Calculation of the Neutron Shielding Properties of Locally Developed Ilmenite-Magnetite (I-M) Concrete

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ABSTRACT

The fast neutron effective removal cross section, $\Sigma_R(cm^{-1})$, plays a significant role in determining the shielding effectiveness of any material against fast neutrons. This study has been concerned with the analytical calculation of $\Sigma_R(cm^{-1})$ of the locally developed Ilmenite-Magnetite (I-M) concrete. For comparisons, the same parameter has been calculated for other types of concretes with different densities and compositions. The calculated value of Σ_R for I-M concrete is 0.09078 cm^{-1} and found to higher than some concretes. The relaxation length and transmission rate of fast neutrons in I-M concrete have been compared graphically with other types of concretes. The results of this study will provide some specific useful information of effective removal cross sections and half value layers of the locally developed I-M concrete and other types of concretes for practical shielding calculations.

Keywords: Fast neutrons, I-M concrete, Effective removal cross section, Relaxation length

1. Introduction

The application of biological shield between the radiation source and the personnel resolves the problem of protection of radiation workers against ionizing radiation. Neutrons are used in many industrial/medical researches and can be produced by different nuclear reactions. Neutron sources can be classified as nuclear fission reactors, radioisotopes, and particle accelerators. The neutrons emitted are mostly high energy neutrons which are known as fast neutrons. The fast neutrons are more difficult to shield because absorption cross sections are much lower at higher energies. Thus fast neutrons must first be thermalized either by elastic or inelastic scattering. In general, an efficient neutron shield is a combination of hydrogenous or low mass number materials to moderate neutrons; high absorption cross section materials to absorb the thermal neutrons and high atomic number materials to absorb the generated gamma-rays [1]. Several investigators have contributed to find the neutron shielding properties of concretes and building materials [2-5], different types of resin [6], different polymers [7-9], compounds [10], borate glasses [11], and multilayered biological shields [12]. Ilmenite-Magnetite (I-M) concrete is a heavy concrete produced locally with sand, stone chips, and cement in 100:100:36 ratios by volume, respectively. The composition of the sand is ilmenite, magnetite, and ordinary sand mixed together in a 2:2:1 ratio by volume, respectively. The density of I-M concrete is 2.78 gcm^{-3} with 279 kg/m^2 (3990-psi) compressive strength (12×6 in. cylinder). This concrete was developed in connection with the construction of the biological shield of the 3MW (thermal) TRIGA MARK-II research reactor at the Atomic Energy Research Establishment (AERE) in Bangladesh. There are some experimental and theoretical studies on the shielding properties of I-M concrete [9, 13-15]. However, in these works shielding of fast neutrons were not considered in details. The present work was undertaken to calculate the neutron attenuation parameters of I-M concrete along with other types of concretes for potential application as shielding material in nuclear power plants as well as in different nuclear facilities.

2. Theoretical calculations

For neutron attenuation calculations, the elastic and inelastic scattering reactions, and neutron capture interaction processes, are of great importance. The effectiveness of the sample of the shielding material can be described by an equivalent absorption cross section, called the effective removal cross section. The removal cross section is the probability that a fast or fission energy neutron will be removed from uncollided neutrons if undergoes a collision. The effective removal cross section is considered to be approximately constant for neutron energies between 2 and 12 MeV. The observed value of the removal cross section is, in fact, roughly equal to 2/3 of the total $\Sigma_t\,(cm^{-1})$ (scattering and capture) cross-section of the given material for neutrons having energies in the range of 6 to 8 MeV. If concrete contains sufficient moderating material, the attenuation of neutrons will be determined by this removal process.

The removal cross-section for compounds may be calculated from the values of mass removal cross sections (Σ_R/ρ) for various elements in the compounds or mixtures by the following mixture rule:

$$\Sigma_R = \sum_i \rho_i (\frac{\Sigma_R}{\rho})_i \qquad (1)$$

where, ρ_i and $(\frac{\Sigma_R}{\rho})_i$ are the partial densities (the density as it appears in the mixture) and mass removal cross-section of the i^{th} constituent, respectively. Transmission factor for fast neutrons have been calculated using the attenuation equation as follows:

$$\frac{I}{I_0} = e^{-x\Sigma_R} \tag{2}$$

The half value layer (HVL), tenth value layer (TVL) and relaxation lengths (λ) for fast neutrons have been calculated using following equations:

$$HVL = \frac{0.693}{\Sigma_R} \tag{3}$$

$$TVL = \frac{2.30}{\Sigma_R} \tag{4}$$

$$\lambda = \frac{1}{\Sigma_R} \tag{5}$$

In this work, the effective removal cross section (Σ_R), HVL, TVL and λ of fast neutrons has been calculated analytically for Ilmenite-Magnetite (I-M) concrete. For comparisons, these parameters for other types of concretes have been calculated in the same method as for I-M concrete. The compositions of barite, serpentine and ordinary concrete-1 have been taken from reference [16] and that of ordinary concrete-2 from reference [17]. The values of the mass removal cross-sections of the elements that constitute these materials have been taken from literature [6, 7].

