INVESTIGATION ON RADIATION SHIELDING PARAMETERS OF ORDINARY, HEAVY AND SUPER HEAVY CONCRETES

by

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Shielding of a reactor is required for protection of people and environment during normal operation and accidental situations. In the present paper we investigated the shielding parameters viz. mass attenuation coefficients, linear attenuation coefficients, tenth-value layer, effective atomic numbers, kerma relative to air and exposure buildup factors for gamma-ray for ordinary, heavy, and super heavy concretes. Macroscopic effective removal cross-sections for fast neutron had also been calculated. Ordinary concrete is economically suitable for mixture high energy gamma-ray and neutron as it has large weight fraction of low-*Z* as compared with super heavy concretes to slow down the neutron. Super heavy concretes are superior shielding for both reactor operation and accident situations. The study is useful for optimizing for shielding design and radiation protection in the reactors.

Key words: buildup factor, super heavy concrete, containment, biological shielding

INTRODUCTION

Radiation protection of people and environment around nuclear reactor installation is ensured by source control during design, operation and maintenance, and assured by monitoring the radiation. Radioactivity released during any accident is controlled inside the containment. The gamma-ray and neutron radiations are high range, which require adequate shielded during design stage. The biological shielding is used around the reactor core. Shielding of gamma-ray and neutron is achieved by various types of the materials or combination of the compounds. Radiations emitted during fission are called primary radiation whereas those which produce as a result of interaction of primary radiation with reflectors, coolant and shielding materials, *etc*. are called secondary radiation.

During reactor operation, gamma photons are emitted from fission products (prompt and delayed) and activation products. The prompt fission gamma-rays have continuous energy spectrum in range 0.5 to 10 MeV but the intensity of radiation is negligible for energies in excess of 7 MeV [1]. Most of elements exhibits capture gamma ray energy ranging up to about 8 MeV and decay gamma-ray having energies over 2 MeV, up to 5.4 MeV [1]. The capture gamma-rays (0-10 MeV) are produced by thermal neutrons with construction materials such as fuel elements (aluminum, beryllium, iron, zirconium, uranium), sodium, deuterium, and shielding materials, *etc*. [1, 2]. The list of typical radio-nuclides produced in a reactor during operation is given in literature [3]. In a reactor, photon emission probability of energy range 0.5 to 4.5 MeV is very large compared with ~5 to 10 MeV [4-6]. During nuclear accident, a mixture of short and long lived radio-nuclides is being released. These radio-nuclides are halogen, telluride, alkali metal, noble metals, refractory oxides, alkaline earth metals, rare earth metals, transuranics, and inert gases. The noble gases are more prone to escape from reactor building during initial phase of the accident. Therefore reactor accident management requires temporary storage of radioactivity to decay in the containment.

The radiation shielding efficiency of a composite material is evaluated by means of mass attenuation coefficients, linear attenuation coefficients, half-value layer or tenth-value layer, effective atomic numbers, kerma relative to air and the exposure buildup factors. The interaction of gamma-ray with material degrades its original energy and buildup in the medium giving rise the secondary gamma radiations. The buildup of gamma photon is estimated by the buildup factor which corrects the response of un-collided photon beam. The buildup is defined as the ratio of total value of specified radiation quantity at any point to the contribution to that value from radiation reaching to the point without having undergone a collision. The exposure buildup factor in

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which quality of interest is the exposure and energy response function is that of absorption in air [7]. There are several studies related to gamma-ray buildup factors in different composites, gaseous mixture, fly-ash brick, alloys, borosilicate glasses, and oxide dispersion strengthened steels [8-12] using the GP fitting parameters. The geometrical progression (GP) fitting has been standardized with ANS, 1991 and MCNP [9, 12].

The hard capture secondary gamma photons and fast neutrons are removed by utilization of the heavy concretes [13, 14]. During reactor accident comparatively low energy gamma photon are emitted. Thus shielding of reactor during operation as well as accident is very important to maintain the ambient radiation level. In the present paper we have investigated the shielding parameters of some ordinary, heavy and super heavy concretes to assess the shielding efficiencies for various applications in reactor and accelerator design.

