

OPTICAL PROPERTIES IMPROVEMENT OF STEEL SLAG GLASS AND THEIR IONIZING RADIATION AND NEUTRON SHIELDING PROPERTIES

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Abstract

In this research, steel slag glass (SSG) system in formula (70-x)steel slag: 20Na₂O: 10CaO: xB₂O₃ where x = 0, 10, 20, 30, 40, and 50 w% were prepared by using conventional melt quenching method at 1,200°C and investigated physical, optical, ionizing radiation (uncharged and charged particles) and neutron shielding properties. Experimental on shielding properties of uncharged particles (γ -rays) were carried out with ²²Ba, ¹³⁷Cs and ⁶⁰Co sources at photon energies from 80-1332 keV while theoretical calculations were carried out with the WinXCom program. The results of γ -rays shielding for both processes are good agreements and the 70steel slag: 20Na₂O: 10CaO glass sample is excellent shielding compared with in glass system. In addition, all glass samples are better γ -rays shielding compared to some standard shielding materials. While charged particles (proton: H⁺, alpha particles: He²⁺) shielding properties of the SSG system have been evaluated using the SRIM program while electron particles were using the ESTAR program. The results found that mass stopping power (MSP) and project range (PR) of proton and alpha particles while electron total stopping power (TSP) and Continuous Slowing Down Approximation (CSDA) for 70steel slag: 20Na₂O: 10CaO glass sample was excellent charged particles shielding glass. Also, SSG's fast and thermal neutron shielding have been evaluated and discussed. The results indicated that the SSG system had the potential to develop transparent and Pb-free shielding material.

Keywords: Gamma-Ray; Neutron; Steel Slag Glass System

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Introduction

Currently, research about photons shielding materials is becoming more important in nuclear physics. Because photons which less mass, have no charge and can penetrate through the medium are very difficult to shield (Akkurt *et al.*, 2005). For shielding material, concrete is common the material used for radiation shielding because of its low cost, ease of installation, and ability to block both neutrons and photons. However, because concrete is opaque, it can be difficult to see through concrete. In addition, high-temperature radiation causes cracks within concrete structures due to H_2O loss, which is used for neutron attenuation. This results in reduced flexibility, density, and structural quality of concrete (Lee *et al.*, 2007; Gencel, 2012). Glass is an interesting material that is used for radiation shielding. Because it is transparent, easy to modify chemical composition and preparation technique (El-Denglawey *et al.*, 2021; Alrowaili *et al.*, 2021). As a result, glass materials are attractive for meeting the requirements of radiation shielding applications (Al-Buriahi *et al.*, 2021a, 2022; Alzahrani *et al.*, 2021). In addition to the foregoing, the ease with which high-density oxides can be added to the glass's chemical structure to increase density is another reason why glass is gaining appeal among radiation shielding researchers (Singh *et al.*, 2021; Al-Buriahi *et al.*, 2021b).

Steel slag (SS) is a byproduct of the steelmaking process which can separate 4 primary types such as blast furnace slag (BFS), basic oxygen furnace slag (BOFS), electric arc furnace slag (EAFS), and ladle furnace slag (LFS). In addition, it was also found that SS contains nickel, cadmium, chromium, and strontium elements. These are toxic compounds that are not only harmful to the environment but also to human health (Yildirim and Prezzi, 2011; Sheen *et al.*, 2013). So, SS recycling has been the topic of extensive research and environmentally friendly technologies. SS removal is the easiest and most cost-effective way to

combine them with building materials such as Portland cement (Yildirim and Prezzi, 2011; Azeez *et al.*, 2013; San-Jose *et al.*, 2014; Rosales *et al.*, 2017; Saha and Rajasekaran, 2017; Santamaría *et al.*, 2017, 2018). However, the SS also has other important elements for forming glass such as Si, Ca and Fe. Sriwongsa *et al.* (2022) where Si, Ca and Fe are networks former, networks modifiers and elements used as radiation shielding material, respectively (Alshahrani *et al.*, 2021).

In this context, steel slag glass (SSG) system with formula (70-x)steel slag: 20Na₂O: 10CaO: xB₂O₃ where x = 0, 10, 20, 30, 40, and 50 w% have been fabricated and investigated physical, optical, ionizing radiation (uncharged and charged particles) and thermal neutron shielding properties. The physical and optical properties of glass samples were investigated density, X-ray diffraction and transmittance, respectively. While uncharged particles (γ -rays) shielding was investigated at photon energy ranging from 80-1332 keV. The results of the experiment were compared with simulated theoretically by the WinXCom program and some standard shielding materials. Also, charged particles (proton, alpha and electron particles), and thermal neutron shielding of the SSG system have been simulated and discussed.

