



Recycling of steel slag aggregates for the development of high density concrete: Alternative & environment-friendly radiation shielding composite

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ABSTRACT

The present study aims in developing high density radiation shielding composite using induction furnace (IF) steel slag as an aggregate (coarse/fine) in concrete. IF steel slag is incorporated in concrete specimens (Mix a - 0% of slag, Mix b - 40% of slag as coarse aggregate, Mix c - 40% of slag as coarse aggregate and 100% as fine aggregate) of size 150 × 150 × 50 mm were fabricated. The presence of various iron (Fe) phases such as hematite, iscorite and almandine in IF steel slag composite were confirmed by XRD analysis. Presently, these types of materials are obtained from natural resources are in use for gamma radiation shielding. Density and compressive strength were studied, further concrete blocks were subjected to irradiation using gamma radiation sources such as ¹³⁷Cs (0.662 MeV) and ⁶⁰Co (1.17 and 1.33 MeV). Concrete specimen morphologies and structural changes of before and after irradiation have been studied using SEM and XRD analysis. The results show that replacement of 40% as coarse aggregate and 100% as fine aggregate of slag in concrete increases the density and compressive strength of conventional concrete from 2.38 g cm⁻³ to 2.85 g cm⁻³ and 27.20 N mm⁻² to 29.38 N mm⁻² respectively. Gamma Attenuation Factor (GAF), Linear Attenuation Co-efficient (LAC) and Half Value Layer (HVL) are better than the conventional concrete. Mix c can be a cost-effective alternate composite for radiation shielding studies and can reduce the exploitation of natural resources.

1. Introduction

Steel slag is an industrial by-product generated during steel production. Slag is used as an alternate material, few types of slag ends in land filling material and poses environmental pollution [1]. Production of steel is increasing every year due to urbanization and industrialization and the by-product slag is also generated on a large scale. During the steel production, 10–15% of slag is generated per tonne of steel production which involves the following furnaces: (i) Basic Oxygen Furnace (BOF), (ii) Electric Arc Furnace (EAF) and (iii) Induction Furnace (IF) [2]. Application of steel slag includes, dye adsorption [3], CO₂ sequestration [4], agriculture [5], antibacterial activity [6], mitigation of methane emission [7], acid-resisting bricks [8], Fenton-like catalyst [9], asphalt mixes [10], binding material [11], mortar [12], concrete [13, 14] and in heavy metal removal [15,16]. BOF and EAF slag is maximum

used in cement production due to high CaO content, where as IF steel slag is not used due to less CaO content.

Globally, after water concrete is the most extensively used material. In modern concrete technology, industrial by-products such as steel slag [17], fly ash [18], copper slag [19], natural zeolite [20], metakaolin [21], limestone powder [22] and other materials are used as coarse/fine aggregate and cementitious material to improve the properties of the concrete. Steel slag has been utilized as a coarse aggregate in asphalt concrete and the study exhibited better mechanical properties, resistance against moisture damage and electrical conductivity [23]. The concrete prepared using EAF slag and ground granulated blast furnace slag (GGBFS) shows better mechanical properties in which concrete contains 30% of GBF as a cementing material. The addition of gypsum to this concrete enhances the compressive strength at 28 days [24]. Concrete containing steel slag shows better strength and superior fracture

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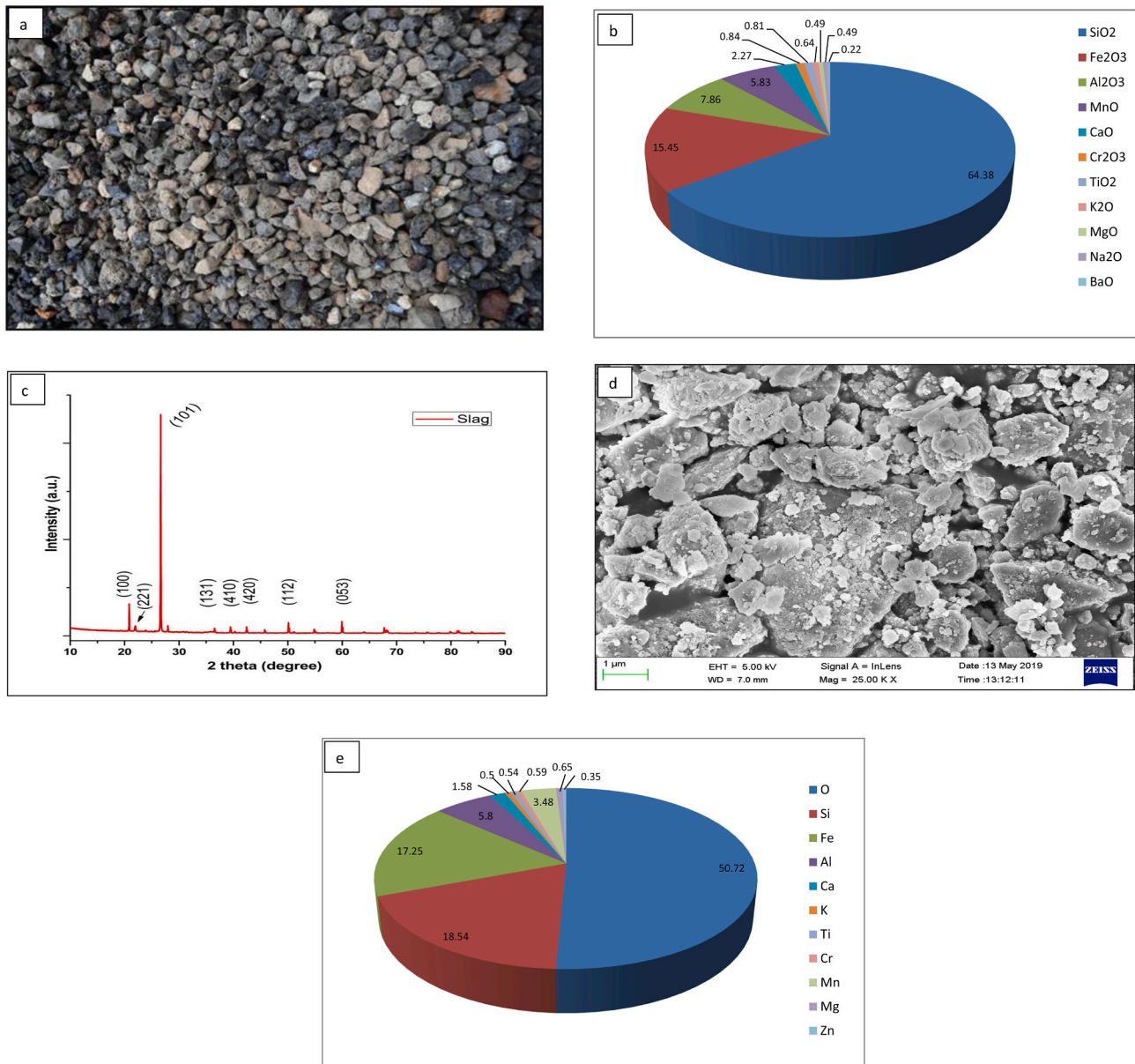