MATERIALS AND METHODS

The concretes whose elemental composition depends on the mix proportions, chemical element and densities ranging from 2.3-5.11 g/m^3 are given in tab. 1 [15, 16]. These concretes are categorized based on densities as ordinary concretes (ρ = 2.3-3.05 g/cm^3); heavy concretes (ρ = 3.5-4 g/cm^3), and super heavy concretes (ρ = 4.5-5.11 g/cm^3). The concretes contain low- and high-Z elements hydrogen to iron with different weight fractions.

Mass attenuation coefficients

The mass attenuation coefficients of the different types of concretes were determined using the transmission method according to Lambert-Beer's law ($I = I_0 e^{-\mu_m t}$), where I_0 and I are the incident and attenuated photon intensity with energy, E, respectively, $\mu_m = \mu/\rho$ [cm^{2}g^{-1}] is the mass attenuation coefficient and t [g/cm^2] is the mass thickness of the concrete (the mass per unit area). The total μ_m values for concretes are evaluated by the mixture rule, $\mu_m = \sum_i^n w_i (\mu/\rho)_i$, where w_i is the proportion by weight and $(\mu/\rho)_i$ is the mass attenuation coefficient of the i^{th} element using WinXcom [17]. The quantity w_i is given by $w_i = n_i A_i / \sum_j^n n_j A_j$ with condition $\sum_i^n w_i = 1$, where A_i is the atomic weight of the i^{th} element and n_i – the number of formula units. The linear attenuation coefficient, μ of a concrete is derived by multiplication of μ/ρ and density of the concrete.

Tenth-value layer

Tenth-value layer (TVL) (in cm) is the thickness of the concrete shielding material to reduce the intensity of gamma-ray to 1/10th of the incident upon it and calculated using formula TVL = 2.303/μ, where μ is linear attenuation coefficient.

Effective atomic numbers

The total atomic cross-sections (σ_t) for the concretes is obtained from the measured μ_m values using the following relation

$$\sigma_t = \frac{\mu_m M}{N_A} \tag{1}$$

where $M = \sum_i^n n_i A_i$ is the molecular weight of the concrete and N_A is the Avogadro's number. The effective atomic cross-section (σ_a) is calculated using the equation

$$\sigma_a = \frac{1}{N_A} \sum_i f_i A_i \left(\frac{\mu}{\rho}\right)_i \tag{2}$$

Table 1. Elemental composition of ordinary, heavy, and super heavy concretes

Concretes	Code	Density [gcm^{-3}]	Z: composition [%]
Ordinary	Ordy	2.30	1: 0.94, 6: 0.09, 8: 53.66, 11: 0.46, 12: 0.12, 13: 1.32, 14: 36.74, 16: 0.08, 19: 0.31, 20: 5.65, and 26: 0.63
Hematite-Serpentine	HeSt	2.50	1: 1.29, 8: 43.51, 12: 6.64, 13: 1.67, 14: 10.53, 16: 0.09, 20: 5.97, and 26: 30.31
Ilmenite-limonite	Ilmn	2.90	1: 0.66, 8: 36.45, 12: 0.15, 13: 0.80, 14: 3.06, 16: 0.08, 20: 5.83, 22: 16.03, and 26: 36.93
Basalt-Magnetite	BaMg	3.05	1: 0.83, 8: 42.30, 11: 1.06, 12: 2.20, 13: 4.22, 14: 13.20, 15: 0.20, 16: 0.09, 19: 0.29, 20: 8.88, 22: 0.60, 25: 0.12, and 26: 26.01
Ilmenite	Ilmt	3.50	1: 0.57, 8: 35.93, 11: 0.06, 12: 1.31, 13: 0.61, 14: 2.40, 16: 0.07, 17: 0.02, 19: 0.03, 20: 3.88, 22: 19.64 and, 26: 34.78
Steel-Scrap	StSc	4.00	1: 0.70, 6: 0.09, 8: 21.09, 11: 0.45, 12: 0.09, 13: 1.20, 14: 10.49, 16: 0.06, 19: 0.30, 20: 4.28, and 26: 61.25
Steel-Magnetite	StMg	5.11	1: 0.51, 8: 15.70, 12: 0.58, 13: 0.66, 14: 2.68, 15: 0.08, 16: 0.06, 20: 3.95, 25: 0.07, and 26: 75.73
Portland	Ptld	2.30	1: 1, 6: 0.1, 8: 53, 11 :1.6, 13 :3.6, 14 :33.67, 20: 5.64, and 26: 1.39
HCON (Cr)	HoCr	4.50	6: 0.06, 8: 36.7, 11: 0.88, 12: 5.93, 13: 5.35, 14: 4.43, 16: 0.61, 20: 3.64, 24: 34.23, and 26: 8.04
HCON (Fe)	HoFe	3.70	1: 0.4, 8: 34.5, 12: 1.9, 13: 1, 14: 6.9, 20: 4.8, and 26: 50.5