Experimental setup and Theory

Glass composition and preparation

This research, steel slag glass (SSG) system with formula (70-x)steel slag: 20Na₂O: 10CaO: xB₂O₃ where x = 0, 10, 20, 30, 40, and 50 w% were weighted to 20 g for each samples. All SSG samples were prepared by conventional melted quenching technique at 1200°C and annealed at 500°C for 3 hours of both processes, after that cut and polished as shown in Figure 1. The chemical composition of the SSG system was exhibited in Table 1.

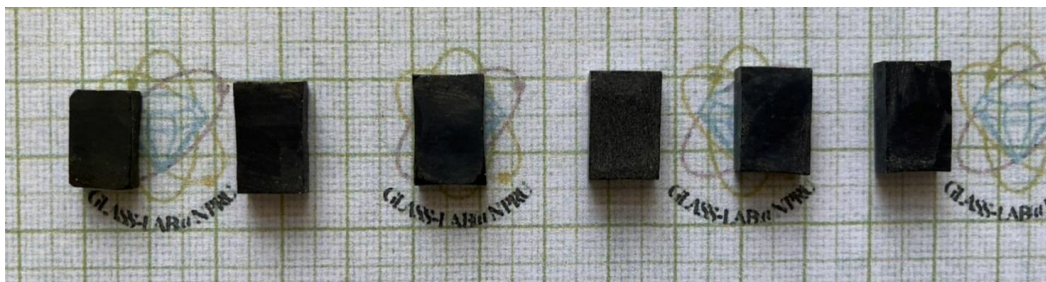
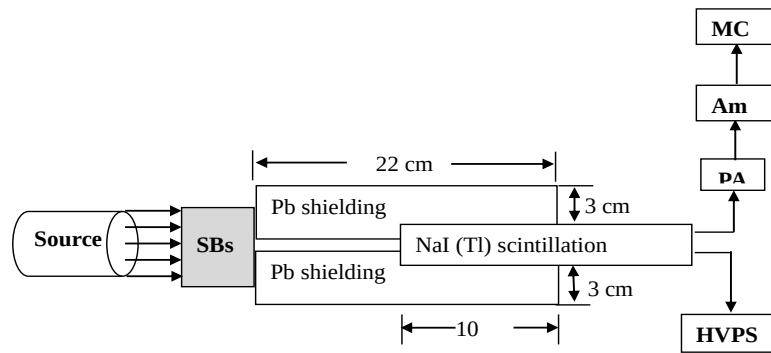


Figure 1. The SSG samples

Table 1. Code, chemical composition (wt%), thickness (cm) and density (g/cm³) for glass system

Sample	SS	B ₂ O ₃	Na ₂ O	CaO	Thickness (cm)	Density (g/cm ³)
SSG1	70	0	20	10	0.32	2.9646
SSG2	60	10	20	10	0.34	2.8501
SSG3	50	20	20	10	0.35	2.7617
SSG4	40	30	20	10	0.33	2.7023
SSG5	30	40	20	10	0.32	2.6659
SSG6	20	50	20	10	0.33	2.5803

**Figure 2. Setting up an experiment at different energies source**

Physical and optical properties

The density of the SSG system has been measured by a 4-digit sensitive microbalance (A&D, HR-200) according to Archimedes method and using the formula: ρ (g/cm³) = $(W_{air} \times \rho_{water}) / (W_{air} - W_{water})$, $W_{water} = 1.000$ g/cm³ at 25°C. The recording transmittance of the SSG system used a UV-VIS-NIR spectrophotometer (Shimadzu UV-3600) at room temperature, made at 300 to 2,500 nm.

Experimental and theoretical γ -rays shielding properties

The mass attenuation coefficient (μ_m) of the SSG system was investigated using the Compton scattering technique and was carried out with ²²Ba, ¹³⁷Cs and ⁶⁰Co sources at photon energies from 80-1332 keV. The measurement was operated using a well-calibrated γ -rays spectrometer. The 2" $\times$ 2" NaI (Tl) scintillation detectors have 8% energy solution at 662 keV (BICRON model 2M2/2), with CANBERRA photomultiplier tube base model 802-5. The experimental setup at various energies was shown in Figure 2. Theoretical simulation for the μ_m values was determined using the WinXCom program.

