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Measurements of neutron shielding properties of heavy concretes using a Cf-252 source

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This investigation reports the experimental results of neutron transport and shielding properties of heavy concretes made from locally available ilmenite and magnetite sand. The experiment has been carried out with a ^{252}Cf source and a BF_3 detector as a long counter. The thickness dependent removal cross section has been investigated and found to vary from 0.0936 cm^{-1} at 5 cm to 0.0346 cm^{-1} at 100 cm and 0.0990 cm^{-1} at 5 cm to 0.0366 cm^{-1} at 100 cm for ilmenite and magnetite concretes respectively. The results illustrate the effectiveness of ilmenite and magnetite heavy concretes so far as their sheilding properties are concerned. These materials may be used as a neutron shield in reactors, accelerators and neutron sources.

1. Introduction

Studies on the spatial energy distributions of nuclear radiations passing through various thicknesses of different materials, are of interest in nuclear technology not only from theoretical point of view, but also from the practical point of view of designing nuclear shielding [1]. A compilation of experimental and theoretical studies deals with radiation penetration through different shields with different radiation sources [2]. Most of these shields are made from different types of concretes such as ordinary, ilmenite, magnetite, barytes, etc., which have proved themselves as the best suitable materials for the attenuation of nuclear radiations. The ilmenite and magnetite concretes are a heavy concrete. The heavy concretes are known to be good radiation shielding materials. A programme has been undertaken to study the radiation attenuating properties of ilmenite and magnetite heavy concrete shields developed indigenously with the objective of avoiding costly imports and also to develop local know how [3–5]. Such study should be of particular interest to Bangladesh because of the availability of ilmenite and magnetite sand as by-products in the beach sand minerals processing plant at Cox's bazar. The present paper deals with studies on the neutron transport and shielding properties of ilmenite and magnetite heavy concretes using a ^{252}Cf source. Moreover, the results of this study will provide some useful information about the shielding material data base for practical shielding calculation.

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2. Experimental procedures

The ilmenite and magnetite heavy concretes were produced locally with cement, sand and stone chips in the ratio 1 : 2 : 3 by volume. The physical and chemical compositions of these two shielding materials are shown in table 1. The physical and structural properties of ilmenite and magnetite heavy concretes were performed using solid cylindrical (15 cm dia. ×30 cm length) slabs after 28 days of curing. These properties were measured experimentally in the Concrete Laboratory, Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka. The physical and structural properties of ilmenite and magnetite heavy concretes are given in table 2.

Table 1
Compositions of heavy concretes

Course aggregate [stone chips 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)
Mix ratio (cement: sand (ilmenite or magnetite): stone chips) = 1:2:3 (vol%)	
Net water/cement ratio = 0.5	
Slump = 1.27 cm	

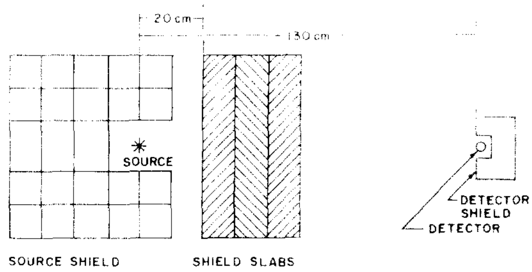

Fig. 1. Block diagram of the experimental set up.

The experimental arrangement for the measurement of neutron transport and shielding properties of the concretes consists of a ^{252}Cf source, a detection system and slabs of the material being investigated. The experimental set-up is shown in fig. 1. The distance between source and detector was 130 cm. The experiment was performed using a ^{252}Cf source of nearly 2 μg strength. The slabs having thickness of 5 cm were used for studying attenuating properties of the concretes. In the detection system, a long counter comprising of a BF_3 proportional counter with suitable cylindical paraffin moderator was used to detect the neutron components [6,7]. At first the incident intensity of neutron flux was measured without any concrete slab between the source and the detector. Then, the experimental data were collected by sequentially adding 5 cm thick slabs starting from the source in the direction of the detector up to 100 cm. In our experiment the lateral dimension of the shield was taken to be enough to include the maximum amount of scattered radiation in the transmitted beam. A negligible contribution may arise from the room scattered neutrons but the count rate for this measurement was sufficiently