The total electronic cross-section (σ_e) for the individual element is calculated using the following equation

$$\sigma_e = \frac{1}{N_A} \sum \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i = \frac{\sigma_a}{Z_{eff}} \tag{3}$$

where $f_i = n_i / \sum_i n_i$ denotes the fractional abundance of the element i with respect to the number of atoms such that $\sum_i^n f_i = 1$, Z_i is the atomic number of i^{th} element. The σ_t and σ_e are related to the effective atomic number, Z_{eff} of a composite material through the following relation

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \tag{4}$$

The effective atomic numbers for the concretes were also calculated using practical formula [18] and Auto-Z_{eff} software [19].

Kerma relative to air

Kerma of the concretes relative to air is defined as

$$K_a = \frac{K_{concrete}}{K_{air}} = \frac{\left(\frac{\mu_{en}}{\rho}\right)_{concrete}}{\left(\frac{\mu_{en}}{\rho}\right)_{air}} \tag{5}$$

The mass energy-absorption coefficient, μ_{en}/ρ are calculated using $[(\mu/\rho)_{en} = \sum_i^n w_i (\mu_{en}/\rho)_i]$ where w_i and $(\mu_{en}\rho)_i$ are the weight fraction and the mass energy-absorption coefficient of the i^{th} constituent elements present in the concretes. The values of $(\mu_{en}\rho)_i$ have been taken from the NIST [20].

Macroscopic effective removal cross-section of fast neutron

The effective removal cross-section for compounds and homogenous mixtures is be calculated from the value of Σ_R [cm^{-1}] or Σ_R/ρ [cm^{2}g^{-1}] for various elements in the compounds or mixtures using formula $\Sigma_R = \Sigma_i \rho_i (\Sigma_R/\rho)_i$ where ρ_t is partial density. The values obtained for effective neutron removal cross-section of this equation are accurate within 10% of the experimental values investigated for aluminum, beryllium, graphite, hydrogen, iron, lead, oxygen, boron carbide, *etc*. [1]. The Σ_R/ρ values of elements are given in the literatures [21, 22].

Exposure buildup factors

The compilation for buildup factors by various codes is reported in ANSI/ANS-6.4.3-1991 [23]. The data in the report cover energy range 0.015-15 MeV up to penetration depth of 40 mean free path (mfp). Harima [24] developed a fitting formula, called GP which gives buildup factors of the good agreement with the ANS, 1991. Harima had extensive historical review and reported the gamma photon buildup factors [7].

The GP fitting parameters are calculated by logarithmic interpolation from the equivalent atomic number, Z_{eq} of the concretes. The buildup of photons in the medium is mainly due to multiple scattering events by Compton scattering. So that Z_{eq} is derived from the Compton scattering. First of all, the Z_{eq} for the concretes are estimated by the ratio of $(\mu/\rho)_{compton}/(\mu/\rho)_{total}$. The Compton partial mass attenuation coefficients were obtained using WinXCom program. The logarithmic interpolation of Z_{eq} is employed using formula as following [25, 26]

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1} \tag{6}$$

where Z_1 and Z_2 are the atomic numbers of the elements corresponding to the ratios R_1 and R_2 respectively. R is the ratio, $(\mu/\rho)_{compton}/(\mu/\rho)_{total}$ and the ratio $(\mu/\rho)_{compton}/(\mu/\rho)_{total}$ for Z_{eq} lies between two successive ratios of the elements. Secondly the GP fitting parameters were also calculated in a similar fashion of logarithmic interpolation method for the Z_{eq}.

The buildup factors are estimated by GP fitting parameters (b, c, a, X_k, and d) in the energy range of 0.015-15 MeV up to a 40 mfp by eqs. [24, 25] as

$$B(E,x) = \begin{cases} 1 + \dfrac{(b-1)(K^x - 1)}{K - 1}, & \text{for } K \neq 1 \\ 1 + (b-1)x, & \text{for } K = 1 \end{cases} \tag{7}$$

$$K(E,x) = cx^a + d\,\frac{\tanh\left(\frac{x}{X_K} - 2\right) - \tanh(-2)}{1 - \tanh(-2)}, \quad \text{for penetration depth } x \leq 40 \text{ mfp} \tag{8}$$

where x is the distance from source (in mfp) and b, the value of the buildup factor at 1 mfp and $K(E, x)$ – the dose multiplicative factor. The variation of $K(E, x)$ with penetration represents the change in the shape of the spectrum from that at 1 mfp which determined the value of b.

