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Technical Note

Shielding and strength tests of silica fume concrete

D. Rezaei-Ochbelagh [a,*], S. Azimkhani [a], H. Gasemzadeh Mosavinejad [b]

[a] *Department of Physics, Faculty of Sciences, University of Mohaghegh Ardabili, P.O. Box 179, Ardebil, Islamic Republic of Iran*
[b] *Department of Civil Engineering, Engineering Faculty, The University of Guilan, Rasht, Islamic Republic of Iran*

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ABSTRACT

In this research, concrete containing different percentages of lead powder and silica fume was investigated as a gamma shield. Gamma photons emitted from gamma sources of ^{137}Cs and ^{60}Co were passed through concrete specimens and detected by two inches NaI(Tl) detector to investigate the attenuation coefficients of the specimens. Next, the compressive strengths of the specimens were experimentally studied. A comparison of concrete with and without silica fume revealed that although the addition of silica fume results in a slight reduction of the attenuation coefficient, which is negligible, it increases the compressive strength of concrete significantly. The results suggest the usefulness of 15% silica fume in concrete containing lead as a gamma shield.

1. Introduction

Concrete as a material commonly used for gamma shielding has been the focus of several studies (Havranek, 1971; Singh et al., 2004; Salinas et al., 2006; Kharita et al., 2010). In recent years, there have been many attempts to increase the capability of concrete for the shielding of gamma rays, with additives being investigated as supplementary materials in concrete (Neville, 1996; El-Hosiny and El-Faramawy, 2000; Basyigit, 2006; Akkurt et al., 2010a,b; El-Khayatt, 2010; Damla et al., 2010). All these studies aimed at increasing the attenuation coefficient of concrete against gamma-rays. As attenuation improves with increase in density, the addition of lead is considered a suitable shield against gamma-rays. As a result, lead is an important additive in concrete for radiation protection (El-Hosiny and El-Faramawy, 2000; Tsoulfanidis, 1995). When additives are utilized as partial replacements for Portland cement, apart from reduced cement use, an improvement in concrete properties such as strength, permeability, corrosion resistance and durability results, and concrete costs are minimized. One such important additive is silica fume. The effects of silica fume on the mechanical properties of concrete have been extensively investigated (Pena et al., 2008; Kadri and Duval, 2009; Song et al., 2010). However, few studies have reported the effect of silica fume on the protection and resistance properties of concrete for gamma shielding (El-Faramawy and El-Hosiny, 1998; Turkmen et al., 2008). To investigate the simultaneous effects of cement replacement materials and substances used to increase the protection properties of concrete on gamma shielding, concrete containing these materials needs to be examined. Therefore, in this research, different percentages of silica fume were added to concrete contained lead, and the gamma shielding property and compressive strength of concrete were investigated. At first, different concrete specimens were prepared with lead and silica fume additives in accordance with ASTM C192 (American Society for Testing and Materials) standards. Next, a flux of gamma-rays was analyzed by NaI(Tl) detector and MCA (Multi-Channel Analyzer). The linear attenuation coefficients of the concrete specimens were calculated by using two gamma sources (^{137}Cs and ^{60}Co). The XRD (X-ray diffraction) patterns from the several concrete specimens were also obtained. Finally, the compressive strengths of the concrete specimens were experimentally examined.

2. Experimental procedures

The materials used to produce concrete were: Portland (type I) cement with a density of 400 Kg/m^3, water (the water-to-cement ratio is 0.45 by weight), concrete plasticizer to increase concrete workability (2.5% of cement weight), aggregate (with a density of 2400 Kg/cm^3 and grain sizes graded according to ASTM C136 standards), lead powder and silica fume.

The concrete specimens were produced with additions of lead (equivalent to 45% of cement weight) and silica fume (replacing 0%, 5%, 10%, and 15% of cement). The other specimens were produced with additions of 10% silica fume and 0%, 45%, and 90% lead.

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[*] Corresponding author. Tel.: +98 451 5514702; fax: +98 451 5514701.
E-mail address: ddrezaey@yahoo.com (D. Rezaei-Ochbelagh).

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After 24 h, concrete specimens were removed from the molds and placed into a water tank for 23 days at regular temperature. The specimens were then taken out of the water tank and dried at an ambient temperature for 48 h. The densities of the specimens were experimentally determined and are listed in Table 1.

