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Radiation Shielding Against Neutron Using Different Fillers: A Review Study

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ABSTRACT

Radiation Shielding Concrete is mixture of cement, water, and heavy weight Aggregates (Fillers) commonly used as shielding against radiation as neutrons that emitted in different facilities as the medical units, particle accelerators. Neutrons causing extra doses to the patient and the occupational workers which is the main issue to grantee radiation safety. Various special Concretes containing fillers have been produced and used for enhancing the radiation shielding characteristics of the ordinary concrete. Only light elements as boron and hydrogen acts as moderate for neutrons that can absorb them. Therefore, for neutrons radiation shielding; concrete must contain light elements beside the heavy elements. Many softwires were employed to examine the effectiveness of the concretes as a radiation shielding materials, also Monte Carlo (MC) simulation program that simulates the transmission and interaction of radiation with different matters. Those software and simulation programs can be used in different fields such as, radiation physics, medicine, and researches. In this paper different fillers added to the ordinary concrete and different measuring methods will be reviewed.

1. INTRODUCTION

With its tremendous potential for newer progress for the benefit of the society, nuclear technology has been used not only in nuclear defense but also in electric power, medical treatment, accelerators, and scientific research. These alications lead to different types of radiation as neutron, alpha, beta, and gamma rays. As known alpha (α) and beta (β) radiations can easily be shielded by simple shielding materials as piece of paper but neutrons and gamma rays, need specific shielding composition because they have higher penetrating powers [1].

Ionizing radiation is very dangerous to human health, so it was necessary to establish methods to protect the occupational workers, patients, and public from the deterministic effect of ionizing radiation. One of the protection methods against ionizing radiation is shielding which is complex especially in case of neutron because neutrons interact with matter only through nuclei, so they do not moderate easily through the exposed matter, and can travel a large distance through most materials without scattering or absorbing. This means that the neutrons have a high ability to penetrate such materials, which makes them dangerous both in terms of material and radiation [2].

The concept of shielding against neutron includes more than one process as moderation, thermalization, and absorption. It differs from shielding against gamma radiations because the design of maze in the radiation facilities with gamma ray emission was found to be effective. To apply the concept of maze design for neutron, a very length maze with appropriate doors are needed to reach the desired dose level in the boundary areas that could pose the cost-benefit effectiveness for neutron. So, in case of Neutron shielding the concern focused on the appropriate material investigation instead of the design [3].

1.1 Production of Neutron

Neutrons are produced in radiation therapy facilities that use photon energies higher than 10 MeV. Photo-neutron interaction (known as (γ, n)) happens by the

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interaction of high energy X-ray photons with high Z materials of Linear Accelerator (LINAC) head and collimation system, this interaction is the main source of neutron production (Contamination of treatment beam) in radiotherapy [4]. In Cyclotron, high energy neutron irradiation from a proton synchrotron, neutrons that could cause activation products in the concrete walls of the vault room. Concrete activation should be taken in consideration to achieve the radiation protection against neutron [5].

1.2 Neutron Attenuation

Neutron radiation interacts with materials via the nuclei of atoms depending mainly on the kinetic energy of the neutrons. The neutrons are classified by their energy into three types: thermal neutrons (lower than 1 eV), epithermal neutrons (between 1 eV and 0.1 MeV), and fast neutrons (above 0.1 MeV). The amount of neutron radiation absorbed in matter is typically expressed by the fluence. The number of neutrons (n) that penetrate a unit area expressed as (n/cm^2) are called Neutron fluence. The neutron radiation rate is measured in units of flux, formulated in terms of ($n/cm^2/s$). During the design of concrete as neutron shielding the fast and intermediate neutrons require being slowed down, and thermal neutrons need to be absorbed or captured. It is, therefore, essential to have a mass of a material that contains atoms has ability to thermalize and capture neutrons [6].

1.3 Radiation Shielding efficiency of Concrete

Design of an effective shielding against neutrons is one of the main requirements to ensure the radiation safety. For proper selection of shielding material and its thickness, some data such as attenuation and mass attenuation coefficient, effective removal cross-sections, half and tenth value lengths are necessary [7].