The γ -rays attenuation coefficient evaluation has been determined from the relationship of transmitted radiation intensity (I) through medium thickness x with incident radiation intensity (I₀). The

linear attenuation coefficient (μ) can be discussed by exponential Beer-Lambert's theory and can be following Eq. (2). This value can be used to calculate the mass attenuation coefficient (μ_m) of the medium as following Eq. (3) and the theoretical value of μ_m can be computed using mixture rule as following Eq. (3) and Eq. (4), respectively (Wagh *et al.*, 2019; Perişanoğlu *et al.*, 2020; Al-Burihi *et al.*, 2020):

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

$$\mu_m = \frac{\ln(I_0/I)}{\rho x} \quad (2)$$

$$\mu_m = \sum_i w_i (\mu_m)_i \quad (3)$$

here, w_i and $(\mu_m)_i$ are the weight fraction and mass attenuation coefficient of the i^{th} element, respectively.

Half value layer (HVL) is a basic parameter using explained interaction of γ -rays with medium which following in elsewhere (Wagh *et al.*, 2019; Halimah *et al.*, 2019).

Charged particles (Proton, alpha and electron particles)

The heavy charged particles (proton and alpha particles) interactions with materials are very

important for investigation and detection according to the Bethe-Bloch method. These interact with the nuclear stopping power of charged particles and the nucleus of the atom as following Eq. (4) (Kilicoglu *et al.*, 2019):

$$-\frac{dE}{dx} = S_e + S_n \quad (4)$$

here, minus sign is the loss of kinetic energy of the charged particle, dE/dx is stopping power, S_e and S_n are electronic stopping power and nuclear stopping force, respectively. The electron stopping power is the interaction of charged particles with orbital electrons while nuclear-stopping power is specific to electron radiation.

The mass stopping power (MSP) is the basic parameter used to explain the loss of kinetic energy (E_k) for proton and alpha particles when they travel through the medium. While the projected range (PR) is the average depth of heavy charged particles penetrating the medium until rest and this value is low indicating for excellent shielding medium. These parameters were simulated using the SRIM program (Kilicoglu *et al.*, 2019; Issa *et al.*, 2019; Olarinoye *et al.*, 2020).

In addition, the electron's total stopping power (TSP) in the medium and Continues Slowing Down Approximation (CSDA) were simulated using the ESTAR program at E_k from 10^{-2} - 10^2 MeV. (Saadi and Machrafi, 2020; Al-Buriahi *et al.*, 2021c).

Neutron shielding properties

The classification of neutrons can be of several types depending on the energy of the neutron such as fast neutron (> 0.1 MeV), intermediate neutron (0.1-100 keV), epithermal neutron (0.1-100 eV) and thermal neutron (0.015 eV). The interaction between neutron and medium consists of transmission, absorption and scattering of neutrons. The possibility of one or more of these processes occurring is through the microscopic cross section

of the reaction (Rammah *et al.*, 2021; Lakshminarayana *et al.*, 2022).

Fast neutrons removal cross section (Σ_R) has been determined applying relationship Eq. (5)

$$\Sigma_R = \sum_i W_i \left(\Sigma_R / \rho \right)_i \quad (5)$$

here $W_i = \rho w_i$ refers to partial density, w_i and ρ refer to a fraction by weight of element i and total density of the medium, respectively.

While thermal neutrons can apply by Eq. (6)

$$\Sigma(E) = N_A \rho \sum_i \frac{W_i}{M_i} \sigma_i(E) \quad (6)$$

here $\sigma_i(E)$ (in barn units), W_i and M_i refer to the microscopic cross section, mass fraction and atomic mass of the i^{th} element in the medium, respectively, while $\Sigma(E)$ (cm^{-1}) and N_A refer to medium's macroscopic cross section and Avogadro's number, respectively (Rammah *et al.*, 2020, 2021; Lakshminarayana *et al.*, 2021, 2022). In addition, both values (Σ_R and $\Sigma(E)$) are basic parameters using calculated the other parameters such as transmission factors (TF), half value layer (HVL), shielding percentage (SP) and relaxation lengths for neutron (Lakshminarayana *et al.*, 2021, 2022; Sahadath and Sarwar, 2015).

