray shielding material because it is easy to find, inexpensive and easy to fabricate. High-density concrete has also been used to shield gamma radiation because it exhibits a higher density and, thus, can shield gamma ray more effectively, resulting in thickness reduction [5]. Addition of different quantities of materials into concrete affects neutron and gamma ray shielding. Important factors to consider when determining neutron attenuation are elastic scattering reaction, inelastic scattering reaction and neutron capture interaction process [6]. Incorporating material composing of heavy elements helps increase the inelastic scattering interaction, while incorporating material composing of light elements such as hydrogen enhances the elastic scattering. Both interactions decrease neutron energy. Neutron-capturing elements help reduce the generation of secondary gamma and thermal neutron [7].

Materials used in the research are Portland cement type I, crumb rubber from waste rubber, barite powder, lead powder and boron carbide powder. Elemental analysis of the materials were performed at Scientific and Technological Research Equipment Centre Chulalongkorn University using scanning electron microscope model JSM6610LV (JEOL) with Energy Dispersive Spectroscopy (EDS). Figures 1 and 2 show results of crumb rubber analysis.

Carbon/Hydrogen/Nitrogen Determinator was used to determine the elemental composition of waste rubber. Results are illustrated in Table 1.

|                  | % C  | % H  | % N | Mass (gram) |
|------------------|------|------|-----|-------------|
| Waste rubber #1  | 80.91| 9.52 | 0   | 0.023       |
| Waste rubber #2  | 80.68| 8.54 | 0   | 0.036       |
| Average          | 80.79| 9.03 | 0   | 0.029       |
2.2. Monte Carlo Simulation

The present study used MCNP version 2.7.0 to simulate the radiation shielding efficiency of each shielding design to determine the most appropriate composition. Am-241/Be was used as a neutron source and Co-60 was used as a gamma ray source. An isotropic point source was assumed with the neutron energy range $5.0 \times 10^{-7} - 1.0 \times 10^{2}$ MeV. The source was placed at the center of one side of the shielding material. The shielding was simulated as a cube with the dimension on each side of 12.7 cm according to British Standard. Surface flux tally was used to determine the amount of radiation passing through the material in the unit of particles/cm$^2$. The standard deviation error was calculated from the simulation and the Dose Energy (DE) and Dose Function (DF) were used to convert flux into dose equivalent rate with the unit of (rem/hr)/particle. The simulated 3D geometries using Vised to study the attenuation and shielding thickness are shown in Figures 3 and 4, respectively.

![Figure 3. Simulated 3D geometry using Vised to study attenuation in MCNP](image1)

![Figure 4. Simulated 3D geometry using Vised to study shielding thickness in MCNP](image2)

Three different compositions of shielding materials were designed and investigated in this research. They were: high-density concrete mixed with crumb rubber (HDCR), high-density concrete mixed with crumb rubber and lead (HDCRL) and high-density concrete mixed with crumb rubber and boron carbide (HDCRB). Table 2 shows the composition of each shielding material. The number after a letter indicates the volume percentage of the component. For example, HDCR5 represents high-density concrete mixed with 5 vol% rubber, HDCR5L2 represents high-density concrete mixed with 5 vol% rubber and 2 vol% lead and HDCR5B2 represents high-density concrete mixed with 5 vol% rubber and 2 vol% boron carbide.

| Specimen assignment | Waste rubber (gram) | Cement (gram) | Barite (gram) | Pb/B$_2$C (gram) | Water (gram) | Density (gram/cm$^3$) |
|---------------------|---------------------|--------------|--------------|-----------------|-------------|----------------------|
| HDCR5               | 94.22               | 1,000        | 5,669        | -               | 450         | 3.35                 |
| HDCR10              | 94.22               | 1,000        | 5,669        | -               | 450         | 2.831                |
| HDCR15              | 94.22               | 1,000        | 5,669        | -               | 450         | 2.782                |
| HDCR20              | 94.22               | 1,000        | 4,771        | -               | 450         | 2.636                |
| HDCR25              | 94.22               | 1,000        | 4,771        | -               | 450         | 2.587                |
| HDCR5L2             | 94.22               | 1,000        | 5,669        | 464.98          | 450         | 2.957                |
| HDCR5L4             | 94.22               | 1,000        | 5,669        | 929.96          | 450         | 3.080                |
| HDCR5L5             | 94.22               | 1,000        | 5,669        | 1,162.45        | 450         | 3.154                |
| HDCR5L6             | 94.22               | 1,000        | 5,669        | 1,394.94        | 450         | 3.219                |
| HDCR5L8             | 94.22               | 1,000        | 5,669        | 1,859.92        | 450         | 3.232                |
| HDCR5B2             | 94.22               | 1,000        | 5,669        | 103.23          | 450         | 2.812                |
| HDCR5B4             | 94.22               | 1,000        | 5,669        | 206.47          | 450         | 2.798                |
| HDCR5B6             | 94.22               | 1,000        | 5,669        | 309.71          | 450         | 2.785                |
| HDCR5B8             | 94.22               | 1,000        | 5,669        | 412.95          | 450         | 2.771                |
2.3. Specimen Fabrication and Attenuation Experiments

2.3.1. Preparation of specimens. Portland cement, barite, water, crumb rubber and/or lead and/or boron carbide with specific portion of each ingredient were mixed thoroughly in a mortar mixer. Waste rubber and fine aggregates were bonded together by Portland cement through the hydration process in the mold. After the curing process in water for 7 days, the shielding materials were tested for radiation attenuation.