Table 1: I-M concrete aggregates [15].

Coarse aggregate [stone chip gradation (vol%)]	
3.81 cm down - 20 black (crusher)	
2.54 cm down - 30 black (crusher)	
1.91 cm down - 35 black (crusher)	
1.27 cm down - 15 black (crusher)	
Fine aggregate composition (vol%)	
Ordinary sand	20
Ilmenite	40
Magnetite	40
Mix ratio (cement:sand:stone chips)	36:100:100
Net water /cement ratio	0.5
Slump (cm)	1.27

Table 2: Elemental composition of I-M concrete [15].

Element	*Atomic number*	*Atomic weight (g)*	*Elemental density (g/cm^3)*	*Weight fraction*	*Total density (g/cm^3)*
H	1	1.008	0.0157	0.005647	
C	6	12.011	0.0022	0.000791	
O	8	16.000	1.0523	0.378525	
Mg	12	24.320	0.1014	0.036474	
Al	13	26.980	0.0497	0.017877	
Si	14	28.090	0.1349	0.048525	
P	15	30.975	0.0002	0.000071	
S	16	32.066	0.0016	0.000575	2.78
Ca	20	40.080	0.2469	0.088812	
Ti	22	47.900	0.3563	0.128165	
V	23	50.950	0.0021	0.000755	
Cr	24	52.010	0.0010	0.000359	
Mn	25	54.940	0.0084	0.003021	
Fe	26	55.850	0.7863	0.282841	
Ni	28	58.710	0.0012	0.000431	

Table 3 Calculation results of fast neutron removal cross section for I-M concrete (ρ=2.78 g/cm^3).

Element	*Weight fraction*	*Partial density (g /cm^3)*	*$\sum_R/\rho$ (cm^2/g)*	*$\sum_R$ (cm^{-1})*
H	0.005647	0.0157	0.5980	0.009388
C	0.000791	0.0022	0.0502	0.000110
O	0.378525	1.0523	0.0405	0.042618
Mg	0.036474	0.1014	0.0333	0.003376
Al	0.017877	0.0497	0.0293	0.001456
Si	0.048525	0.1349	0.0252	0.003399
P	0.000071	0.0002	0.0283	0.000005
S	0.000575	0.0016	0.0277	0.000044
Ca	0.088812	0.2469	0.0243	0.005999
Ti	0.128165	0.3563	0.0205	0.007304
V	0.000755	0.0021	0.0213	0.000044
Cr	0.000359	0.0010	0.0208	0.000020
Mn	0.003021	0.0084	0.0203	0.000170
Fe	0.282841	0.7863	0.0214	0.016826
Ni	0.000431	0.0012	0.0190	0.000022
			Total =	*0.09078*

Table 4: Calculation results of fast neutron removal cross section for Ordinary concrete-1 (ρ=2.3 g/cm^3). [16]

Element	*Weight fraction*	*Partial density (g /cm^3)*	*$\sum_R/\rho$ (cm^2/g)*	*$\sum_R$ (cm^{-1})*
H	0.0221	0.05083	0.5980	0.03039
C	0.0025	0.00575	0.0502	0.00028
O	0.5775	1.32825	0.0405	0.05379
Na	0.0152	0.03496	0.0341	0.00119
Mg	0.0013	0.00299	0.0333	0.00009
Al	0.0210	0.04830	0.0293	0.00141
Si	0.3056	0.70288	0.0252	0.01771
K	0.0108	0.02484	0.0247	0.00061
Ca	0.0439	0.10097	0.0243	0.00245
Fe	0.0070	0.01610	0.0214	0.00034
			Total =	*0.10831*

Table 5: Calculation results of fast neutron removal cross section for Ordinary concrete-2 (ρ=2.35 g/cm³).[17]

Element	*Weight fraction*	*Partial density (g /cm³)*	*$\sum_R/\rho$ (cm²/g)*	*$\sum_R$ (cm⁻¹)*
H	0.0056	0.01316	0.5980	0.00786
O	0.4956	1.16466	0.0405	0.04716
Na	0.0171	0.04018	0.0341	0.00137
Mg	0.0024	0.00564	0.0333	0.00018
Al	0.0456	0.10716	0.0293	0.00313
Si	0.3135	0.73672	0.0252	0.01856
S	0.0012	0.00282	0.0277	0.00007
K	0.0192	0.04512	0.0247	0.00111
Ca	0.0826	0.19411	0.0243	0.00471
Fe	0.0122	0.02867	0.0214	0.00061
			Total =	*0.08482*

