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INVESTIGATION OF FAST NEUTRON ATTENUATION COEFFICIENTS FOR SOME IRAQI BUILDING MATERIALS

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ABSTRACT This research aims to improve the radiation shielding properties of polymer-based materials by mixing PVC with locally available building materials. Specifically, two key parameters of fast neutron attenuation (removal cross-section and half-value layer) were studied for composite materials comprising PVC reinforced with common building materials (cement, sand, gypsum and marble) in different proportions (10%, 30% and 50% by weight). To assess their effectiveness as protection against fast neutrons, the macroscopic neutron cross-section was calculated for each composite. Results show that neutron cross-section values are significantly affected by the reinforcement ratios, and that the composite material PVC + 50% gypsum is an effective shield against fast neutrons.

Keywords: half-value thickness; building materials**;** reinforced polymer composite

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1. INTRODUCTION

Nuclear technology is employed advantageously in many areas, including industry, medicine, agriculture and scientific research. However, associated ionizing radiation poses dangers for human health and the environment [1, 2] which necessitate identification of suitable methods of protection. Ionizing radiation (e.g. gamma rays, X-rays and neutrons) is of concern because of its ability to penetrate materials and cause cell damage. Different radiation types interact with protective materials in diverse ways. Hence the most appropriate protective material depends on the radiation type, the radioactive source and the dose rate activity. Other criteria that influence the selection of shielding material include cost, weight and ease of manufacture [3, 4]. In this context, research into radiation absorption by locally-available materials has become important, particularly for protection against neutrons and gamma rays.

The concept of removal cross-section is useful to describe the attenuation of high-energy free neutrons (‘fast neutrons’) in protective materials [5]. Removal cross-sections serve as important reference values for shielding design in different applications [6]. Fast neutrons travelling through protective material may lose energy, due to elastic and inelastic dispersion, becoming thermal neutrons, with a much higher probability of absorption into the shielding medium. The components of a high-energy neutron beam that do not suffer any major collisions are commonly referred to as 'uncollided' neutrons. The property describing the effectiveness of fast neutron shields is the 'effective removal cross-section', representing the number of neutrons removed from the original incident neutron beam [7, 8]. In this report, five materials based on the common polymer polyvinyl chloride (PVC) have been studied for their neutron shielding parameters: pure PVC, PVC + cement, PVC + sand, PVC + gypsum and PVC + marble. Table 1 shows the chemical composition of the compounds involved. The value of each element's removal cross-section has been used to compute the overall removal cross-sections for the different shielding materials.

2. THEORETICAL BASIS

Neutrons are uncharged particles which interact with matter through different mechanisms. The probability of a nuclear interaction is defined by the gross effective cross-section, which is the sum of all microscopic cross-sections along the path of a neutron beam through the material, i.e.:

$$\sigma_t = \sigma_s + \sigma_a \qquad (1)$$

where σ_t is the gross microscopic cross-section, σ_s the cross-section of microscopic scattering, and σ_a the cross-section of microscopic absorption. The gross macroscopic cross-section, $\sum_t$, is the physical quantity which connects these two variables, and is given by [9, 10, 11]:

$$\sum_t = \frac{\rho N_a}{A}\,\sigma_t \qquad (2)$$

where ρ is the atomic density (g cm^{-3}), Na is the Avogadro number, A is the mass of an atom; $\sum_t$ have units of cm^{-1}.

2.1 Neutron attenuation

For a neutron beam travelling through a certain material, the neutron intensity is reduced by collisions with nuclei in the material, achieved through dispersion (elastic and inelastic) or absorption [12, 13]. The magnitude of neutron attenuation by a material is given by an exponential equation based on the absorber thickness and the neutron removal cross-section, $\Sigma(cm^{-1})$ [14]:

$$I_x = I_o\, e^{-\Sigma x} \qquad (3)$$

where I_o is the incident beam intensity and I_x is the intensity after penetrating a material of thickness x and Σ neutron removal cross-section.
The fast neutron deletion cross-section, the probability that a neutron will lose all of its energy, is also represented by $\Sigma(cm^{-1})$ [15]. Neutron removal coefficients can vary greatly from element to element. By applying the mixture rule to the value of $\Sigma(cm^{-1})$ or Σ_R/ρ (cm^2/g) for each element in the composite materials, it is possible to compute the effective removal cross-section. The weight fraction term is replaced by partial density, and the mass attenuation coefficient is replaced by the neutron removal cross-section [16, 17]:

$$\Sigma_R = \sum_i \rho_i \left(\frac{\Sigma_R}{\rho}\right)_i \quad (4)$$

where ρ_i is partial density (mixture density) and $\frac{\Sigma_R}{\rho}$ is the cross-section of mass removal for an *ith* component, calculated using the following equation [18]:

$$\frac{\Sigma_R}{\rho}\left(\frac{cm^2}{g}\right) = 0.206\, A^{-1/3}\, Z^{-0.294} \quad (5)$$

where A denotes atomic weight and Z is the element's atomic number. Multiplying the neutron mass removal coefficient by the density of the absorber yields the neutron removal coefficient.