Fig. 1. Analysis of Induction furnace steel slag: a) Induction furnace steel slag (10–12.5 mm); b) XRF analysis of induction furnace steel slag; c) XRD analysis of induction furnace steel slag; d) Surface morphology of induction furnace steel slag; e) Elements present in induction furnace steel slag.

properties compared to conventional concrete [25]. EAF steel slag has been used in concrete as coarse aggregate for the development of radiation shielding concrete and the experimental results reveal that, the density (2.80 g cm^{-3}) and compressive strength (65 Mpa) has been higher than that of conventional concrete prepared [26]. Concrete specimens incorporated with 100% EAF slag as aggregates of diameter up to 31.5 mm has been investigated and the results are compatible with the conventional concrete [27].

In radiation shielding application, concrete has been widely used in nuclear industries of reactors, spent fuel storage areas and other radiation associated structures [28]. Further, it can be casted into various structures as a potential material to attenuate gamma rays due to its density and intrinsic water content [29]. Structural integrity of concrete using various aggregates as replacements, radiation shielding structures can be designed and implemented in nuclear power plants by considering the durability of concrete [30,31]. Studies are in progress for materials such as heavy density aggregates [32], lead slag [33], lead-zinc slag [34], EAF steel slag [35] and ground granulated

blast-furnace slag (GGBFS) [36] that are compatible in concrete for radiation shielding applications. Incorporation of barite, serpentine and steel-magnetite in concrete is tested for gamma shielding studies and among them, the steel-magnetite mix has higher shielding capacity than the other mixes that were tested [37]. Boron ore szaibelyite incorporated concrete shows better gamma radiation shielding when compared with the ludwigite ore of boron [38]. Iron waste fillings (30%) as an additive increases the bulk density of concrete thus exhibiting better attenuation property than conventional concrete [39]. Incorporation of hematite in concrete by 50% of total aggregate has higher gamma ray attenuation capability than the conventional concrete [40]. Currently, in nuclear industry the concretes used for construction contains natural resources such as hematite, magnetite, barite, serpentine and limonite [41]. To reduce utilization of natural resources and the cost involved, there is a need for alternate materials towards radiation shielding.

IF steel slag composite is a mixture of metal oxides consisting of major elements such as silicon, iron, aluminum, manganese and calcium. In India around 450,000 t of steel slag of is generated through IF

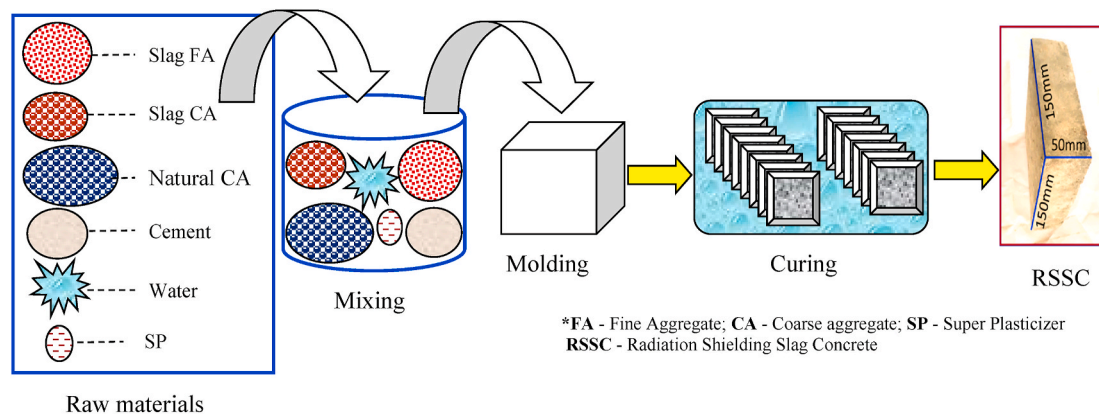


Fig. 2. Schematic representation of radiation shielding slag concrete (RSSC) preparation.