2.3.2. Radiation shielding tests.

2.3.2.1. Neutron Attenuation Experiment. The neutron attenuation coefficients were determined by performing a transmission experiment. All measurements were performed under the same geometry and experimental setup. The detection system consisted of Am-241/Be neutron source with strength $3.08 \times 10^3$ n-cm$^{-2}$ s$^{-1}$, acrylic plates and boron trifluoride ($BF_3$) detector. The distance from source to neutron detector was 51.5 cm. The $BF_3$ detector was operated with the high voltage of 1,075 V. The counting time was 10 minutes. The experiment setup is shown graphically in Figure 5.

2.3.2.2. Photon Attenuation Experiment. The attenuation coefficients of gamma ray of shielding materials were measured at energies 1173 and 1332 keV using Co-60 source. The NaI(Tl) detector was CANBERRA Model 802-2x2, crystal size 2 x 2 inch with the source-to-detector distance of 17 cm. The height of the detector from floor was 9.8 cm. The photon measurement set up is shown graphically in Figure 6.

3. Result and Discussions

3.1. Simulation results
The MCNP simulation was first performed to determine the most appropriate portion of waste rubber in the high-density concrete. The studied volume percentages were 5, 10, 15, 20 and 25. Results revealed that neutron attenuation increased with increasing waste rubber percentage as shown in Figure 7a. This is because light elements in rubber are effective in attenuating fast neutrons. However, for the case of gamma ray attenuation, high-density concrete alone exhibited the best performance as shown in Figure 7b. This is because heavy elements as well as the high-density characteristic of the high-density concrete are effective in gamma ray shielding. Because the aim of this research was to design the shielding material for both neutron and gamma ray and because the mechanical strength of the shielding material needs to be maintained as well, the waste rubber percentage of 5% was decided to be most suitable and this composition was used throughout the remaining simulations when adding lead or boron carbide to the shielding material.
Simulation results of gamma ray and neutron transmissions are illustrated in Figures 8 and 9 for different shielding thickness. For the case of gamma ray transmission, lead was used as additive to HDCR5, and for the case of neutron transmission, boron carbide was used as additive to HDCR5. Simulated shielding thicknesses were 6.38, 12.7, 19.08 and 25.46 cm. It was found that the \( \ln(I/I_0) \) value, where \( I \) and \( I_0 \) represent transmitted radiation in the presence of the shielding and without the shielding, respectively, decreased with increasing shielding thickness according to the Beer-Lambert’s law, as the curve of \( \ln(I/I_0) \) vs. shielding thickness exhibited a linear form. Moreover, for the case of gamma ray transmission, the more volume percentage of lead added, the better the shielding efficiency. This behavior is expected since lead is a very effective gamma ray shielding material.

3.2. Experimental results

Results from the attenuation experiments indicate that high-density concrete mixed with 5, 10, 15, 20 and 25 vol% of waste rubber can shield fast neutron better than high-density concrete alone, and that addition of waste rubber more than 5 vol% resulted in the detrimental effect as the fast neutron transmission increased, as shown in Figure 10. The neutron transmission was lowest at 43.2% for 5 vol% waste rubber addition, and this optimum content was chosen to perform all remaining experiments. Waste rubber enhanced fast neutron attenuation because of the hydrocarbon content of waste rubber. Atomic hydrogen and carbon undergo elastic scattering with fast and intermediate energy neutrons to reduce their energy. However, addition of waste rubber more than 5 vol%
effectively reduced the amount of high-density concrete and, subsequently, reduced the fast neutron attenuation. This is because barite in high-density concrete (presence as BaSO\(_4\)) contributed 45.45% by weight. Reduction of Ba quantity in the shielding material (as a result of increasing the waste rubber content) reduced the probability of fast neutron undergoing inelastic scattering interaction with Ba.