Radiation shielding concrete, also called atomic energy protection concrete, has served as shield against high-energy photons (gamma) and neutrons in all radiation facilities that emits gamma and neutron radiation. the widest and most commonly used material as shielding material is the heavy weight concrete, it is a mixture of a fairly high atomic number nuclei, and light nuclei (as hydrogen in chemically bound water for neutrons). These components gave it a high density, large of crystal water, good strength characteristics, flexibility to be introduced into desired forms, less maintenance and satisfactory protection characteristics against gamma and neutron radiation [8].

1.4 Modification of the Ordinary Concrete by Use of hydrogenous Aggregates and different Fillers

Several attempts have been made to investigate the protective properties of concrete mixtures, using various rich sources of hydrogen. Since the elimination cross-section theory is predicated on the presence of hydrogen (or moderator materials) in the absorber. neutrons suffering elastic and inelastic collisions; inelastic collisions in a heavy substance they will be captured by hydrogen and going to lose a big chunk of their energy (or any moderator material). If they run into an elastic collision with a heavy nucleus as hydrogen (and another moderator materials), they will lose their energy causing a large energy transfer. In these situations, the neutron will likewise be successfully eliminated. So, the neutron attenuation coefficient has been expressed as functions of total moderator materials and hydrogen contents of the concretes [9]. The aggregate contents of concrete that combine several elements of heavy elements plays a crucial function in raising the concrete shielding properties and offers good shielding qualities for the reduction of photons and neutrons. the most effective shielding material against neutron is acquired by combining heavy metal elements, hydrogenous materials, and other neutron absorbers [10].

This study aims to review the Efficiency of different Fillers to augment the Neutron capture properties of the Concrete

Researchers have looked into the neutron-shielding capabilities of concrete with various amounts of barite as an aggregate [11]. they produced three different ratios of barite with the concrete as follows of 0%, 50% and 100%. They tested the radiation shielding properties of the three types of concrete against neutron by calculating the effective fast neutron removal cross-section. They found that the neutron attenuation coefficients have decreased linearly with the increase in the proportion of barite in concrete. They also found that the proportion of barite best for sequential protection against neutrons is around 53.8%. They also observed that, the optimal concrete density value for sequential neutron shielding is 3.02 g/cm3.

The work presented by Park et al. [12] explains the consequences resulting from the computational study to examine the properties of concrete with regard to neutron activation and shielding containing boron carbide and polyethylene, they used double-layered concrete structure. The quantities of polymer aggregates that exist in the first layer application are about 2 wt%, 4 wt% followed by 10 wt% then 20 wt% and also contains 50 wt% chemical composition of the shielding material. On the other side, borated concrete exists in the second layer composed of 1 wt% from boron carbide. The thickness of all the shielding wall reached 30 cm. The ORIGEN-S module which is the depletion and decay module of the SCALE code system was used in the provoked activities of the concrete. This module has a wide range of utilization in the study of nuclear reactor design and in radiation safety analysis. From these studies, they observed that: in case of the neutron shielding used in the high nuclear facilities, the presence of the combination of borated concrete with polyethylene aggregate enhances the efficiency of attenuation and also leads to a reduction in the shielding thickness. By using this double layered concrete structure, the construction cost becomes lower due to reducing the quantity used from boron carbide.

The mix of high-density polyethylene (HDPE) composites with the modified boron nitride (mBN) filters used with an oraganosilane was mixed by Wook-Shin et al. [13] out of conventional melt-extrusion processing techniques. There was a comparison of characteristics and abilities between these composites and other composites that contains pristine BN and boron carbide (B_4C) fillers. The neutron shielding characteristics for HDPE/BN, HDPE/mBN, and HDPE/B_4C composites at a lot of filler contents were achieved. The authors[13] found that the presence of the silane functionalization of the BN filler helped in the enhancement of the interfacial adhesion between HDPE and mBN and also given a good dispersion for mBN fillers in this matrix. Therefore, the HDPE/MBN composite proved preferable dispersion case of fillers, better modulus of tensile, better effective thermal conductivity, and robust neutron shielding material characteristic compared with the HDPE/BN and also the HDPE/B_4C composites.