RESULTS AND DISCUSSION

The variation of mass attenuation coefficients, linear attenuation coefficients, tenth-value layer, effective atomic numbers and kerma relative to air with gamma-ray energy are shown in figs. 1-5, respectively. The variation of the exposure buildup factors

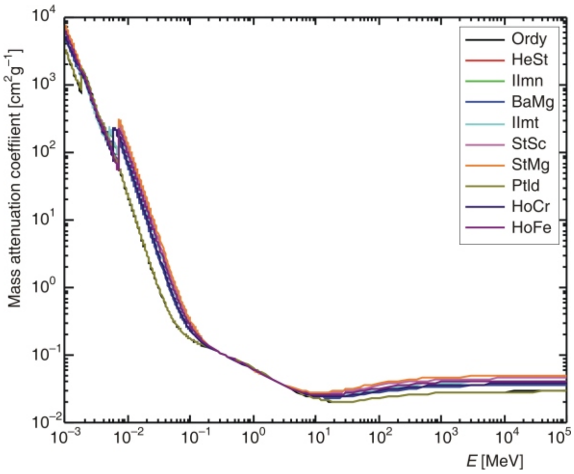

Figure 1. Mass attenuation coefficients of ordinary, heavy, and super heavy concretes *vs.* photon energy

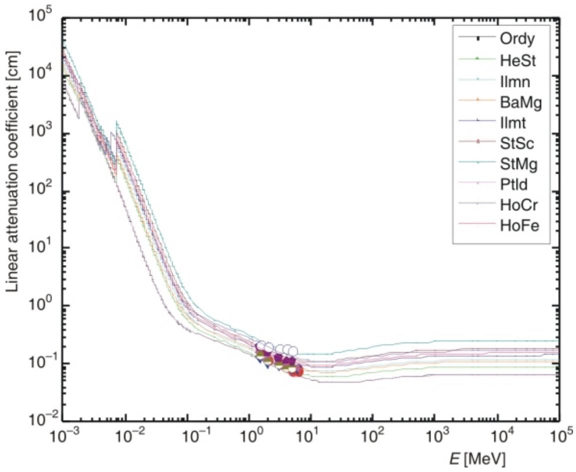

Figure 2. Linear attenuation coefficients of ordinary, heavy, and super heavy concretes *vs.* photon energy

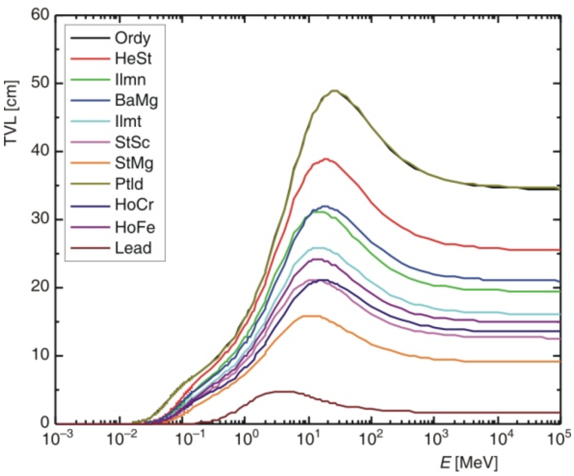

Figure 3. Tenth-value layer of ordinary, heavy, and super heavy concretes *vs.* photon energy

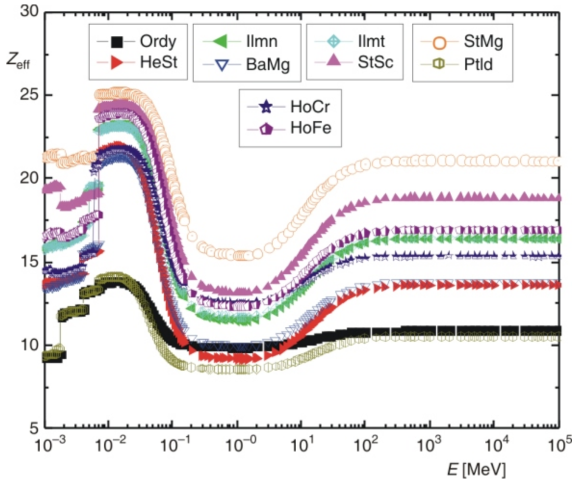

Figure 4. Effective atomic numbers of ordinary, heavy, and super heavy concretes *vs.* photon energy