2.2 Half-Value Layer ($X_{1/2}$)

The thickness of material required to reduce the intensity of an incident neutron beam to half its initial value is indicated by the following equation [19]:

$$X_{1/2} = \frac{0.693}{\Sigma} \quad (6)$$

2.3 Composite Material Density

The density of the compound material is calculated from the relationship [20]:

$$\rho = \boldsymbol{V_f * \rho_f + (1 - V_f) * \rho_m} \quad (7)$$

where ρ is the density of the composite, V_f is the volumetric fraction and ρ_f, ρ_m are the density of the reinforcement and of the base material, respectively.

3. RESULTS AND DISCUSSION

Density values were calculated for five PVC samples with different proportions of cement, sand, gypsum and marble (Table 1). These samples were used to study the influence of different proportions of each reinforcing material on shielding effectiveness against fast neutrons.

Table 1. Density values for different composites.

Chemical Formula	Density	V_f (10%)	ρ of composite	V_f (30%)	ρ of composite	V_f (50%)	ρ of composite
C2H3CL	1.406	0.100	1.406	0.300	1.406	0.500	1.406
CaO6SiAl2	1.505	0.094	1.415	0.285	1.434	0.482	1.453
SiO2	1.600	0.088	1.423	0.273	1.459	0.467	1.496
CaCO3	2.560	0.057	1.472	0.190	1.625	0.354	1.815
CaSO6H4	2.780	0.053	1.479	0.178	1.650	0.335	1.867

Table 2 summarises the elemental composition of each constituent, arranged in increasing order of atomic weight, atomic number and mass removal cross-section. Elemental compositions of the building materials were calculated using the following website: https://www.convertunits.com/molarmass/.

Table 2. Atomic weight, atomic number and mass removal cross-section for each sample component.

Element	A	Z	$\sum/\rho$ (cm^2/g)
H	1.007	1	0.205
C	12.010	6	0.053
O	15.999	8	0.044
Al	26.9818	13	0.032
Si	28.0855	14	0.031
S	32.065	16	0.028
Cl	35.453	17	0.027
Ca	40.078	20	0.024

Tables 3–7 show the elemental composition, weight fraction, removal cross-section, partial density (part.density) and macroscopic fast neutron removal for each of the five sample materials (pure PVC, PVC + cement, PVC + sand, PVC + gypsum and PVC+ marble). It is clear from these data that the removal cross-section values are determined by the type and density of the constituent elements. Furthermore, the contribution of light elements to the total deletion cross-section is critical. This could be because hydrogen has a relatively high mass cross-section deletion relative to heavier elements. Therefore, as its mass fraction rises, so does its contribution to the total removal cross-section; this is supported by previous research [21]. From Tables 3–7 and Figure 1, it is also clear that the sample PVC+ 50% gypsum has the maximum removal cross-section value (0.080787 cm^{-1}). The minimum value (0.059562 cm^{-1}) is for the sample PVC+ 50% cement (Fig. 1).

Table 3. Effective removal cross-sections for pure PVC.

PVC (PURE)	Density (g/cm^3)	Weight Fraction	part.density	∑/ ρ (cm^2/g)	∑ (cm^-1)	Total ∑
H	1.406	0.048	0.068	0.205	0.0139	0.064
C		0.384	0.540	0.053	0.0287	
CL		0.567	0.797	0.027	0.0217	

Table 4. Effective removal cross-sections for PVC + cement.

PVC+ (10%Cement)	Density (g/cm^3)	Weight Fraction	part.density	∑/ ρ (cm^2/g)	∑ (cm^-1)	Total ∑
H	1.415	0.043	0.061	0.205	0.012	0.063
C		0.3459	0.4895	0.053	0.026	
O		0.0440	0.062	0.044	0.002	
Al		0.0247	0.035	0.032	0.001	
Si		0.0128	0.018	0.031	0.001	
Cl		0.5105	0.722	0.027	0.019	
Ca		0.0183	0.025	0.024	0.001	
PVC+ (30%Cement)	**Density (g/cm^3)**	**Weight Fraction**	**part.density**	**∑/ ρ (cm^2/g)**	**∑ (cm^-1)**	**Total ∑**
H	1.434	0.033	0.048	0.205	0.009	0.067
C		0.269	0.385	0.053	0.020	
O		0.132	0.189	0.044	0.008	
Al		0.074	0.1064	0.032	0.003	
Si		0.038	0.055	0.031	0.001	
Cl		0.397	0.569	0.027	0.015	
Ca		0.055	0.079	0.024	0.001	
PVC+ (50%Cement)	**Density (g/cm^3)**	**Weight Fraction**	**part.density**	**∑/ ρ (cm^2/g)**	**∑ (cm^-1)**	**Total ∑**
H	1.453	0.024	0.035	0.205	0.007	0.059
C		0.192	0.279	0.053	0.014	
O		0.220	0.319	0.044	0.014	
Al		0.123	0.179	0.032	0.005	
Si		0.064	0.093	0.031	0.002	
Cl		0.283	0.412	0.027	0.011	
Ca		0.091	0.133	0.024	0.003	