Ferro boron (Fe – B) and boron carbide (B_4C) particle alloys were introduced to concrete shields as a shielding material, and the FLUKA Monte Carlo simulation system was used to analyze these shields' properties. The concentrations of B_4C and Fe-B in concrete are raised from 0 to 20 percent. Because concrete has a lower density than B_4C and Fe-B, the addition of high-density materials can boost the effectiveness of neutron shielding and decrease the thickness of the concrete according to additional content. When compared to concrete with B_4C content, the shield thicknesses of concrete with +Fe - B composition are significantly lower. This work reveals that the neutron shielding properties of high-density Fe-B are better than those of B_4C. Iron is a crucial material to slow down fast neutrons beneath 1Mev, while boron is an excellent thermal neutrons absorber substance. Therefore, Fe-B should be added to the concrete as a plausible material for fast neutron shielding applications.

Fast neutron slowing and thermal neutron absorption are the two phenomena that establish the foundation for neutron shielding. Presented experimental measurements as well as the outcomes of MCNP simulations using ordinary concrete (OC), magnetite heavy-weight concrete (MC) as references, and polymer cement concrete (PCC) which had the same base composition but were modified with 10% epoxy resin and hardener (OC-PCC and MC-PCC). They came to the conclusion that heavy-weight concrete is more effective at shielding neutrons than OC. Additionally, the polymer was added to OC and MC to enhance their neutron shielding capabilities. According to the experimental findings, OC outperforms MC in fast neutron attenuation, but in thermal neutron absorption, it is nullified.

The study of DiJulio et al. (16) indicated that the special concrete provided by it will be used in the accelerator-based facilities to study neutron research and possibly also in reactor applications. Developing this concrete relied on the relative increase of the hydrogen content to improve the concrete’s shielding against neutrons, by incorporating the hydrogen atoms present in the forms of polyethylene (PE) and B_4C with the concrete. It has also been found that 50-50 mixture besides the weight of 2.5 mm and 5.0 mm of PE granules is the best homogeneous mixture of PE that can provide throughout the concrete given that 0.76% wt.% B_4C has also been mixed into the concrete. In the MeV energy range, the new special concrete produced approximately 40% fewer neutrons than the standard concrete. In the eV-keV range, the improvements were about a factor of 10 and were more effective at lower energy.

In the work by Malkapur et al. [17] A novel polymer-incorporated self-compacting concrete (PISCC) mix's features for shielding against Neutron Rays are investigated. They used three different reference volumes of Pulverized high-density polyethylene (HDPE) material, as a partial substitute for river sand in conventional concrete mixes. The goal of this partial sand substitution with polymer is to increase the hydrogen content added to these concrete mixes and its impact on their ability as shield against neutron radiation. Here, the neutron radiation shielding properties of ten different concrete mixtures were investigated. One of as the study clarified the characteristics of ten (PISCC) mixtures in varying percentages and proportions, and one of them was a reference mixture (CC). It was found that the new concretes had desirable and significantly increased neutron radiation shielding properties and it has been observed that with the increase in polymer contents of all (PISCC) blends reaching 8.5% maximum in reference to (CC) we find that the flux transmission factors trend in a downward trend.

Three new heavy concrete samples were developed by Aygün et al.[18] (NHC1 (ρ = 4.03 g/cm^3), NHC2 (ρ = 3.81 g/cm^3), and NHC3 (ρ = 3.91 g/cm^3), which are characterized by their high thermal strength. As these samples contain different ratios from minerals which are chromium ore ($FeCr_2O_4$), hematite (Fe_2O_3), limonite [FeO (OH) n H_2O], siderite ($FeCO_3$), barite ($BaSO_4$), titanium oxide (TiO_2), aluminium oxide (Al_2O_3), nickel oxide materials (NIO) and alumina cement, where chromium was used to increase the concrete's resistance to radiation and temperature , and by analyzing the results obtained using the BF_3 detector and by measuring the equivalent doses of neutron absorption and absorbed dose rates, in addition to determining the macroscopic cross-sections (MCSs) (cm^{-1}) for new concrete samples using the (GEANT4) code for Monte Carlo simulation, it was found that all newly produced concretes have excellent neutron shielding performance, particularly when compared to standard neutron shielding materials such as paraffin and normal weight concrete. In particular, the sample NHC3 (containing 35% chromium ore) showed the best neutron protection ability.