[42]. Though, IF steel slag is not utilized in cement production, iron oxide and other iron compounds present in IF steel slag (hematite, iscorite and almandine phases) makes the material suitable for gamma radiation shielding. In the present investigation, IF steel slag composite has been used as a complete replacement of fine and partial replacement of coarse aggregate in concrete. The casted concrete specimens were tested for its density and compressive strength. The prepared concrete specimens were subjected to irradiation using gamma radiation sources such as ^{137}Cs (0.662 MeV) and ^{60}Co (1.17 and 1.33 MeV). Gamma attenuation factor (GAF), linear attenuation co-efficient (LAC) and Half Value Layer (HVL) has been studied in detail.

2. Experimental section

2.1. Materials

Concrete specimens were prepared using IF steel slag, natural fine and coarse aggregate, cement (Zuari, Ordinary Portland Cement - 53G) and water as raw materials. IF steel slag (Fig. 1a) were obtained from

Jeppiaar Furnace and Steels, Pvt., Ltd., Kanchipuram, Tamil Nadu, India and size reduction were carried out using the ball milling process. Slag materials of size <4.75 mm (fine aggregate) and size between 10 and 12.5 mm (coarse aggregate) were used in the study. Stainless steel concrete moulds of size $150 \times 150 \times 50$ mm were used to cast concrete specimens.

2.2. Steel slag characterization

IF steel slag composite is rich in iron oxide (Fe_2O_3) and iron compounds. The presence of Fe as Fe_2O_3 (15.45%) were confirmed using X-ray Fluorescence analysis (XRF) (Fig. 1b) along with SiO_2 (64.38%), Al_2O_3 (7.86%), MnO (5.83%), CaO (2.27%) and some trace metal oxides such as Cr_2O_3 , TiO_2 , K_2O , MgO , Na_2O and BaO . Fig. 1c shows the XRD analysis of IF steel slag. Silica as quartz (SiO_2 - 2θ value 20.8 and 26.7, corresponding planes 1 0 0 and 1 0 1, JCPDS 46-1045), iron oxide as hematite ($\epsilon\text{-Fe}_2\text{O}_3$ - 2θ value 36.5 and 40.4, corresponding planes 1 3 1 and 4 2 0, JCPDS 52-1449), iron silicate as iscorite ($\text{Fe}_7\text{SiO}_{10}$ - 2θ value 39.4, 50.2 and 60.0, corresponding planes 4 1 0, 1 1 2 and 0 5 3, JCPDS

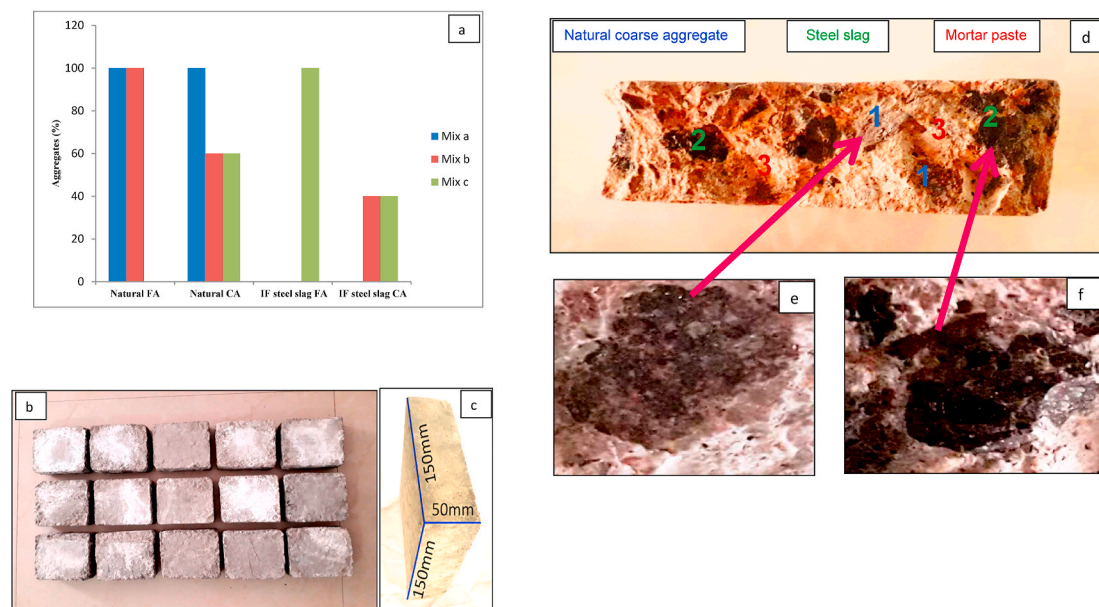


Fig. 3. Preparation of concrete specimens: a) Radiation shielding composites with various percentages of induction furnace steel slag replacement; b) Fabricated gamma radiation shielding concrete specimens; c) Dimensions of prepared concrete specimen ($150 \times 150 \times 50$ mm).

d) Cross sectional view of prepared concrete block: 1. Steel slag coarse aggregate, 2. Blue metal coarse aggregate, 3. Mortar paste of concrete; e) natural coarse aggregate (zoom in); f) induction furnace steel slag (zoom in).