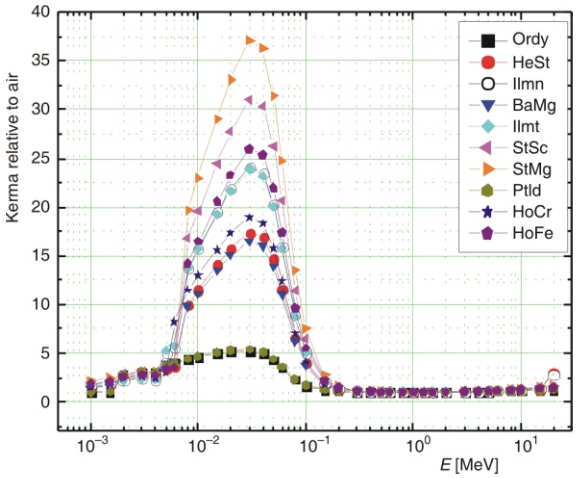

Figure 5. Kerma elative to air for of ordinary, heavy, and super heavy concretes *vs.* photon energy

with the energy is shown in fig. 6 and mixture dependency is shown in fig. 7. The macroscopic effective fast neutron removal cross-sections of the concretes are shown in fig. 8.

Mass attenuation coefficients and linear attenuation coefficients

The variation of mass attenuation coefficients, μ/ρ and linear attenuation coefficients, μ for the concretes with photon energy (1 keV-100 GeV) are shown in figs. 1 and 2, respectively. It can be found that the μ/ρ and μ values are highest in photoelectric absorption region and constant in pair production region beyond 100 MeV. However a slow variation of μ/ρ and μ values is observed in Compton scattering region. This variation of μ/ρ and μ can be explained by the depend-

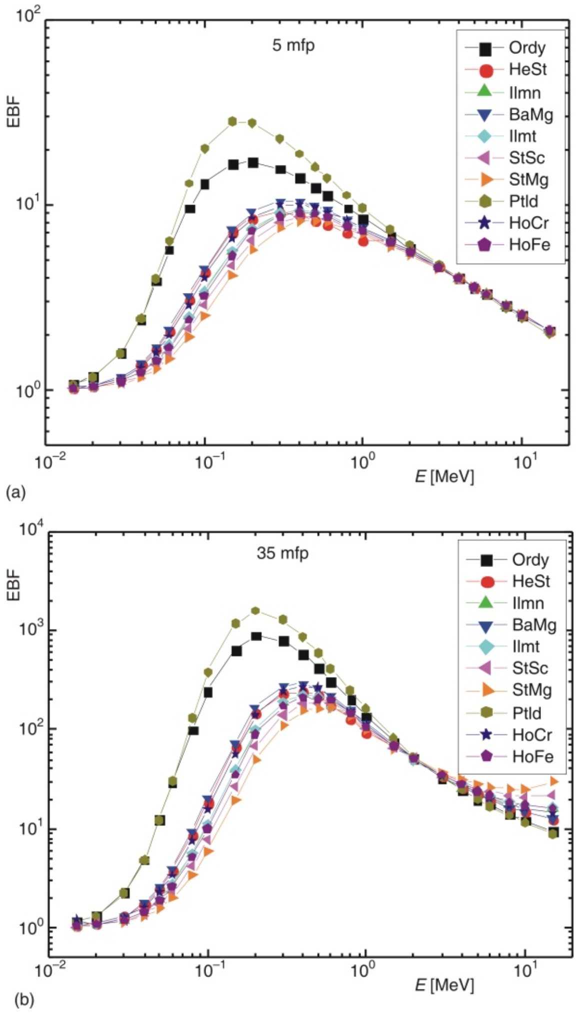

Figure 6(a-b). Exposure buildup factors of ordinary, heavy, and super heavy concretes *vs.* photon energy at 5 and 35 mfp penetration depths

ency of attenuation cross-section on atomic number of the constituent elements of the concretes and the energy. Experimental values of μ at 1.5, 2-5, and 6 MeV [15] have been compared with the theoretical data (as shown in fig. 2) and found in good agreement. The μ values of the super heavy concretes (Steel-Magnetite and HCON (Cr)) are found largest among all the selected concretes. Therefore super heavy concretes are superior shielding materials.