Dong et al.[19] presented an investigation on the study of the shielding coefficients of some boron resources, where the study focused on five compositions, each of which has a different density of boron. There is Ludwigite (B1), boron bearing iron concentrate (B2), boron concentrate (B3), and boron rich slag (B4), and boron mud (B5) and by measuring the mass attenuation coefficients of boron for the previous samples using XCOM software and Geant4 simulation. It was concluded that the boron-containing resources have a high ability to use it as an additive in concrete, and the boron boring iron concentrate (B2) sample was determined to be the best that offers protection for both Gamma rays and a fast neutron.

[20] tested how well high-density concretes containing ferro boron (FB) in different concentrations (25%, 50%, and 75%) substituting granite aggregate might shield against neutron, denoted as 25FB, 50FB, and 75FB, respectively. The transmission rate was calculated for the prepared samples to assure the effectiveness of these samples as neutron radiation shielding. Conclusion: Compared to standard concrete sample, FB25, FB50, and FB75 mixes had shielding capabilities that were 2, 2.57, and 3.27 times higher respectively. For all the concrete mixes that contain ferro boron, there has been a noticeable improvement in the neutron radiation shielding capabilities. The increase in the proportion of ferroboron in the concrete mix can be linked to the neutron transmission rate's observed declining tendency. The choice of the ideal mix design and necessary shielding thickness heavily rely on taking into account a number of variables, including cost, shielding space, and radiation intensities.

[21] investigated the shielding properties of or three different materials of barite, water, and boron against neutron particles emitted by spontaneous fission source ^{252}Cf, using FLUKA Monte Carlo simulation code. They measured dose rate, mean free path, and total neutron cross-section for the three materials. they concluded that, the boron is the best neutron shielding material in comparison with the others

[22] investigated waste boron's impact on radiation-shielding qualities. Three different densities of cement have been used according to the percentage of boron waste added to the cement (Cement's density was reduced by boron waste addition). They used a free online platform called Phy-X\PSD software to evaluate the radiological parameters for three different cement samples. They observed that as the boron content in cement grew, so did the neutron attenuation coefficient, gamma and neutron behaviours are demonstrated by employing boron in cement in two different ways. The addition of waste boron to cement leads to the decreasing the gamma ray attenuation properties of cement and enhancing the neutron's shielding capabilities. This might unequivocally demonstrate the value of using boron waste in neutrons attenuation proposals.

[23] investigated Barite concrete composite materials as neutron shielding materials using monte carlo computation method. The particle and Heavy Ion Transport code system (PHITS) 3.10 version, was used

to calculate the shielding properties of that three various materials (barite concrete, barite cement, and barite aggregate) that utilized as structural walls in fixed neutron and gamma industrial radiography for non-destructive testing applications. The most effected materials among the investigated ones is barite concrete. The main explanation of the efficiency of barite concrete is due to that the hydrogenous materials and iron composite composites combination.

The summary of the selected aggregates and the main findings from the previous studies is presented in table 1.

Some of studies are directed to the use of these aggregates in their nano size

[24] conducted a study on the impact of shielding material whose thickness being up to 8 mm, its B_4C content are about 1, 3 and 5 wt%, and the particle size for B_4C of it is about 20 and 150 m on the performance of the neutron shielding. The foil activation approach was used to evaluate the fabrication of composites' ability to shield neutrons. The most popular method for measuring thermal neutron fluence is foil activation. They came to the conclusion that high absorbability of the boron element resulted in improvement of the neutron attenuation coefficient of enhanced composites with increasing the concentration of B_4C reaching 0.345 cm-1 for a B_3C (20m, 5 wt%)/ epoxy composite shield.

The research [25] presented on the impact of tungsten oxide (WO_3) nanoparticles on concrete's mass attenuation coefficients using MCNPX (version 2.4.0). They contrasted the simulation's findings with typical XCOM data for concrete's mass attenuation coefficients. The density of the concrete sample has increased as a result of the WO_3 particle doping. They came to the conclusion that because nanoparticles are smaller than microparticles, the crackle is stopped more effectively and they have better attenuation properties. The shielding properties of concrete then greatly improved over micro-WO_3 doped concrete. On the other hand, where experimental results are unavailable, MCNPX is a powerful and useful tool for research on nanoscale materials.