*Mix a – Conventional concrete (0% IF steel slag); Mix b – 40% induction furnace steel slag as coarse aggregate; Mix c – 40% induction furnace steel slag as coarse aggregate and 100% as fine aggregate. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

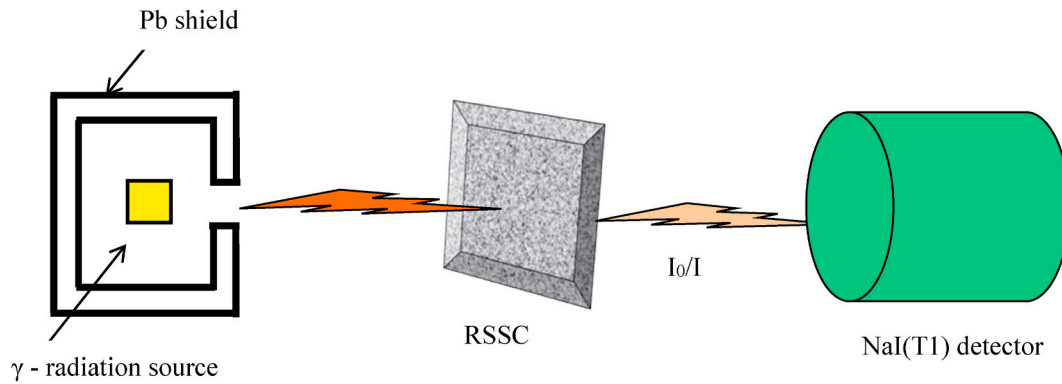


Fig. 4. Gamma radiation shielding - experimental setup.

22-1118) and iron aluminium silicate ($\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ - 2θ value 22.01, corresponding plane 2 2 1, JCPDS 41-1423) as almandine were the compounds and their corresponding phases present in IF steel slag. Fig. 1d represents surface morphological analysis of IF steel slag using SEM, it can be observed that the particles/elements present were dissimilar in size and shape. This enhances the property of binding with cementing materials in concrete mixture. The major elemental composition from EDAX analysis is 18.54% Si, 17.25% Fe, 5.8% Al, 1.58% Ca with 50.72% O and some trace elements such as Ca, Mn, Mg, Cr, Ti, K and Zn (Fig. 1e).

2.3. Preparation of concrete specimens

Concrete blocks of M20 grade with the size of $150 \times 150 \times 50$ mm were prepared as per IS:10262-2009: guidelines for concrete mix design [43]. The schematic representation of fabrication of concrete specimen is shown in Fig. 2. IF steel slag as fine and coarse aggregate has been replaced in concrete with various proportions. The mix combinations of the prepared concrete specimens are as follows; Mix a – Conventional concrete; Mix b – 40% IF steel slag as coarse aggregate; Mix c – 40% steel slag as coarse aggregate and 100% as fine aggregate (Fig. 3a). The prepared concrete specimens with steel slag materials and its dimensions are shown in Fig. 3b and c respectively. The fabricated concrete blocks were subjected to curing at room temperature (28°C) for 28 days.

2.4. Characterization of concrete specimens

Cross sectional view of the prepared concrete specimen is shown in Fig. 3d. Density has been measured for all the mixes prepared and the impact of addition of IF steel slag incorporated in the concrete as fine aggregate/coarse aggregate were tested. Compressive strength were performed using digital compression testing machine (CTM- Aamil - 3000 kN capacity) with the compression rate of 0.6 N mm^{-2} per sec. A set of five specimens of each mixes were tested for the compressive strength after 28 days.

2.5. Gamma radiation shielding studies

The prepared concrete specimens were studied for its gamma attenuation at Indira Gandhi Centre for Atomic Research (IGCAR), Department of Atomic Energy (DAE), Government of India, Kalpakkam, Tamil Nadu, India. Gamma radiation sources ^{60}Co (1.17 & 1.33 MeV) and ^{137}Cs (0.662 MeV) were used to emit gamma photons for the study. The source strength of ^{60}Co source is 1.5 mCi and ^{137}Cs source is 10 mCi which is of lower energies has been used in this gamma attenuation study. Concrete specimens cured for 28 days were tested for gamma radiation shielding property.

2.6. Gamma shielding - experimental setup

The experimental setup includes gamma source, shielding arrangement around source, collimator and NaI (Tl) gamma spectrometer which is shown in Fig. 4. ^{137}Cs emits 0.662 MeV with emission probability of 0.85 and ^{60}Co source which generates two photons with energy 1.33 MeV and 1.17 MeV with 100% emission probability. The photons emitted from the source after collimation were allowed to transmit through different concrete specimens. The counts were recorded in spectrometer under the photo peak are measured for each specimen.

The following relationship is used to obtain the attenuation of gamma radiation.

$$I = I_0 \exp(-\mu_m \rho t)$$

Where, I_0 - Dose rate at detector location without concrete specimen.