Results and Discussion

Physical and optical properties

Density is the foundational property of glass samples using explained the changing of formation for glass samples. The density of the SSG system as exhibited in Figure 3, decreased due to the decrease in the composition of high molecular mass elements in the SSG system as shown in Table 1, which was replaced by B_2O_3 content (Chanthima and Sittichai, 2017; Kaur *et al.*, 2018). The X-ray diffraction

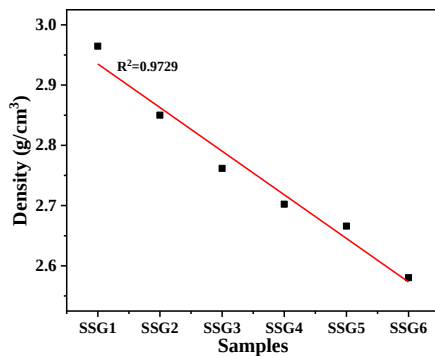


Figure 3. The density of the SSG system

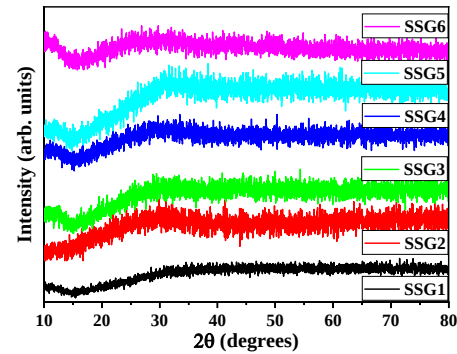


Figure 4. The XRD pattern of the SSG system

(XRD) pattern of the SSG system was shown in Figure 4. The huge-broad XRD pattern confirms the amorphous nature of the SSG system (Kaur *et al.*, 2018).

The transmittance spectrum of the SSG system has been investigated at room temperature and the result was exhibited in Figure 5. The result found that the SSG6 sample had the highest transmittance. It indicated that this glass sample is the best transparency compared with all samples.

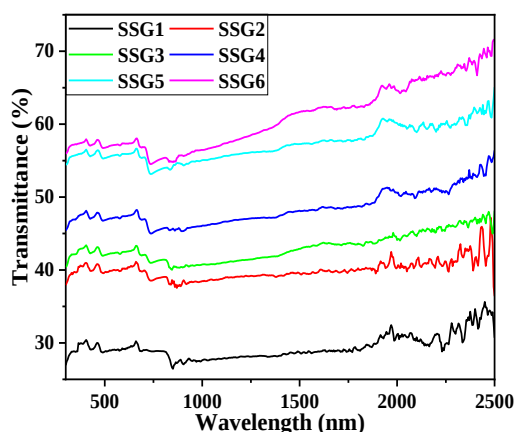


Figure 5. The transmittance of the SSG system versus the wavelength at 300 to 2,500 nm

Ionizing radiation shielding properties

Uncharged particles (γ -rays): The γ -rays shielding competences of the SSG system were measured. The μ_m of the SSG system has been evaluated results by experimental and the WinXCom program as shown in Figure 6. The results found that the μ_m decreased with increasing energy which was discussed on the interaction of γ -rays with the medium. At low energy ranging, photoelectric effect (PE) which cross-section $\propto E^{-3.5}$ is the main process and intermediate energy ranging, Compton scattering (CS) which cross-section $\propto E^{-1}$ is the major process while high energy ranging, pair production (PP) which cross-section $\propto \log E$ is the main interaction (Agar *et al.*, 2019; Sriwongsa *et al.*, 2022). In addition, the SSG1 sample had the highest μ_m value which indicated the SSG1 sample had excellence γ -rays shielding and the results of the experimental with theoretical were consistent.

Figure 7, shown that the characterize of HVL for the SSG system compared with ordinary concrete, hematite-serpentine and commercial window glass at an energy ranging 81-1332 keV. The HVL value of the SSG system is lower than that of the three kinds of standard shielding medium and the SSG1 is the lowest value. It indicated that the SSG1 sample is an excellent γ -rays shielding medium (Shamshad *et al.*, 2017).

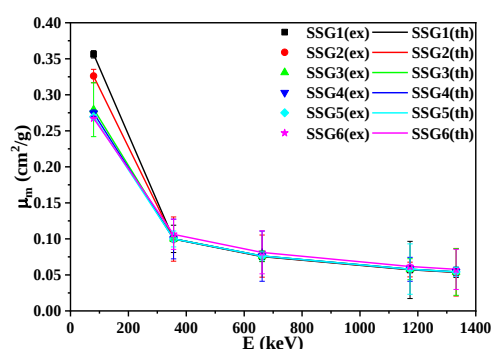


Figure 6. The μ_m of γ -rays versus energy ranges at 81-1332 keV of the SSG system