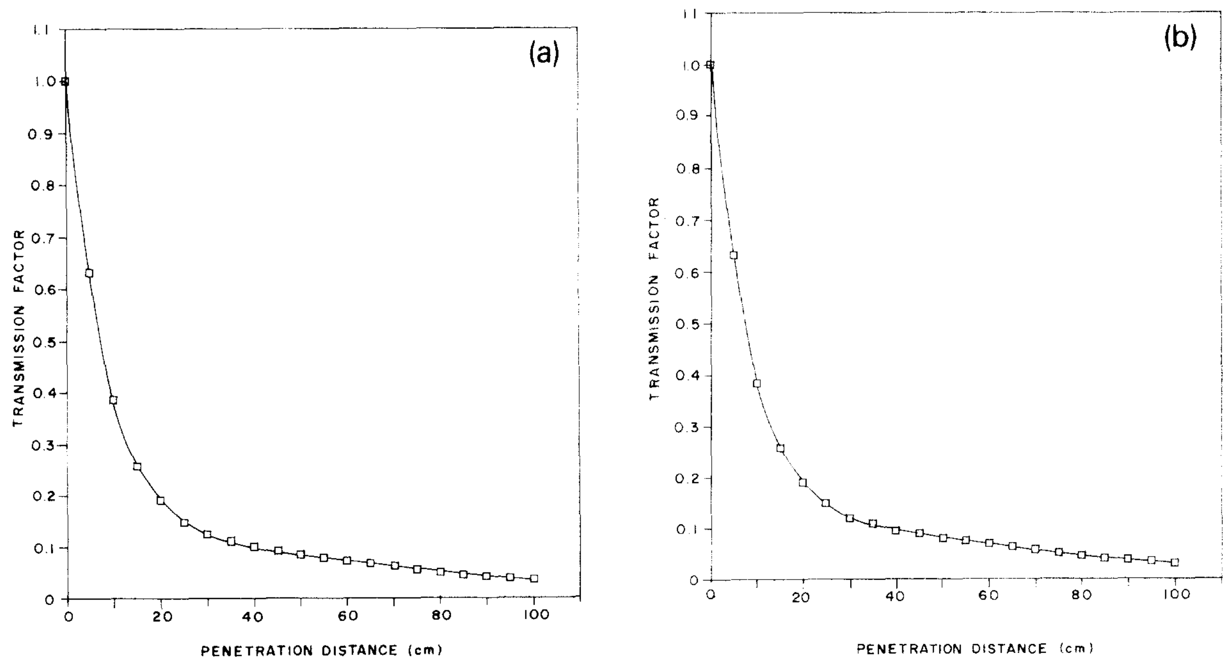

Fig. 2. (a) Neutron transmission through ilmenite concrete; (b) neutron transmission through magnetite concrete.

Table 2
Structural and physical properties of heavy concretes

Type of concrete	Density (g/cm^3)	Compressive strength (kg/cm^2)	Modulus of elasticity (kg/cm^2)	Tensile strength (kg/cm^2)
Ilmenite	2.88	217.70	22.47×10^4	26.10
Magnetite	2.82	211.54	19.39×10^4	25.48

high to neglect these effects. The detailed experimental procedures are described elsewhere [4].

3. Results and discussion

The measured neutron flux attenuations as a function of penetration distance for both heavy concretes are shown in figs. 2a and 2b. It is found from fig. 2a that 50% of the initial neutron flux is cut-off by 7.40 cm of ilmenite concrete. To cut-off 50% of the initial flux the shield thickness requirement of magnetite concrete is 7.00 cm (fig. 2b). At 100 cm of shield thickness the ilmenite concrete transmits 3.3% initial neutron flux, whereas, magnetite concrete transmits 3.5%.

The penetration of fast neutrons through concretes of various compositions has been studied both experimentally and theoretically [2,5,8–11]. The attenuation of neutron is generally characterized by removal cross section (Σ_r), relaxation length (λ) and half value thickness (HVT). These parameters were measured based on the experimental data from the attenuation curves and the results are given in table 3. A comparison of the measurement of neutron attenuation characteristics with those obtained in other investigations can not be made directly because different compositions and constituents of the concretes have been used. Furthermore, data on the attenuation of neutrons from ^{252}Cf for concretes could not be found in the literature. However, for comparison, the available data on Σ_r for neutron in different materials are shown in table 4. The values of Σ_r obtained in this study are generally comparable with published data (table 4), being slightly better for a few case. This illustrates the effectiveness of locally developed ilmenite and magnetite heavy concretes so far as their neutron shielding properties are concerned.

Table 3
Neutron attenuation parameters for heavy concretes

Type of concrete	Σ_r values (cm^{-1})	λ (cm)	Half value thickness (cm)
Ilmenite	0.0936	10.68	7.40
Magnetite	0.0990	10.10	7.00

Table 4
Comparison of removal cross sections of different shielding materials

Materials	Density (g/cm^3)	Σ_r (cm^{-1})	Reference
Ordinary concrete	2.30	0.0819	[2]
Limonite	2.70	0.1111	[2]
Ilmenite	3.52	0.0746	[2]
Magnetite	3.50	0.0952	[2]
Magnetite	3.29	0.1124	[2]
I-M concrete	2.78	0.0929	[5]
Poly-boron	0.98	0.1610	[12]
Ilmenite	2.88	0.0911	This study
Magnetite	2.82	0.0949	This study
Paraffin	1.00	0.1193	[11]
Graphite	1.70	0.0775	[11]
Polethene–boron–lead	3.8	0.1124	[11]
Polethene–lithium	1.20	0.1312	[11]

The removal cross section (Σ_r) provides a quick method for neutron deep penetration calculation, but Σ_r is highly dependent on thickness of the shielding materials [5,10,12,13]. Thus, the thickness-dependent, Σ_r, which is the reciprocal of relaxation length (λ), was derived from the measured instantaneous relaxation length, $\lambda(t)$. The $\lambda(t)$ is given by [8]

$$\lambda(t) = -F(t)/[\mathrm{d}F(t)/\mathrm{d}t], \qquad (1)$$

where $F(t)$ is the measured attenuation function $I(t)/I_0$ [I_0 and $I(t)$ are the integrated counts in cases without shield and with shield in thickness of t respectively].