I - Dose rate at detector location with concrete specimen (15 cm thickness).

μ_m - Mass attenuation coefficient (cm^2/g) and

ρ - Density of the concrete specimen under study

t - Physical thickness of the shielding material (cm).

2.7. Gamma Attenuation Factor (GAF)

To determine the effect of replacement of IF steel slag in concrete on gamma attenuation characteristics, the following formula has been used to calculate GAF.

$$GAF = \frac{C_0 - C_t}{C_0}$$

Where, C_0 is dose rate observed in the detector without concrete, C_t is the dose rate measured with concrete specimen.

2.8. Linear attenuation coefficient (LAC)

Linear attenuation coefficient (μ) is used to study the interaction of photons with the given material and is described as photon interaction per unit length. LAC has been measured in cm^{-1} .

2.9. Half Value Layer (HVL)

HVL of any material has been defined as thickness, where the 50% of the incident energy is reduced and is measured in cm. The following formula has been used to calculate HVL.

$$HVL = \frac{0.693}{\mu}$$

Where, μ is the linear attenuation co-efficient in cm^{-1} .

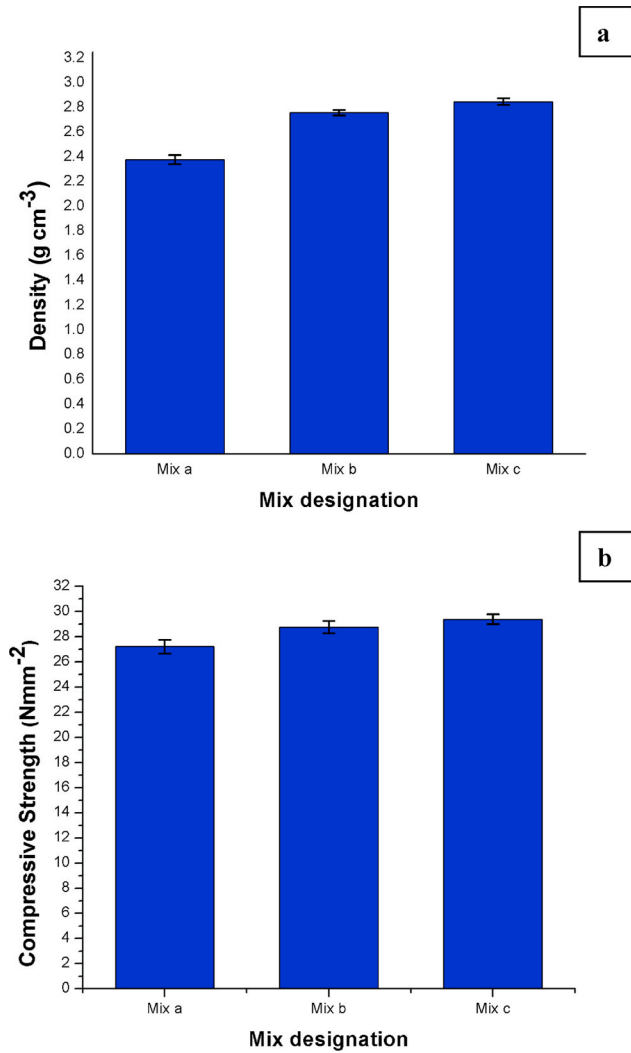


Fig. 5. Density and compressive strength of various concrete mixes prepared. a) Density; b) Compressive strength.

3. Results and discussion

3.1. Density

The density of concrete specimens prepared with replacement of IF steel slag of various proportions is shown in Fig. 5a. Hematite aggregate incorporation in concrete increases the workability of fresh concrete [44], further drying shrinkage of concrete has decreased on using hematite [45]. Density of the conventional concrete specimens prepared without IF steel slag for 28 days curing were 2.38 g cm^{-3} . The obtained density for 40% replacement of IF steel slag as coarse aggregate is 2.76 g cm^{-3} . Concrete specimens prepared with 40% coarse aggregate and 100% fine aggregate of IF steel slag replacement, the obtained density is 2.85 g cm^{-3} . Concrete specimens replaced with IF steel slag as coarse aggregate (40%) and fine aggregate (100%) shows increase in density when compared to other mixes prepared. Hematite aggregate increases the density of concrete with increasing percentage of hematite [46]. The presence of hematite and other mineralogical phases of iron in IF steel slag increase the density of the concrete.

3.2. Compressive strength

The compressive strength of various concrete specimens are shown in Fig. 5b. Compressive strength of concrete specimens prepared without