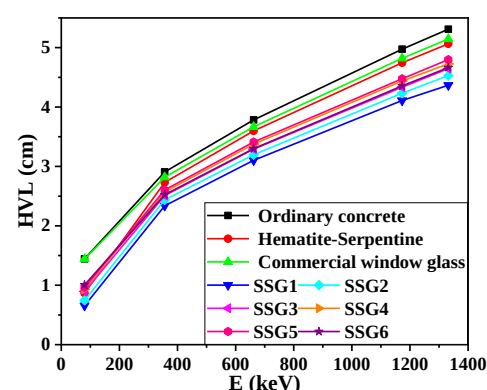


Figure 7. The HVL of the SSG system compare with some standard shielding

Charged particles (Proton and alpha particles): The shielding properties of charged particulates (proton: H^+ and alpha particle: He^{2+}) for the SSG system were discussed by the important parameters such as mass stopping power (MSP) and projected range (PR) using the SRIM program.

The MSP of the SSG system for H^+ and He^{2+} at E_k from 10^{-2} - 10^2 MeV is illustrated in Figure 8(a-b). From the figure, the MSP value of H^+ and He^{2+} particles increased with increasing E_k until the highest values at 0.1 MeV and 0.7 MeV for H^+ and He^{2+} particles, respectively, after that these values decreased. These are because of $MSP \propto 1/v^2$ and α ion charge. In addition, the MSP of H^+ is lower than He^{2+} due to H^+ had higher velocity and lower charge compared with He^{2+} .

The projected range (PR) values for H^+ and He^{2+} particles with plotted in Figure 9(a-b). From the figure, PR values of both particles for the SSG system increased with increasing E_k and the PR value of H^+ was higher than He^{2+} because of they are lighter than He^{2+} particles. In addition, the SSG1 sample had the lowest PR these results indicated that this sample is an excellent H^+ and He^{2+} particles shielding compared with all samples (Rammah *et al.*, 2020, 2021).

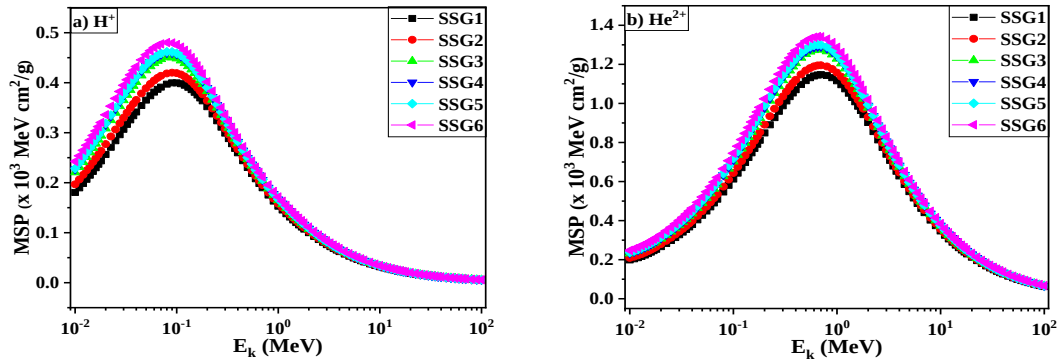


Figure 8. The MSP versus E_k of (a) proton and (b) alpha particles for the SSG system

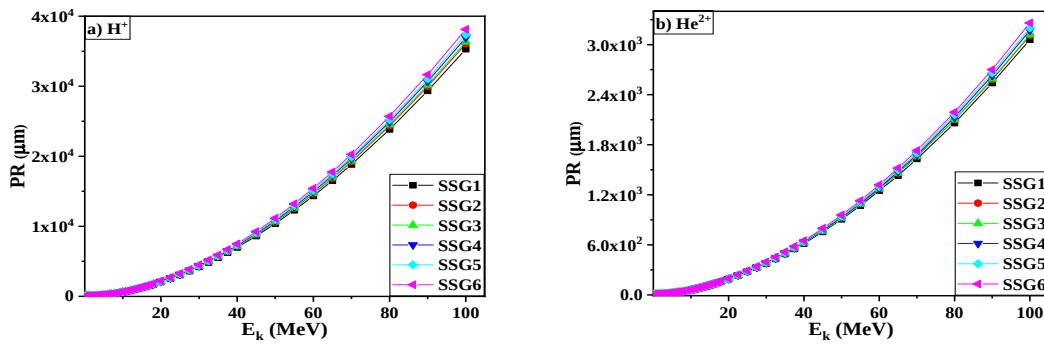


Figure 9. The PR versus E_k of (a) proton and (b) alpha particles for the SSG system