Tenth-value layer

The variation of tenth-value layer, TVL with photon energy (1 keV-100 GeV) of all the concretes is shown in fig. 3. The TVL values of lead are also being plotted in fig. 3. It is observed that the TVL values of the concretes are small in low-and high-energies with a peak near 10 MeV energy. The TVL values of lead are lowest at all the energies. We found that TVL values of super heavy concretes such as steel-magnetite (StMg) and HCON (Cr) (HoCr) are lowest when compared with the ordinary and heavy concretes.

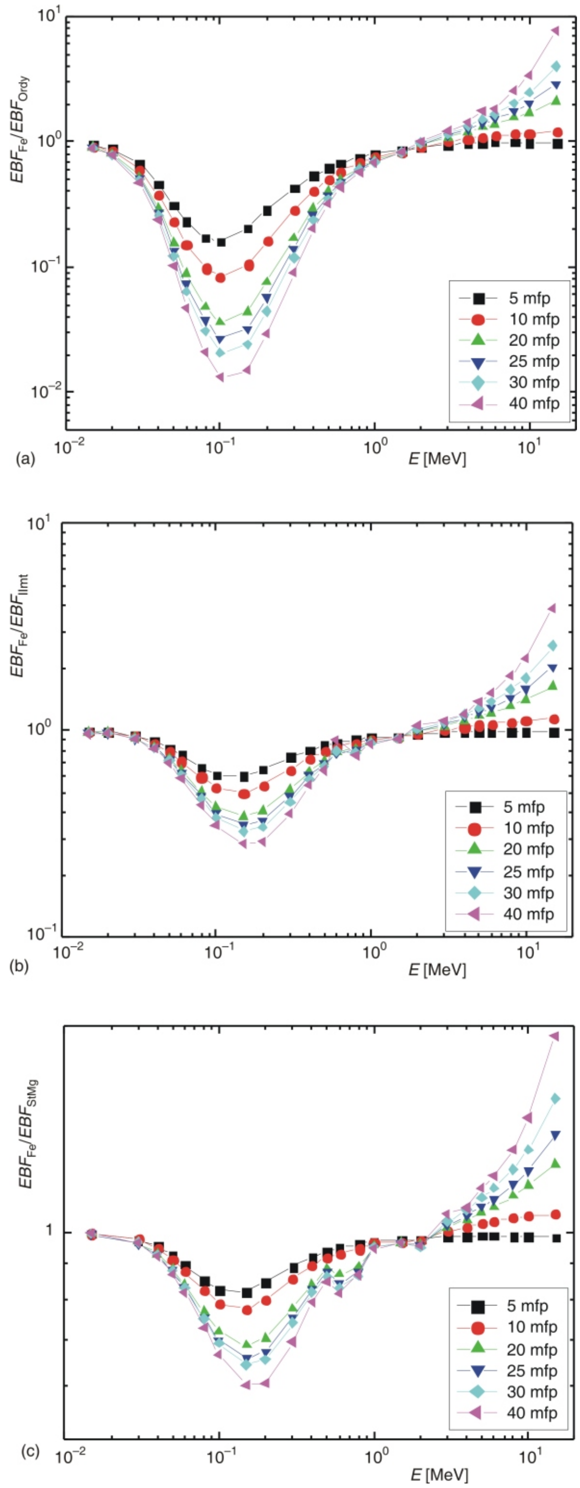

Figure 7(a-c). Ratio of exposure buildup factor of iron to ordinary, heavy, and super heavy concretes *vs.* photon energy at 5, 10, 20, 25, 30, and 40 mfp penetration depths

Effective atomic numbers

The effective atomic numbers, Z_{eff} signifies the shielding efficiency against gamma-ray and neutron. The variation of Z_{eff} for all the concretes with energy is shown in fig. 4. From fig. 4, it can be concluded that