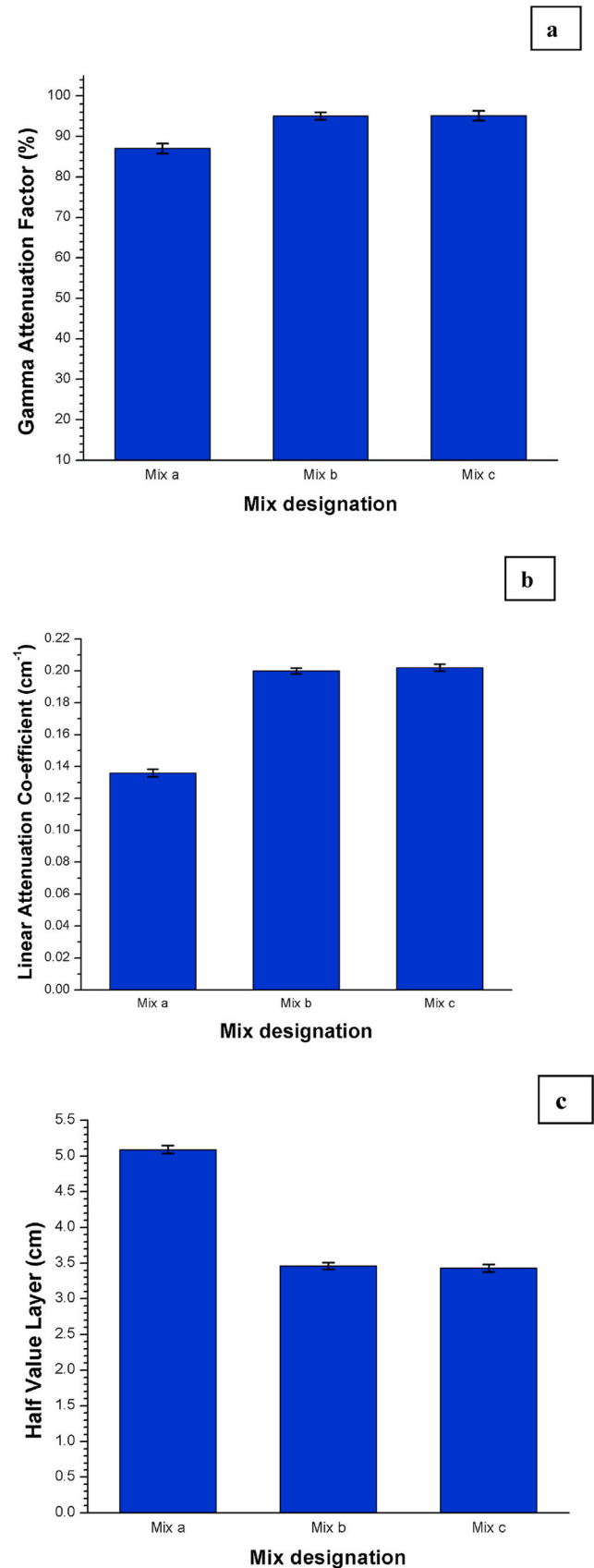


Fig. 6. Gamma radiation shielding studies (^{60}Co source). (a) Gamma attenuation factor; (b) Linear attenuation co-efficient; (c) Half Value Layer.

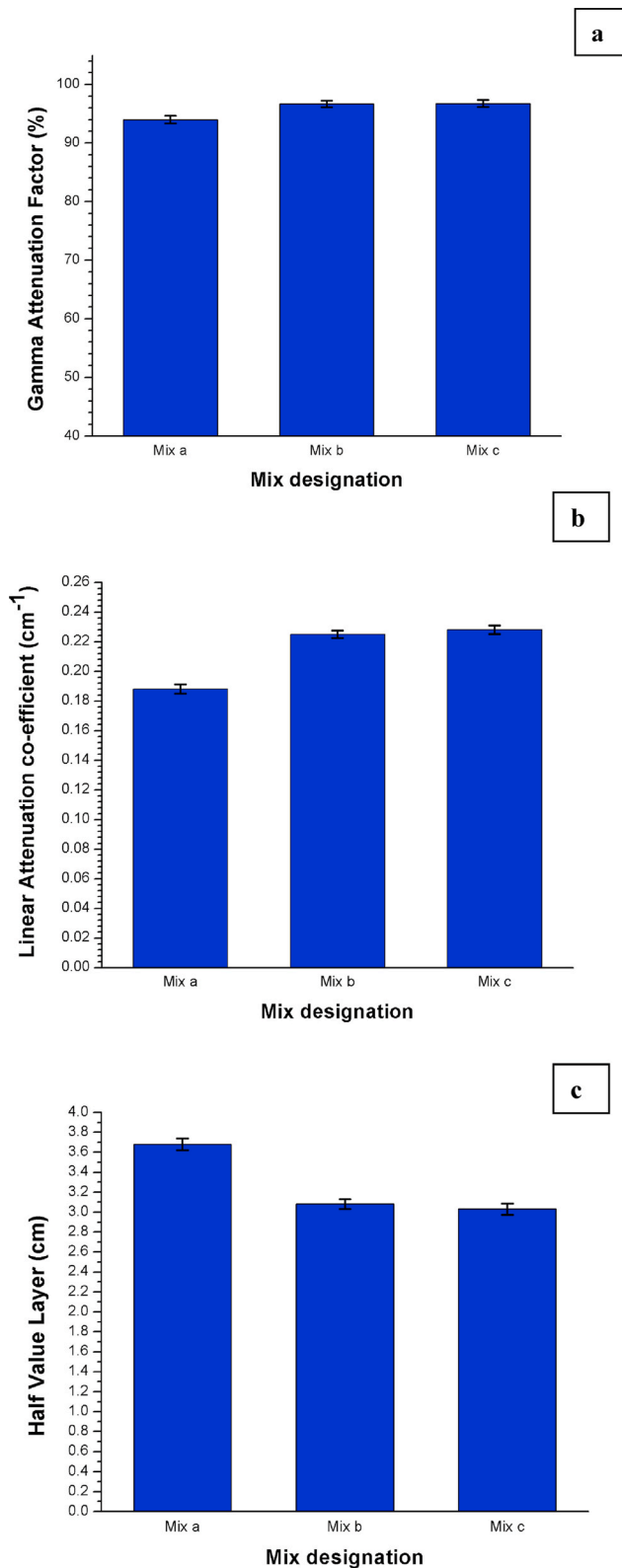


Fig. 7. Gamma radiation shielding studies (^{137}Cs source). (a) Gamma attenuation factor; (b) Linear attenuation co-efficient; (c) Half Value Layer.