On the 27th day, the concrete specimens were prepared to be radiated by the gamma sources. Each specimen was radiated for 6 h by ^{137}Cs and ^{60}Co sources with activities of 3.7 MBq and 0.296 MBq, respectively. Fig. 1 displays a photograph of the experimental set up. A NaI(Tl) detector 2×2 in dimension was used to detect gamma-rays passing through the specimens. An MCA was used to analyze the experimental data. All the experimental equipment set up was made by the German LYBOLD Company. To reduce background radiation effects a Pb shield was used as shown in Fig. 1. The concrete specimen was placed between the gamma source and the detector at a distance of 2 cm from the source and 5 cm from the detector.

Table 1
Measured densities of concrete specimens with different percentages of lead and silica fume.

Lead%	Silica Fume%	Density (gr/cm^3)
0	0	2.2150
0	10	2.1990
45	0	2.3920
45	5	2.3860
45	10	2.3792
45	15	2.3719
90	0	2.5160
90	10	2.4930

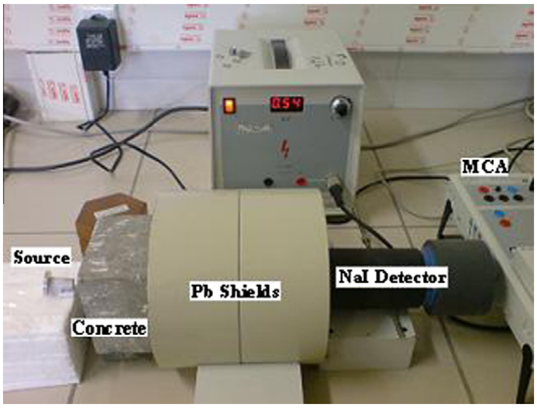

Fig. 1. Photograph of experimental setup.

3. Results and discussion

Fig. 2 shows the spectrum of gamma energy obtained using NaI(Tl) detector for concrete specimens with 45% lead and different percentages of silica fume. To investigate the effects of silica fume on concrete containing different percentages of lead, 10% silica fume was added to concrete specimens with 0%, 45%, and 90% lead and the spectrum of gamma energy for these specimens are shown in Fig. 2. To calculate linear attenuation coefficients, the formula $N = N_0 B e^{-\mu x}$ was used, where N and N_0 indicate the total experimental counts with and without concrete specimens, respectively, x is the thickness of the specimen (10 cm), μ is the linear attenuation coefficient and B, the buildup factor, which is equal to 1 for good geometric conditions. In this study, the buildup factor B was extracted from relevant tables (Shimizu et al., 2004). Fig. 3 shows changes in linear attenuation coefficients with increasing silica fume percentages in concrete specimens with 45% lead as well as with 0% and 10% silica fume in concrete specimens with increasing percentages of lead. Mass attenuation coefficients were also calculated and plotted as a function of silica fume percentage (with 45% lead) and lead (with 0% and 10% silica fume) in concrete specimens (Fig. 4).

As observed in Fig. 3a, while concrete (with 45% lead) without silica fume has the maximum linear attenuation coefficient, increases in silica fume percentage are associated with increases in linear attenuation coefficients using sources ^{137}Cs and ^{60}Co, with greater increases noted for ^{60}Co. With source ^{60}Co, the linear attenuation coefficient of concrete containing 15% silica fume is almost equal to that of concrete without silica fume, and the mass attenuation coefficient of concrete containing 15% silica fume exceeds that of concrete without silica fume. Fig. 3b reveals that the linear attenuation coefficients of concrete specimens with 0%, 45%, and 90% lead and without silica fume decrease with the addition of 10% silica fume.

Following the radiation of the concrete specimens, their compressive strengths were experimentally measured after a period of 28 days. The compressive strengths of concrete with 45% lead and different percentages of silica fume as well as the compressive strengths of concrete with different percentages of lead and with 0% and 10% silica fume are presented in Fig. 5. In order to investigate the effect of silica fume, the XRD patterns of concrete with 45% lead and 15% silica fume and those of concrete with 90% lead and 10% silica fume were compared with the XRD patterns of concrete without lead or silica fume (Fig. 6). The latter was obtained in a previous study (Rezaei-Ochbelagh et al., 2011).