A study conducted in [26] they prepared shielding material against the photo-neutrons in the high energy LINAC room. They prepared a composition of materials in both nano and micro scales the to assess the impact of particle size on concrete shielding properties, the materials including PbO_2, Fe_2O_3, WO_3 and H_4B (Boronium). The current investigation used two distinct compositions: (1) 50% regular concrete plus 50% nanoparticle. (2) A mixture of 50% regular concrete and 50% microparticles. In order to complete all MC simulations and calculations, the MCNPX MC algorithm (2.7.E) was used. Overall, the neutron and photon attenuation of regular concrete increased with the addition of all four particles. In comparison to microparticles, the nanoparticles had higher photon attenuation coefficient (8%) and neutron removal cross section (7%) values. It is advised to incorporate nanoscale materials into the mix of future concretes to provide dual protection from neutrons and photons.

As in another study conducted on nano-TiO_2 combined cement mud, it demonstrated greater compressive strength and density than ordinary mud. This improvement in mechanical performance was because of nano-TiO_2 filling, and the neutron shielding performance improved for each of the thermal neutrons - slow neutrons - intermediate neutrons. to radiation because there is a small difference in the neutron interaction cross-section of the elements Ti, Ca and Si in this energy region [27].

Similar to previous study on cement mud with nano-TiO2 mixed, it demonstrated greater compressive strength and density than regular mud. The nano-TiO2 filling was responsible for this improvement in mechanical performance, and each of the thermal neutrons slow neutrons and intermediate neutrons had better shield performance. due to a slight discrepancy in the cross sections of the neutron interactions with the elements Ti, Ca, and Si in this energy range.

Future work recommended

1. It is advised that future research calculate the attenuation coefficients of these nano-concrete materials against more energetic neutrons, photons, and other particles.
2. Research the radiation damage to HPDE polymeric material and evaluate material stability.
3. It is important to look into how changes in cement hydrate characteristics are affected by the mechanical deterioration of concrete caused by continuous radiation exposure.
4. Since nanotechnology has also recently been generated for a variety of radiation shields and technologies, MCNPX geometry can be used for potential future study.

Table (1): The summary of the selected aggregates and the main findings from different studies.

Research	Fillers	Method	Result
Akkurt et al.,	Barite	Experimental study	Best proportion of barite in concrete is about 53.8%.
Park et al.,	PE-B_4C-concrete	Computational study (ORIGEN-S)	improved the attenuation efficiency and reduces the thickness of the shielding, reduces the construction cost.
Wook Shin et al.	HDPE/BN	Experimental study	superior neutron shielding property
Sariyer et al.	B_4C and Fe -B	Simulation study (FLUKA MC)	Addition of Fe - B to concrete enhance shielding material properties against neutron than B_4C.
Piotrowski et al.	MC	Experimental and MCNP simulation study	For fast neutron attenuation, OC is superior to MC, but not for thermal neutron attenuation. Good agreement between Experimental results and Simulation
Dijulio et al.	PE-B_4C-concrete	Experimental and simulation study (Geant-4)	40% fewer neutrons, compared to a standard concrete. Good agreement between Experimental results and Geant4 Simulation
Malkapur et al.	PISCC	Experimental study	improvements in the neutron radiation shielding properties up to 8.5% max
Bünyamin Aygün et al.	Alumina cement	Experimental and simulation study (Geant-4)	The new heavy concretes have a greater capacity for neutron absorption than paraffin and regular weight concrete. Good agreement between Experimental results and Geant4 Simulation
Dong et al.	five different samples of B containing resources	Experimental, XCOM program and Geant4 simulation	Boron bearing iron concentrate is the better one as shielding against both fast neutron and gamma ray. Good agreement between results of Experimental, XCOM program and Geant4 Simulation
Roslan et al.	FB	Experimental study	shielding efficiency of FB25, FB50, and FB75 mixes was better than ordinary concrete.
Obaidi et al.	Barite, H_2O, and B	FLUKA Monte Carlo simulation code	boron is the best neutron shielding material in comparison with H_2O and B
Korkmaz et al.	B	Phy-X/PSD software	B addition to concrete improved the shielding properties for neutron
Cebastien et al.	barite concrete, barite cement, and barite aggregate	Monte Carlo simulation code	barite concrete is better than barite cement, and barite aggregate

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