IF steel slag replacement is 27.20 N mm^{-2} for 28 days curing. In 40% of IF steel slag replacement of coarse aggregate, the obtained compressive strength is 28.42 N mm^{-2} . Concrete specimens prepared with 40% coarse aggregate and 100% fine aggregate by IF steel slag showed the

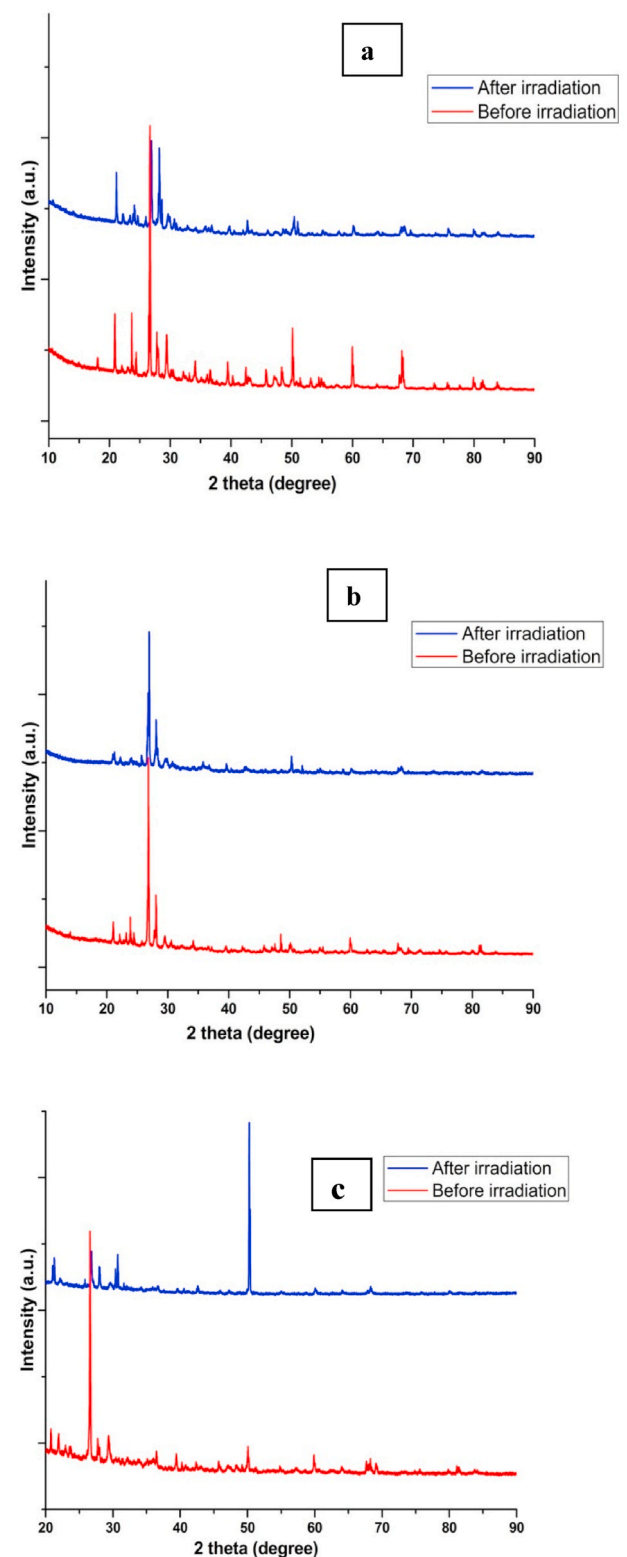


Fig. 8. XRD analysis of concrete specimens. a) Mix a before and after irradiation b) Mix b before and after irradiation; c) Mix c before and after irradiation.

maximum compressive strength of 29.38 N mm^{-2} . Rough surface of hematite and other mineralogical phases of iron present in IF steel slag composite is the rationale for binding with cement paste by causing adhesion for mechanical interlocking [32]. During the process of concrete curing, hydration occurs within the concrete material which leads