Table 6: Calculation results of fast neutron removal cross section for Barite concrete (ρ=3.35 g/cm³). [16]

Element	*Weight fraction*	*Partial Density (g /cm³)*	*$\sum_R/\rho$ (cm²/g)*	*$\sum_R$ (cm⁻¹)*
H	0.0036	0.01206	0.5980	0.00721
O	0.3118	1.04453	0.0405	0.04230
Mg	0.0011	0.00368	0.0333	0.00012
Al	0.0042	0.01407	0.0293	0.00041
Si	0.0104	0.03484	0.0252	0.00087
S	0.1078	0.36113	0.0277	0.01000
Ca	0.0502	0.16817	0.0243	0.00408
Fe	0.0475	0.15912	0.0214	0.00340
Ba	0.4634	1.55239	0.0129	0.02002
			Total =	*0.08844*

Table 7: Calculation results of fast neutron removal cross section for Serpentine concrete (ρ=2.6 g/cm³). [16]

Element	*Weight fraction*	*Partial density (g /cm³)*	*$\sum_R/\rho$ (cm²/g)*	*$\sum_R$ (cm⁻¹)*
H	0.0720	0.18720	0.598	0.11194
C	0.0015	0.00390	0.0502	0.00019
O	0.5560	1.44560	0.0405	0.05854
Mg	0.1020	0.26520	0.0333	0.00883
Al	0.0250	0.06500	0.0293	0.00190
Si	0.1755	0.45630	0.0252	0.01149
K	0.0008	0.00208	0.0247	0.00005
Ca	0.0564	0.14664	0.0243	0.00356
Fe	0.0108	0.02808	0.0214	0.00060
			Total =	*0.19713*

Table 8: Comparison of shielding parameters of different concretes for fast neutron.

Concrete Type	*Density (g/cm³)*	*$\sum_R$ (cm⁻¹)*	*HVL (cm)*	*TVL (cm)*	*Relaxation length (cm)*
I-M	2.78	0.09078	7.63	25.33	11.015
Ordinary-1	2.3	0.10831	6.40	21.24	9.233
Ordinary-2	2.35	0.08482	8.17	27.11	11.789
Barite	3.35	0.08844	7.84	26.00	11.306
Serpentine	2.6	0.19713	3.52	11.67	5.073

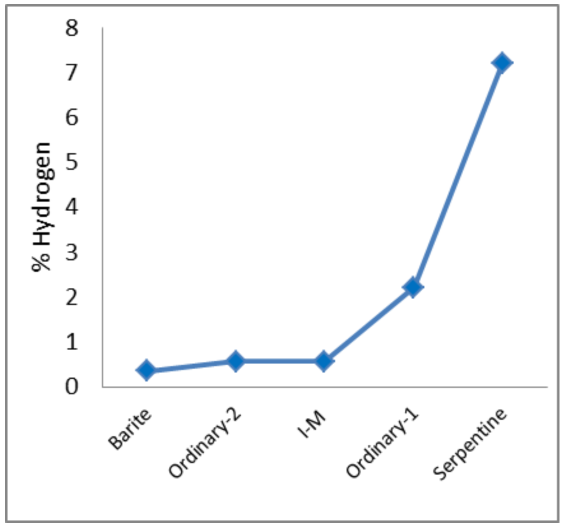

Fig. 1. Variation of hydrogen content in different concretes.