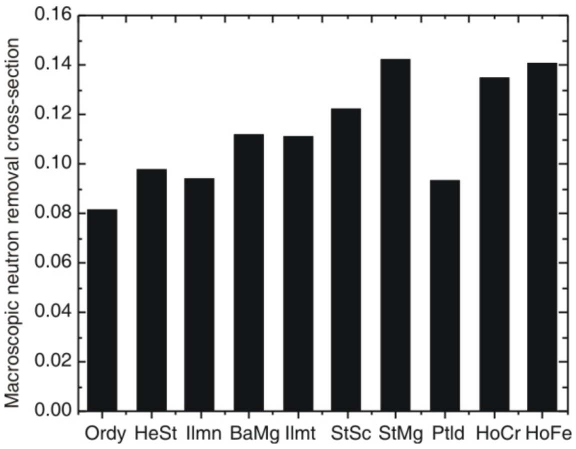

Figure 8. Macroscopic effective neutron removal cross-section of ordinary, heavy, and super heavy con-

the super heavy concretes (StMg, HoCr) are the superior gamma-ray shielding materials due to highest Z_{eff} values. In addition, we have compared effective atomic numbers using practical formula and Auto-Z_{eff} software as given in tab. 2. A slight variation in effective atomic numbers is to be noted.

Kerma relative to air

The variation kerma relative to air, K_a, with photon energy for all the concretes is shown in fig. 5. It is found that the K_a values of all the concretes reach unity at around 200 keV energy. However below 200 keV energy, there is a peak at 30 keV. Highest peak of K_a is found for StMg concrete indicates that the kinetic energy released per unit mass is the largest. Similarly, gamma-ray energy loss in Ordy concrete and Ptld are the lowest. Therefore photon removal capacities of super heavy concretes are the largest.

Exposure buildup factors

The variation of exposure buildup factors, EBF values of the selected concretes with photon energy at 5 and 35 mfp penetration depth are shown in figs. 6(a-b). It is to be noted that the EBF values of the concretes are minimum in low- and high-energies whereas it is the highest in the intermediate-energy. The EBF values in low-energy are small because the photons are completely absorbed by photoelectric absorption, gradually increases with energy due to multiple scattering by Compton scattering and finally again reduces in high-energy region due to pair-production. The investigation shows that StMg is suitable for shielding as it has low EBF values compared with the other concretes for small penetration depth (say 5 mfp) below 3 MeV. However opposite pattern is noted for large penetration depths (say 40 mfp) beyond 3 MeV energy.

The EBF values at 0.015 MeV energy are roughly constant (~unity) and increase with the penetration depths. It can be seen that the EBF values increase with Z_{eq} at 15 MeV as penetration depth increases. The reason may be that beyond 3 MeV, the

Table 2. Effective atomic numbers of ordinary, heavy, and super heavy concretes using practical formula and Auto-Z_{eff} software

Description	Type	E [MeV]					
		10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}	10^{3}
Ordy	$Z_{eff, auto}$	11.63	10.51	9.91	10.16	10.39	10.43
	Z_{Pleff}	11.87	5.33	4.54	5.17	6.25	6.34
HeSt	$Z_{eff, auto}$	14.86	12.42	9.19	10.27	11.23	11.31
	Z_{Pleff}	20.89	8.32	5.16	6.74	9.64	9.93
Ilmn	$Z_{eff, auto}$	17.19	15.60	11.51	12.81	13.77	13.84
	Z_{Pleff}	22.61	11.69	7.18	9.40	12.83	13.13
BaMg	$Z_{eff, auto}$	15.04	13.00	10.00	10.97	11.77	11.85
	Z_{Pleff}	20.33	8.80	5.72	7.26	9.91	10.16
Ilmt	$Z_{eff, auto}$	17.24	15.72	11.71	12.98	13.89	13.96
	Z_{Pleff}	22.53	11.80	7.33	9.53	12.87	13.15
StSc	$Z_{eff, auto}$	19.02	17.90	13.18	14.75	15.78	15.82
	Z_{Pleff}	24.09	15.40	10.29	12.93	16.60	16.91
StMg	$Z_{eff, auto}$	20.86	20.16	15.50	17.13	18.09	18.11
	Z_{Pleff}	25.01	18.30	12.93	15.83	19.38	19.65
Ptld	$Z_{eff, auto}$	11.26	9.36	8.59	9.04	9.50	9.55
	Z_{Pleff}	12.17	4.83	4.05	4.74	6.07	6.21
HoCr	$Z_{eff, auto}$	16.59	15.45	12.55	13.34	13.91	13.95
	Z_{Pleff}	22.86	17.19	13.32	15.20	17.38	17.53
HoFe	$Z_{eff, auto}$	17.81	16.55	12.35	13.60	14.47	14.53
	Z_{Pleff}	23.31	12.87	7.96	10.23	13.52	13.79

pair-production is dominant on the Compton scattering and produces the electron-positron pairs. These particles may escape from the concrete of smaller thickness whereas multiple scatter appears in large thickness due to secondary photons. Analysis signifies that the EBF values for Ordy concrete for a particular thickness are higher for same thickness of StMg concrete. Therefore less thickness of the StMg is sufficient to provide same degree of protection compared with the Ordy concrete.