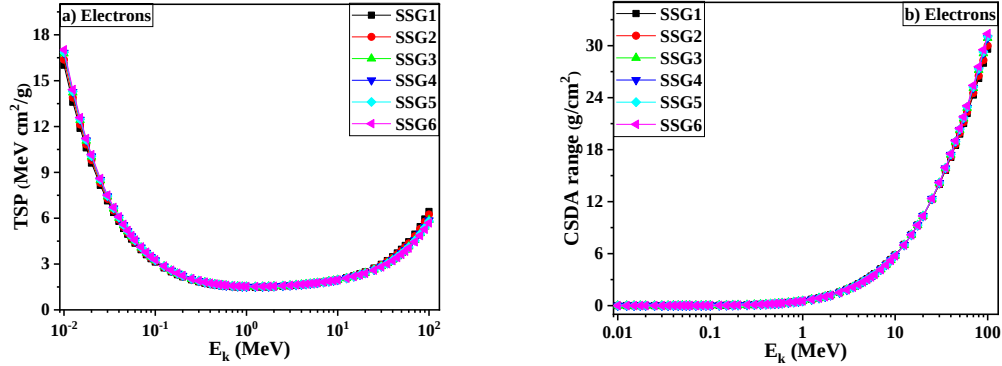


Figure 10. (a) the TSP and (b) the CSDA versus E_k for the SSG system

Electron particles: For electrons that are the lightest charged particle, the TSP and the CSDA are values using a design medium for shielding. In this context, the SSG system was predicted at E_k ranging from 10^{-2} - 10^2 MeV as illustrated in Figure 10(a-b). From Figure 10(a), the TSP value decreased with increased E_k , this event can explain by electron interaction. When electrons pass through a medium, the total E_k of the electron is lost from collisional (interactions with atomic electrons) and radiative (electrons' acceleration in nuclei's Coulomb field which is called Bremsstrahlung). In addition, electrons with high E_k have a high chance of radiative mechanisms. In general, the TSP value

depends on the E_k of electrons and the atomic number (Z) of the target medium. Besides, the TSP values increased with increasing B_2O_3 content.

The travelled distances of electrons until they are stopped are called CSDA and are shown in Figure 10(b). The CSDA range for the SSG system very little increased and then increased with E_k of electrons increasing and increased with increasing B_2O_3 content.

From the results of the TSP and the CSDA range calculation, it was found that the SSG6 sample had the highest electron shielding compared to the other SSG samples (Lakshminarayana *et al.*, 2021; Sakar and Arda, 2021; Boukhris *et al.*, 2021).

Neutron shielding properties

Fast Neutron: The fast neutrons removal cross section, Σ_R (cm^{-1}) of the SSG system was simulated using the partial density method and exhibited in Figure 11. It found that Σ_R values of the SSG6 sample had the highest this value. The transmission factor (TF) is the value to explain the behavior of the neutron shielding medium. Figure 12 exhibited the TF of the SSG system with the thickness (mm). It found that the SSG6 sample had TF lowest value at the same thickness and all samples decreased with increasing thickness. In addition, the HVL of fast neutrons for the SSG samples is shown in Figure 13. It found that the HVL of the SSG6 sample was the lowest value while neutron shielding percentage (SP) had the highest value as exhibited in Figure 14. The relaxation lengths of the SSG6 sample had the lowest value is shown in Figure 15. These results indicated that the decreasing steel slag content which decreased density of the SSG system resulted in a better fast neutron shielding because steel slags were composted high atomic number so the decreasing steel slag content that is to decrease the number of heavy elements as well (Sahadath and Sarwar, 2015; Rammah *et al.*, 2021).