As can be seen in Fig. 5, the compressive strength of concrete containing lead powder increased with increasing percentages of silica fume. Furthermore, as revealed in Fig. 6, peaks appearing on the XRD patterns of concrete specimens with 45% lead and

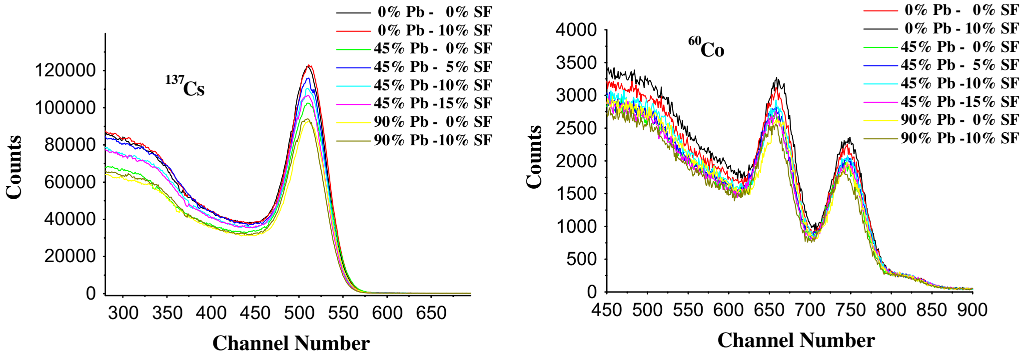

Fig. 2. Energy spectrums of the γ-ray obtained from ^{137}Cs and ^{60}Co source for concrete with and without different percentages of silica fume and lead.

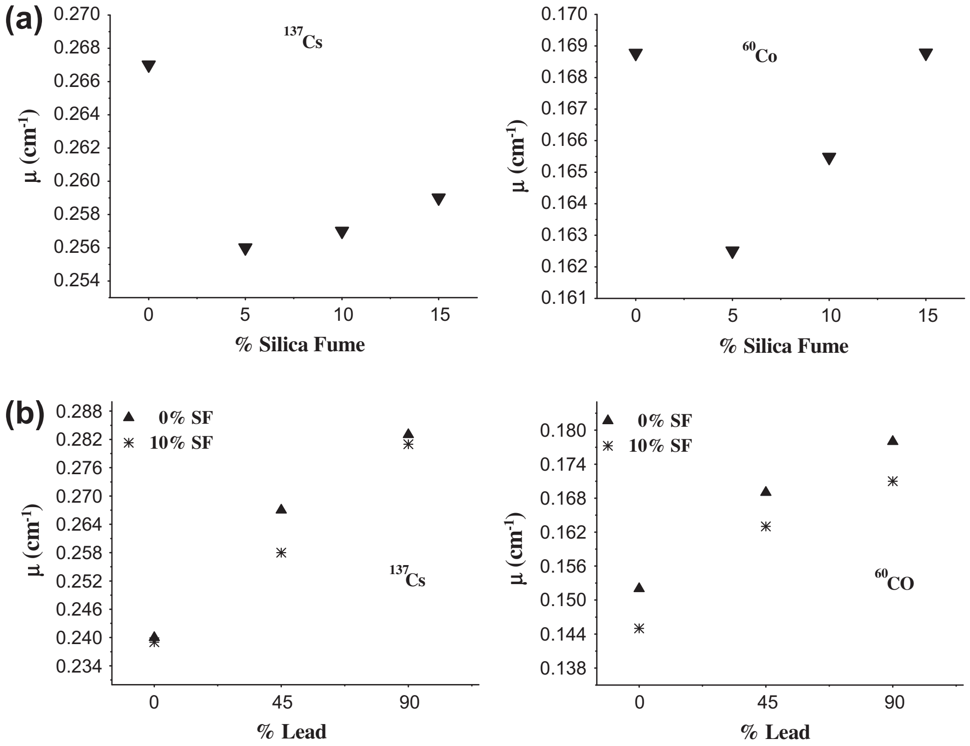

Fig. 3. The linear attenuation coefficients as a function of (a) silica fume rate in concrete with 45% lead and (b) lead rate in concrete with and without silica fume for gamma energies emitted from ^{137}Cs and ^{60}Co sources.