![Figure 10. Experimental results of fast neutron transmission for HDC with various vol% of waste rubber](image)

![Figure 11. Experimental results of thermal neutron transmission for HDCR5 with various vol% of boron carbide](image)

With the waste rubber content held constant at 5 vol%, addition of 2, 4, 6 and 8 vol% of boron carbide provided better thermal neutron shielding than HDCR5 alone, as can be seen in Figure 11. As boron is a very effective thermal neutron absorber, addition of boron carbide into concrete shielding significantly increased thermal neutron shielding efficiency. Moreover, as the hydration process of cement in concrete increased, the neutron attenuation was enhanced [8]. Experimental results in Figure 11 may be compared to simulation results in Figure 9. From Figure 9, although it appears that HDCR5 with 6 vol% boron carbide exhibited a slightly better performance than the rest, the difference is small and it can be said that addition of boron carbide anywhere from 2 – 8 vol% (the range used in the present study) provided the same benefit. In Figure 11, although 4 and 8 vol% boron carbide addition offered a slightly better performance than the rest, the difference is not large and there can always be small fluctuations in experimental outcomes resulting from many factors inherent to radiation counting experiments. Thus, the same conclusion can be made with experimental results that addition of boron carbide anywhere from 2 – 8 vol% provided roughly the same benefit.

According to Figure 12, addition of waste rubber of 5, 10, 15, 20 and 25 vol% resulted in a slightly lower gamma ray attenuation at 1332 keV compared to 1173 keV. However, when HDCR5 was added with 2, 4, 6 and 8 vol% lead content, the attenuation of 1332 keV gamma ray became better than that of 1173 keV gamma ray, as can be observed from the higher linear attenuation coefficient value in Figure 13. Moreover, the more lead percentage, the better the gamma ray shielding capability because lead is a very effective gamma ray shielding material. This experimental result is in good agreement with the simulated result in Figure 8. Another added benefit of lead is the increased inelastic scattering with fast neutron resulting in the enhanced neutron attenuation ability.

![Figure 12. Gamma ray attenuation coefficient of HDC mixed with various waste rubber content](image)

![Figure 13. Gamma ray attenuation coefficient of HDCR5 mixed with various lead content](image)
Figure 14 shows results of fast neutron transmission experiment when lead powder was added to HDCR5. With 5 vol% of added lead powder, the fast neutron transmission was lowest. Lead, a heavy element, undergoes inelastic scattering interaction with fast neutron and reduces the transmitted fast neutron flux. Thus, 5 vol% of added lead powder was the optimal composition.

![Figure 14. Experimental results of fast neutron transmission for HDCR5 with various lead powder content](image)

The last step of this work is to compare the effectiveness of lead addition to boron carbide addition on neutron and photon transmissions. With crumb rubber content being 5 vol%, 5 vol% lead content was compared to 8 vol% boron carbide content. Simulated results of ratio of neutron and photon transmission percentages of various shielding material designs to those of ordinary concrete are shown in Figure 15. In the Figure, HDCR5L5 performed the best for photon attenuation and almost the best for neutron attenuation. When considering both photon and neutron attenuations together, HDCR5L5 was the most suitable shielding material. It is interesting to observe that HDCR5L5 shielded against neutron even more effectively than HDCR5B8. The latter contained boron, a strong thermal neutron absorber, so it should absorb neutrons much more effectively. The reason is that HDCR5B8 contained no lead to undergo inelastic scattering interaction with fast neutron, so it was not an effective fast neutron moderator compared to HDCR5L5. With less thermal neutron generated, the presence of boron provided little benefit. For the case of HDCR5L5, barium present in barite and hydrogen present in high-density concrete as well as in waste rubber help capture thermal neutron.

![Figure 15. Ratio of neutron and photon transmission percentages of various shielding material designs to those of ordinary concrete](image)
4. Conclusions
The radiation shielding materials fabricated from high-density concrete mixed with crumb rubber capable of shielding both neutron and gamma ray were designed using the MCNP computer code and verified by radiation attenuation experiments. From experimental results, it was found that addition of crumb rubber increased the neutron shielding efficiency, and that addition of more than 5 vol% actually lowered the neutron shielding efficiency because the barite content of high-density concrete was reduced. Addition of lead to high-density concrete mixed with 5 vol% crumb rubber increased both neutron and gamma ray attenuation. Moreover, addition of boron carbide, a strong thermal neutron absorber, to high-density concrete mixed with 5 vol% crumb rubber increased thermal neutron attenuation. However, the best neutron and gamma ray shielding material was determined to be high-density concrete mixed with 5 vol% crumb rubber and 5 vol% lead powder. The precence of lead effectively moderates fast neutron through inelastic scattering. This shielding material increased the neutron attenuation by 64% and photon attenuation by 68% compared to ordinary concrete. This research offered a new method to recycle used rubber for radiation shielding purposes. This not only helps reduce environmental problems, but also enhances radiation safety in nuclear and other related works.

Acknowledgement
This study was supported by Synchrotron Light Research Institute (Public Organization) and Ministry of Science and Technology of Thailand. The authors would like to thank Dr. Nawin Juntong for providing the MCNP program.

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