An empirical formula has been derived to fit the experimental values of Σ_r at different thickness for ilmenite and magnetite heavy concretes. The experi-

Table 5
Coefficients of the empirical formula for Σ_r

Coefficients	Ilmenite concrete	Magnetite concrete
A (cm^{-1})	0.106577	0.114746
B (cm^{-2})	-0.147380×10^{-2}	-0.171985×10^{-2}
C (cm^{-3})	0.760355×10^{-5}	0.947209×10^{-5}

Table 6
Removal cross sections as a function of penetration distance for ilmenite concrete

Penetration distance (cm)	Experimental $\Sigma_r(t)$ (cm^{-1})	Calculated $\Sigma_r(t)$ (cm^{-1})	Difference
5	0.0936	0.0994	−0.0058
10	0.0928	0.0926	0.0002
15	0.0915	0.0862	0.0053
20	0.0844	0.0801	0.0043
25	0.0773	0.0745	0.0028
30	0.0714	0.0692	0.0022
35	0.0640	0.0643	−0.0003
40	0.0593	0.0598	−0.0005
45	0.0540	0.0556	−0.0016
50	0.0508	0.0519	−0.0011
55	0.0470	0.0485	−0.0015
60	0.0449	0.0455	−0.0006
65	0.0425	0.0429	−0.0004
70	0.0408	0.0407	0.0001
75	0.0402	0.0388	0.0014
80	0.0388	0.0373	0.0015
85	0.0379	0.0362	0.0017
90	0.0369	0.0355	0.0014
95	0.0361	0.0352	0.0009
100	0.0346	0.0352	−0.0006

Table 7
Removal cross sections as a function of penetration distance for magnetite concrete

Penetration distance (cm)	Experimental $\Sigma_r(t)$ (cm^{-1})	Calculated $\Sigma_r(t)$ (cm^{-1})	Difference
5	0.0990	0.1063	−0.0073
10	0.0985	0.0984	0.0001
15	0.0955	0.0912	0.0043
20	0.0890	0.0841	0.0039
25	0.0820	0.0777	0.0053
30	0.0752	0.0717	0.0035
35	0.0675	0.0662	0.0013
40	0.0575	0.0611	−0.0036
45	0.0539	0.0565	−0.0026
50	0.0496	0.0524	−0.0028
55	0.0476	0.0488	−0.0012
60	0.0450	0.0457	−0.0007
65	0.0433	0.0430	0.0003
70	0.0419	0.0408	0.0011
75	0.0408	0.0390	0.0018
80	0.0399	0.0378	0.0021
85	0.0386	0.0370	0.0016
90	0.0380	0.0366	0.0014
95	0.0372	0.0368	0.0004
100	0.0366	0.0375	−0.0009

mental values of Σ_r were fit by a least-squares method to an analytical expression given by

$$\Sigma_r(t) = A + Bt + Ct^2, \qquad (2)$$

where the coefficients A, B and C have been determined and are shown in table 5. In the fitting procedure, the quality of the fit was performed by adopting the Chi-square goodness fit method [5,12]. The thickness dependent $\Sigma_r(t)$ obtained from the measured data for ilmenite and magnetite concretes along with calculated values are shown in tables 6 and 7 respectively. In our investigation, the experimental values of Σ_r varied from 0.0936 cm^{-1} at 5 cm to 0.0345 cm^{-1} at 100 cm and 0.0990 cm^{-1} at 5 cm to 0.0366 cm^{-1} at 100 cm for ilmenite and magnetite heavy concretes respectively. There are reports that Σ_r varies with thickness of the shielding materials [5,10,12,13]. From our study, it is also clear that Σ_r varies with deep penetration in the ilmenite and magnetite heavy concretes. This variations led us to formulate the simple analytical expression for thickness dependent $\Sigma_r(t)$ given in eq. (2). The calculated values given in tables 6 and 7 reproduced the experimental data within 6.2% and 7.4% errors for ilmenite and magnetite concretes respectively.

4. Conclusion

The locally available ilmenite and magnetite sand have great economic potential for use in the development of high density concrete for biological shielding. The removal cross section (Σ_r) measured in this study reflects the good quality of these locally developed shielding materials (table 4). The parameters of Σ_r and HVT can be effectively used for practical shielding calculations. The Σ_r is found to be highly dependent on the thickness of the shielding materials which led to derive equation (2). Reasonably good agreement has been achieved between the Σ_r values derived from equation (2) and the corresponding experimental values. This study will provide the basic data to a shielding material data base for neutron transport calculation. These materials can be effectively utilized as the biological shields surrounding the nuclear installations to reduce the emitted radiations to the permissible level.

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