Figures 7(a-c) shows the variation of ratio of EBF values of iron to different types of concretes with photon energy at 5, 10, 20, 25, 30, and 40 mfp penetration depths. It is observed that the ratio is high at low as well as high-energies whereas minimal in the intermediate energies. The ratio increases with the increase of iron contents for photoelectric absorption and Compton scattering regions whereas decreases for pair-production region. It is to be noted that the ratio reaches to unity as the iron contents in concretes increases (refer Fe composition for Ordy, Ilmt and StMg in tab. 1). This clearly shows the mixture dependency of EBF with photon energy.

The selection of the concrete for biological shielding and containment is based on the shielding efficiency of the concrete. The density of concrete may decrease with the increase in temperature due to interaction heat hence the biological shielding requires continuous cooling to maintain effective shielding. Since during reactor accident the energy of gamma photons is smaller as compared with the operation, the shielding against it may be achieved by using ordinary concretes alone. Nowadays the ordinary concretes with steel patching or lining are being used for the reactor building containment in new reactors design. These steel lining in the containment serve both the purposes of improvement in radiation shielding and containment of radioactivity during accident.

Macroscopic effective removal cross-section of fast neutron

The macroscopic effective fast neutron removal cross-section for the concretes is shown in fig. 8. From fig. 8, it is found that the Σ_R value is maximum, 0.1421 cm^{-1} for StMg followed by 0.1409 cm^{-1} for HoFe concrete. Our theoretical analysis shows that Σ_R for neutron emitted from the reactors can effectively be shielded by StMg concrete. Also HoFe may be other choice for fast neutron shielding.

CONCLUSION

In the present work we studied radiation shielding parameters of ordinary, heavy, and super heavy concretes. Attenuation coefficients of super heavy concretes are the largest and TVL values are lesser than the heavy and ordinary concretes. The effective atomic numbers of super heavy concretes are the largest followed by heavy concretes. The effective fast neutron removal cross section for steel-magnetite is the highest followed by HCON (Fe). Exposure buildup factors of super heavy concretes are found the lowest whereas the largest for ordinary and heavy concretes for energy up to 3 MeV. The super heavy concretes are superior shielding for reactor operation as well accidental situations.

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AUTHOR CONTRIBUTIONS

The idea for investigation of the ordinary, heavy, and super heavy concretes was put forward by V. P. Singh for various reactor applications, the calculations were done by V. P. Singh, and analysis and discussion was carried out by V. P. Singh and N. M. Badiger. The manuscript and figures were prepared by V. P. Singh.

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ИСТРАЖИВАЊЕ ПАРАМЕТАРА ЗАШТИТЕ ОД ЗРАЧЕЊА ОБИЧНОГ, ТЕШКОГ И СУПЕР ТЕШКОГ БЕТОНА

Реакторски штит потребан је ради заштите људи и животне средине током нормалног рада реактора као и у случајевима акцидената. У овом раду испитани су заштитни параметри обичног, тешког и супер тешког бетона: масени и линеарни коефицијенти слабљења, фактори слабљења зрачења у слоју, ефективни атомски бројеви, керма у односу на ваздух и фактори нагомилавања услед излагања гама зрачењу. Такође, израчунат је и макроскопски ефективни пресек за уклањање брзих неутрона. Обичан бетон економски је погодан за мешавину високоенергетског гама зрачења и неутрона јер има велику тежинску фракцију материјала са ниским атомским бројем Z, у поређењу са супер тешким бетонима. Супер тешки бетони су у предности за заштиту током нормалног рада реактора као и у акциденталним случајевима. Ова студија корисна је за оптимизацију пројектовања заштите реактора.

Кључне речи: фактор нагомилавања, тешки бетон, реакторска зграда, биолошки штит