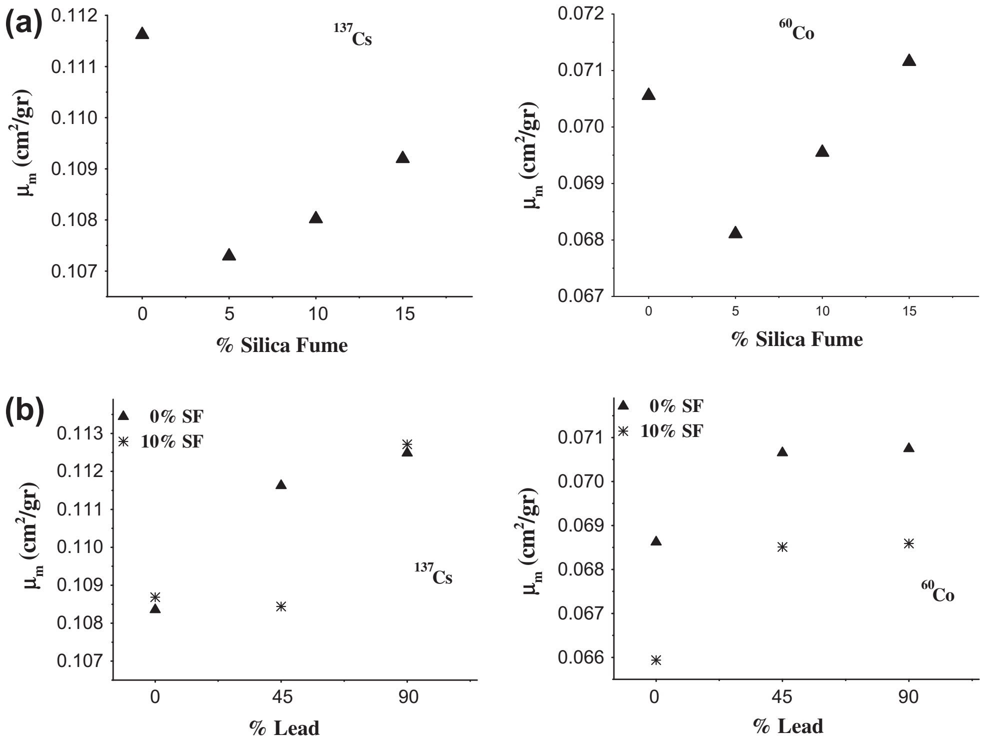

Fig. 4. The mass attenuation coefficients as a function of (a) silica fume rate in concrete with 45% lead and (b) lead rate in concrete with and without silica fume for gamma energies emitted from ^{137}Cs and ^{60}Co sources.

15% silica fume, 90% lead and 0% silica fume, and 0% lead and 10% silica fume (patterns b, c and d) are indicative of the presence of lead and silica fume. As silica fume is lighter than cement, adding silica fume to concrete results in a decrease in the density of concrete and an increase in the flux passing through concrete.

Macroscopic scale studies show that particles of silica fume are very smooth, small and spherical in shape. With an average diameter of about 0.1 μm, silica fume particles are approximately 100 times finer than cement particles, filling the space between particles of cement and other constituents of concrete and causing

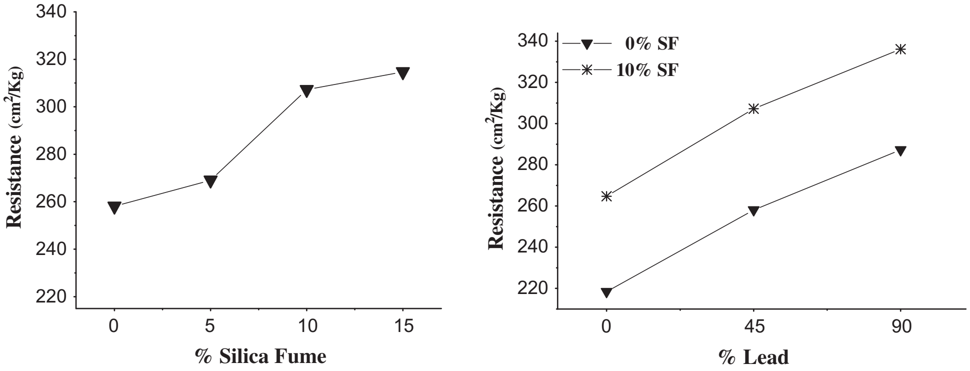

Fig. 5. Variations of compressive strength (kg/cm^2) of concrete with 45% lead versus silica fume percentage and with silica fume (0% and 10%) versus lead percentage.