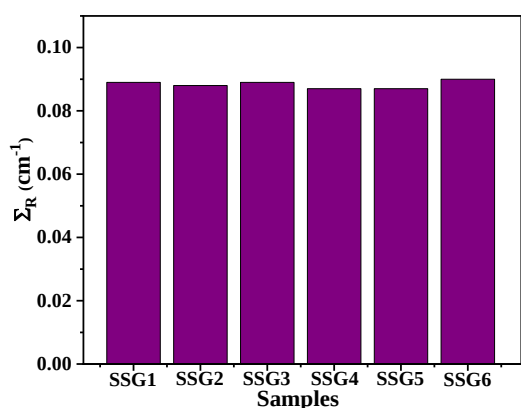


Figure 11. The Σ_R for the SSG system

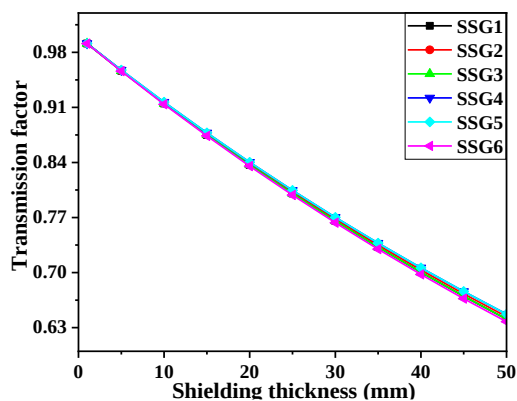


Figure 12. The TF of fast neutron versus thickness (mm) for the SSG system

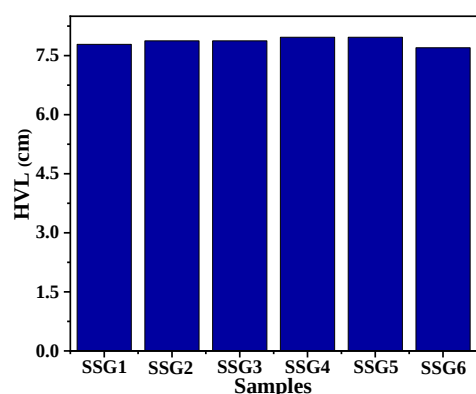


Figure 13. The HVL of fast neutron for the SSG system.

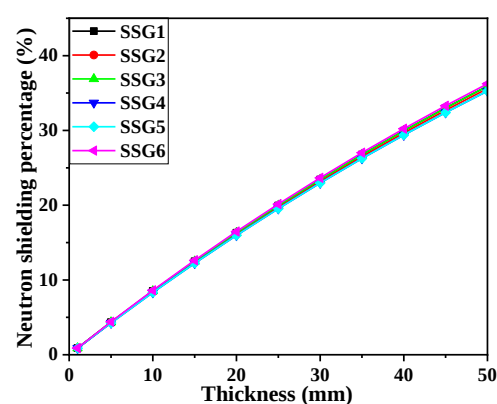


Figure 14. The fast neutron SP versus thickness for the SSG system

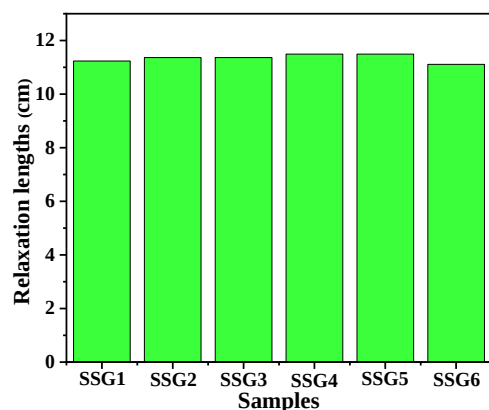


Figure 15. The relaxation length of fast neutron for the SSG system

Thermal Neutron: The thermal neutron shielding for the SSG system was estimated using the total macroscopic cross section (Σ_{total} : cm^{-1}) and exhibited in the Figure 16. It found that Σ_{total} values of the SSG1 sample had the highest in this value. The transmission factor (TF) of the SSG system with the thickness (mm) was shown in Figure 17. It found that the SSG1 sample had TF the lowest value

at the same thickness and the TF value for all samples decreased with increasing thickness. The HVL of thermal neutrons for the SSG samples is shown in Figure 18. It found that the HVL of the SSG1 sample was the lowest value while thermal neutron shielding percentage (SP) had the highest value as exhibited in Figure 19. The relaxation lengths of the SSG1 sample had the lowest value as shown in Figure 20. These results indicated that the decreasing steel slag content resulted in lesser thermal neutron shielding. This is because the SSG1 sample which had the highest density, made the inelastic scattering of fast neutrons increase as a result the rate of fast neutrons degradation increased, and this event produced newly thermal neutrons. Therefore, this sample is the highest effect on the absorption of thermal neutrons (Abdelmonem, 2021; Rammah *et al.*, 2021).