Table 5. Effective removal cross-sections for PVC + sand.

PVC+ (10%sand)	Density (g/cm^3)	Weight Fraction	part.density	∑/ ρ (cm^2/g)	∑ (cm^-1)	Total ∑
H	1.423	0.043	0.061	0.205	0.012	0.064
C		0.345	0.4923	0.053	0.026	
O		0.053	0.075	0.044	0.003	
Si		0.046	0.066	0.031	0.002	
Cl		0.510	0.726	0.027	0.019	
PVC+ (30%Sand)	**Density (g/cm^3)**	**Weight Fraction**	**part.density**	**∑/ ρ (cm^2/g)**	**∑ (cm^-1)**	**Total ∑**
H	1.459	0.033	0.049	0.205	0.010	0.063
C		0.269	0.392	0.053	0.020	
O		0.159	0.233	0.044	0.010	
Si		0.140	0.204	0.031	0.006	
Cl		0.397	0.579	0.027	0.015	
PVC+ (50%Sand)	**Density (g/cm^3)**	**Weight Fraction**	**part.density**	**∑/ ρ (cm^2/g)**	**∑ (cm^-1)**	**Total ∑**
H	1.496	0.024	0.036	0.205	0.007	0.062
C		0.192	0.287	0.053	0.015	
O		0.266	0.398	0.044	0.017	
Si		0.233	0.349	0.031	0.010	
Cl		0.283	0.424	0.027	0.011	

Table 6. Effective removal cross-sections for PVC + gypsum.

PVC+ (10 Gypsum)	Density (g/cm^3)	Weight Fraction	part.density	∑/ ρ (cm^2/g)	∑ (cm^-1)	Total ∑
H	1.4791	0.045	0.067	0.205	0.0139	0.067
C		0.345	0.511	0.0531	0.027	
O		0.055	0.082	0.044	0.003	
S		0.018	0.027	0.028	0.001	
Cl		0.510	0.755	0.027	0.020	
Ca		0.023	0.034	0.024	0.001	
PVC+ (30 Gypsum)	**Density (g/cm^3)**	**Weight Fraction**	**part.density**	**∑/ ρ (cm^2/g)**	**∑ (cm^-1)**	**Total ∑**
H	1.650	0.040	0.067	0.205	0.013	0.073
C		0.269	0.444	0.053	0.023	
O		0.167	0.276	0.044	0.012	
S		0.055	0.092	0.028	0.002	
Cl		0.397	0.655	0.027	0.017	
Ca		0.069	0.115	0.024	0.002	
PVC+ (50 Gypsum)	**Density (g/cm^3)**	**Weight Fraction**	**part.density**	**∑/ ρ (cm^2/g)**	**∑ (cm^-1)**	**Total ∑**
H	1.867	0.035	0.067	0.205	0.013	0.080
C		0.192	0.358	0.053	0.019	
O		0.278	0.520	0.044	0.023	
S		0.093	0.173	0.028	0.004	
Cl		0.283	0.529	0.027	0.014	
Ca		0.116	0.217	0.024	0.005	

Table 7. Effective removal cross-sections for PVC + marble.

PVC+ (10 Marble)	Density (g/cm^3)	Weight Fraction	part.density	∑/ ρ (cm^2/g)	∑ (cm^-1)	Total ∑
H	1.472	0.043	0.064	0.205	0.013	0.066
C		0.357	0.527	0.053	0.027	
O		0.047	0.070	0.044	0.003	
Cl		0.510	0.751	0.027	0.020	
Ca		0.040	0.058	0.024	0.001	
PVC+ (30 Marble)	**Density (g/cm^3)**	**Weight Fraction**	**part.density**	**∑/ ρ (cm^2/g)**	**∑ (cm^-1)**	**Total ∑**
H	1.625	0.033	0.055	0.205	0.011	0.070
C		0.305	0.495	0.053	0.026	
O		0.143	0.233	0.044	0.010	
Cl		0.397	0.645	0.027	0.017	
Ca		0.120	0.195	0.024	0.004	
PVC+ (50 Marble)	**Density (g/cm^3)**	**Weight Fraction**	**part.density**	**∑/ ρ (cm^2/g)**	**∑ (cm^-1)**	**Total ∑**
H	1.815	0.024	0.043	0.205	0.009	0.075
C		0.252	0.457	0.053	0.024	
O		0.239	0.435	0.044	0.019	
Cl		0.283	0.514	0.027	0.014	
Ca		0.200	0.363	0.024	0.009	