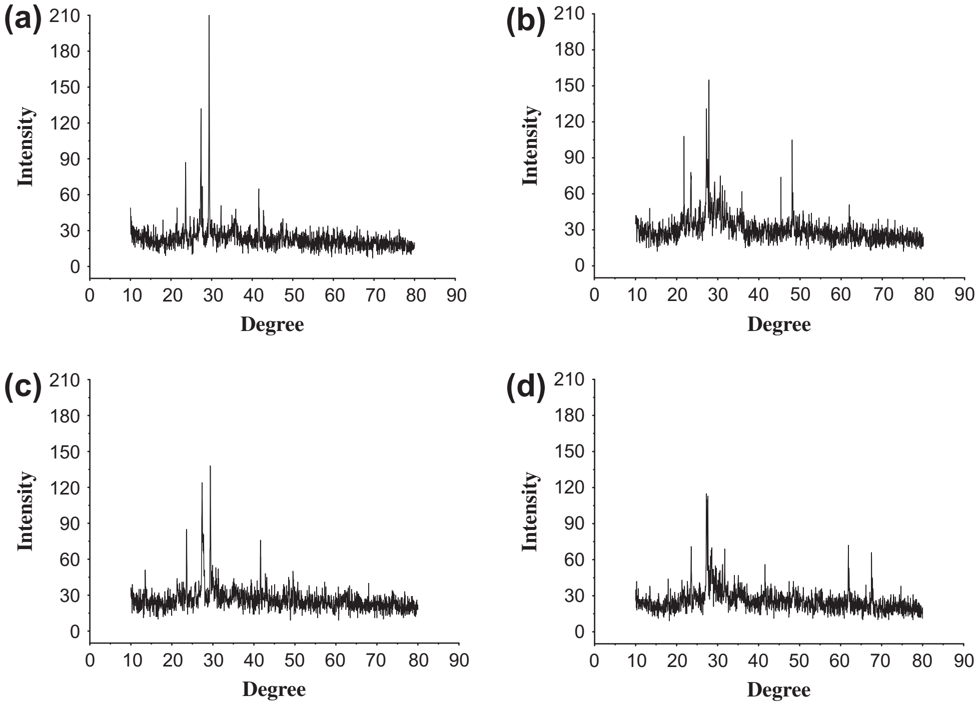

Fig. 6. (a) X-ray patterns of concrete without lead and silica fume, (b) concrete with 45% lead and 15% silica fume, (c) concrete with 10% silica fume and without lead and (d) concrete with 90% lead and without silica fume.

impaction to decrease the porosity of concrete. In fact, adding silica fume modified the structure of concrete and the filling property of silica fume brought about a homogeneous and uniform distribution of the hydration products obtained, thereby increasing the impermeability of concrete. Furthermore, the reduction of cavities and improvement in the microstructure of concrete increases the compressive strength of concrete, decreasing the rate of penetration of gamma rays. On a microscopic scale, silica fume is not chemically active at first, but in the cement hydration stage, the pozzolanic reaction of silica fume with hydration products begins, producing compounds such as calcium hydroxide $Ca(OH)_2$. Next, silica materials of silica fume react with these compounds to form new compounds such as CSH (calcium silicate hydrate) which is the main cause of the extra strength of concrete containing silica fume. In low silica fume percentages, this bond is weak but with increasing percentages of silica fume, that is, with increasing proportions of SiO_2, the CSH bond becomes stronger. Therefore, the strength of the concrete is increased and its permeability is reduced (Bentz et al., 2000). It should also be noted that the presence of lead in concrete results in a $Pb(OH)_2$ bond during the hydration process which affects the CSH and other compounds formed in the hydration stage (El-Faramawy and El-Hosiny, 1998). Findings of the present study imply that to ensure better reactions of silica fume in the hydration process, concrete with higher percentages of lead would be better than concrete with no lead. Therefore, in concrete containing 45% lead, low percentages (5% and 10%) of silica fume show insufficient pozzolanic reaction, so the decrease in the density of concrete results in an increase in the flux emitted from the concrete. However, on increasing the percentage of silica fume to 15%, a perfect pozzolanic reaction with hydration products occurs, modifying the structure of concrete, decreasing its permeability and increasing the attenuation coefficient. Yet, the amount of flux emitted is greater than that in concrete without silica fume.

4. Conclusions

The results of an experiment exposing concrete specimens with a thickness 10 cm to gamma rays emitted from ^{137}Cs and ^{60}Co sources shows that the addition of silica fume to concrete containing 45% lead partially increased the flux of gamma rays emitting from it. With increases in silica fume percentages, the resistive strength of concrete specimens increases. Therefore, in order to reduce costs and increase the resistance of concrete used as a shield against gamma rays, silica fume can be used as a partial cement replacement. For this purpose, a proportion of 15% is suggested. The addition of 15% silica fume in concrete (with 45% lead) increases the strength of the concrete by about 22%. In addition, the linear attenuation coefficient rate decreases to 2.9% with a ^{137}Cs source, but shows no significant change with a ^{60}Co source.

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