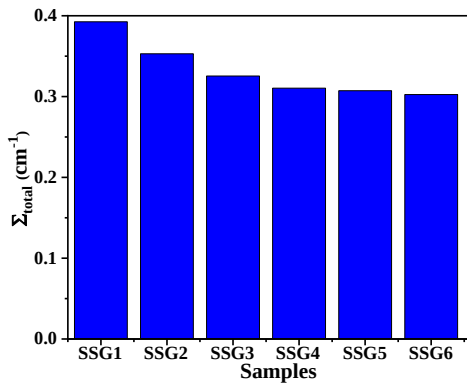


Figure 16. The Σ_{total} of thermal neutron for the SSG system

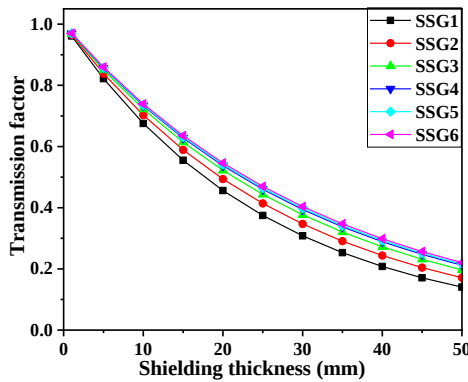


Figure 17. The TF of thermal neutron versus thickness for the SSG system

Conclusion

This research, steel slag glass (SSG) system in formula (70-x)steel slag: 20Na₂O: 10CaO: xB₂O₃ where x = 0, 10, 20, 30, 40, and 50 w% were

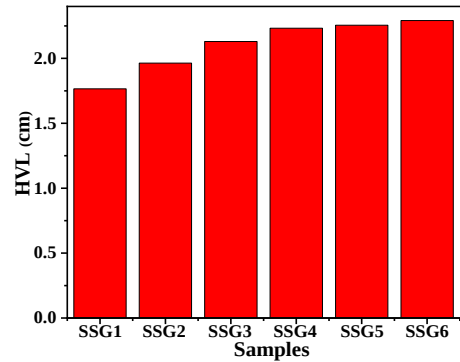


Figure 18. The HVL of thermal neutron for the SSG system

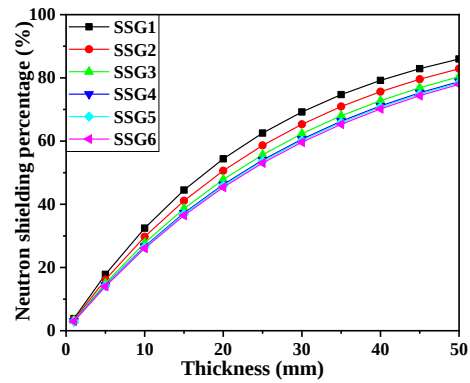


Figure 19. The thermal neutron SP versus thickness for the SSG system

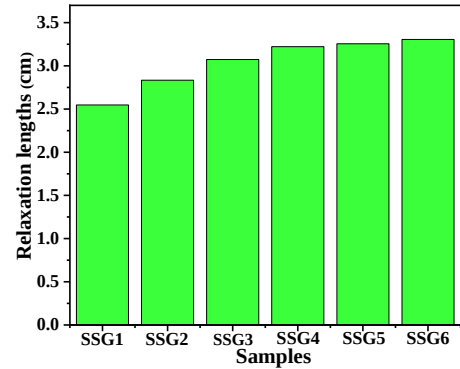


Figure 20. The relaxation length of thermal neutron for the SSG system

prepared by using conventional melt quenching method at 1,200°C. The SSG system were investigated physical, optical, ionizing radiation (uncharged: γ -rays while charged particles: H⁺, He²⁺ and electrons) and neutron shielding properties. The experimental on γ -rays shielding were studied on different sources at an energy ranging from 80-1332 keV and the results from the experiment were compared with theoretical values which were

simulated using the WinXCom program. The results from both processes were good agreements and the 70steel slag: 20Na₂O: 10CaO glass sample was excellent shielding. In addition, all glass samples were compared with some standard shielding materials. The results found that all glass samples were better γ -rays shielding some standard shielding materials. The charged particles (proton: H⁺, alpha particles: He²⁺) shielding properties of the SSG system were discussed by basic parameters such as the mass stopping power (MSP) and the project range (PR). While electrons particles were explained by the total stopping power (TSP) and the Continues Slowing Down Approximation (CSDA) values. The results found that the 70steel slag: 20Na₂O: 10CaO glass sample was excellent charged particles shielding glass. The neutron shielding (fast and thermal neutron) was investigated on basic parameters such as fast neutrons removal cross section, the total macroscopic cross section, transmission factors, half value layer, neutron shielding percentage and relaxation length. The results found that the 20steel slag: 20Na₂O: 10CaO: 50B₂O₃ glass sample was excellent fast neutron shielding while the 70steel slag: 20Na₂O: 10CaO glass sample was superb thermal neutron shielding.

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