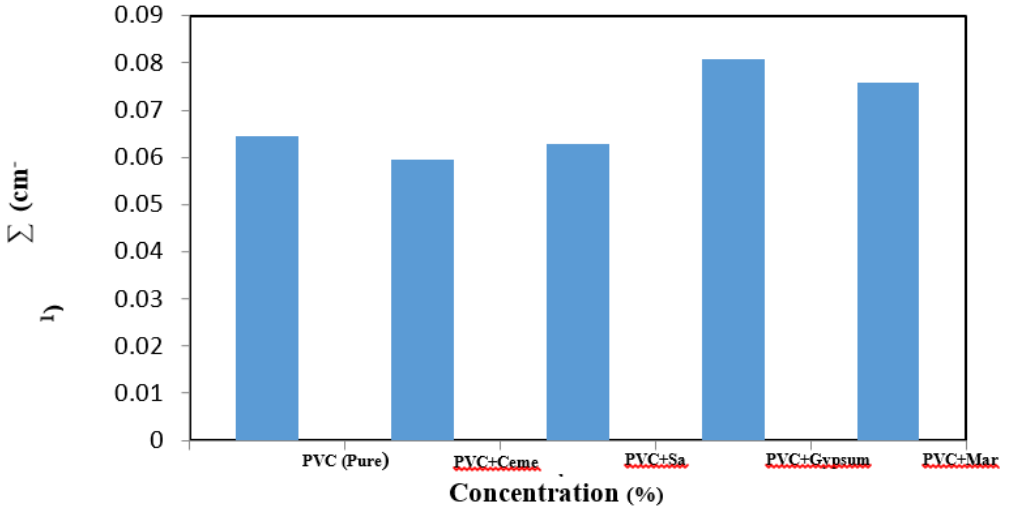

Figure 1. Removal croos section section as a Function of reinforced materials at concentration 50%.

Figure 2 illustrates the relationship between the half-value layer and the concentration of the reinforcing material. The half-value layer decreases as the proportion of gypsum and marble materials increases. The lowest half-value layer is for the sample PVC + gypsum at 50% concentration (Fig. 2). For cement and sand, the half-value layer increases with concentration, indicating that these materials are ineffective for shielding against fast neutrons

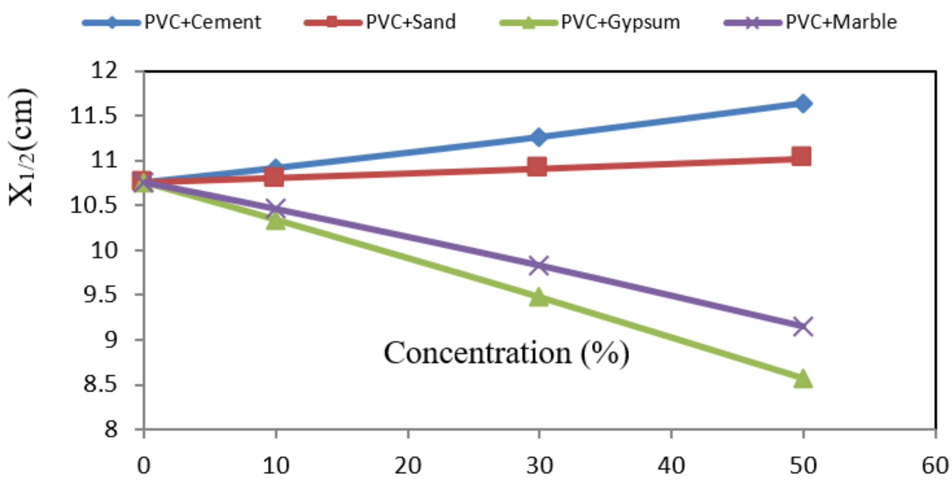

Figure 2. Half-value layer as a function of concentration.

4. CONCLUSIONS

This work derived neutron removal cross-sections for a range of composite shielding materials. Results suggest that the chemical composition of the materials controls their removal cross-sections for fast neutrons. The composite PVC + 50% gypsum is determined to be an effective shield against fast neutrons due to its large removal cross-section.

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