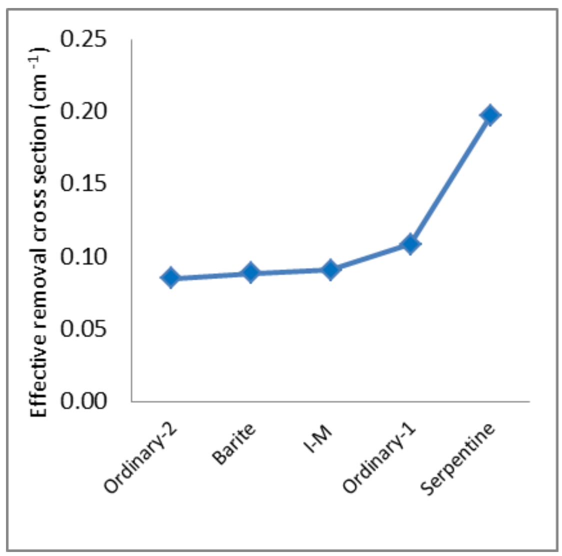

Fig. 2. Variation of effective removal cross section in different concretes

3. Results and discussions

Being an uncharged particle, neutron shielding is a bit complicated. The basis of neutron shielding is first reducing its energy through moderation (thermalization) and then placing shielding material with high neutron absorption cross section between the object and the source. The fast neutrons lose almost half of their energy by a single elastic collision with hydrogen atom. Therefore hydrogenous materials are most effective for fast neutron shielding. Concrete is an essential mixture of light and heavy nuclei that possesses the essential characteristics for both neutrons and gamma-rays. It has satisfactory mechanical and structural properties and it also involves relatively low manufacturing as well as maintenance cost. Also the easy process of construction makes concrete especially suitable for radiation shielding. Hence today it is widely and extensively used as biological shield material. The I-M concrete aggregates and its composition is shown in Table 1 and Table 2 respectively. The calculation of the fast neutron effective removal cross section of I-M concrete is shown in Table 3 and compared with other types of concretes in Table 8. Tables 4–7 represent the same calculations for other types of concretes. The calculated value of (Σ_R) for I-M concrete is 0.09078 cm^{-1} which is close to the experimental value 0.0929 cm^{-1} [15] and have been found higher than barite and ordinary concrete-2. This is because of the higher percentage of low atomic number elements in I-M concrete. The energy loss of fast neutrons per collision is higher in I-M concrete and the neutrons are removed from the fast energy region within a short penetration distance. That is why the half value layer and tenth value layer of this locally developed concrete are lower than the barite and ordinary concrete-2. Ordinary concrete-1 is slightly better than I-M concrete for its higher percentage of hydrogen. Serpentine which contains more than seven percent hydrogen has the highest value of Σ_R. From the transmission curve as shown in Fig.3. it is seen that I-M concrete has lower transmission, i.e., higher attenuation of fast neutrons than barite and ordinary concrete-2 which proves its effectiveness. Also as shown in Fig.4., the relaxation length for fast neutrons in I-M concrete is lower due to its higher values of Σ_R. Due to the presence of heavy elements in I-M concrete it will be more effective against the gamma-rays generated from the inelastic scattering and radiative capture reactions of neutrons with nuclei.

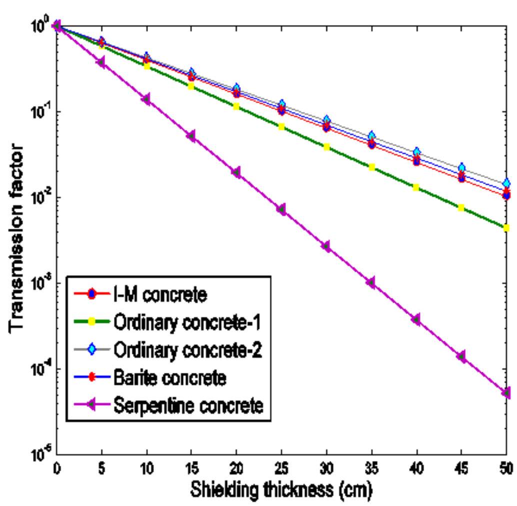

Fig. 3. Variation of fast neutron transmission factor with shielding thickness

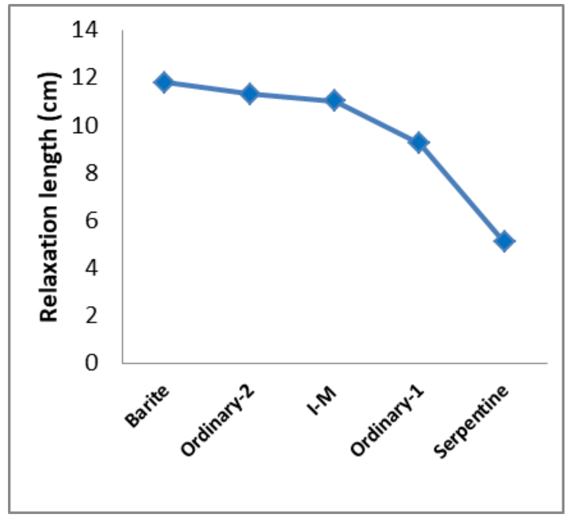

Fig. 4. Variation of relaxation length for fast neutrons in different concretes.

4. Conclusions

In this study the fast neutron effective removal cross section of I-M concrete has been calculated analytically and compared with Ordinary concrete-1 & 2, Serpentine and Barite. It is found that this locally developed concrete is more effective than ordinary concrete-2 and barite concrete for its higher effective removal cross section. It is also found that hydrogenous material is best for neutron shielding. The results also illustrate the effectiveness of I-M concrete so far as its shielding properties are concerned. It can be concluded that I-M concrete is a good neutron shielding material and it can be used as a biological shield especially in nuclear reactors as well as accelerators, radioactive sources etc.

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