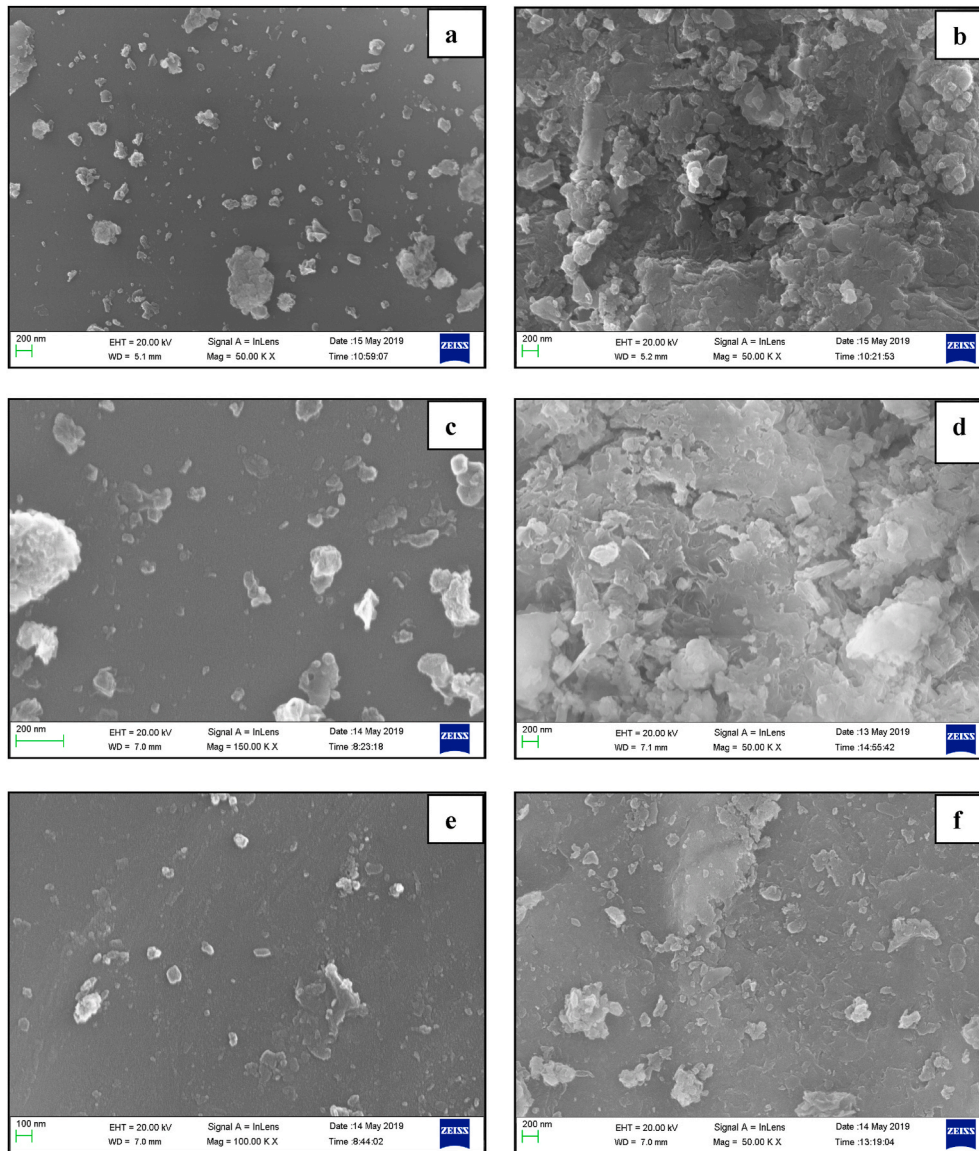


Fig. 9. FE-SEM analysis of concrete specimens.

a) and b) Mix a before and after irradiation respectively; c) and d) Mix b before and after irradiation respectively; e) and f) Mix c before and after irradiation respectively.

to the formation of hydration products and has large specific volume. The hydrated products can act as a filler material in voids within the concrete leading to decrease in porosity and increase in compressive strength [47]. In concrete, hematite aggregate enhances the formation of bond in the interfacial transition zone (ITZ) and increases the mechanical properties of concrete [48]. Incorporation of hematite aggregate in concrete has positive impact on compressive strength [44] and hence the presence of iron oxide as hematite and other iron compounds in IF steel slag increases the compressive strength.

3.3. Gamma radiation shielding studies

Gamma radiation shielding is primarily induced by the interaction between γ -ray and the electrons in the shield material by interaction of γ -ray with an atom of shielding material resulting in the ejection of an electron [49]. The intensity of γ -ray will be decrease during the γ -ray passing through the shielding material.

The prepared concrete specimens (Mix a, Mix b, Mix c) were studied for gamma radiation shielding. The experimental results of gamma

radiation shielding for ^{60}Co source (1.17 & 1.33 MeV) is shown in Fig. 6. The obtained experimental values of Gamma Attenuation Factor (GAF), Linear attenuation co-efficient (LAC) and Half Value Layer (HVL) for the prepared Mix a is 87%, 0.136 cm^{-1} and 5.095 cm respectively. The resulted experimental values of GAF, LAC and HVL for the prepared Mix b are 95.1%, 0.2 cm^{-1} and 3.458 cm respectively. The obtained experimental values of GAF, LAC and HVL for the prepared Mix c are 95.2%, 0.202 cm^{-1} and 3.433 cm respectively. Among the concrete mixes prepared, with the replacement of IF steel slag as coarse and fine aggregate, Mix c shows maximum gamma radiation shielding properties.

The experimental results of gamma radiation shielding for ^{137}Cs source (0.662 MeV) is shown in Fig. 7. The obtained experimental values of GAF, LAC and HVL for the prepared Mix a is 94%, 0.188 cm^{-1} and 3.695 cm respectively. The experimental values of GAF, LAC and HVL for the prepared Mix b are 96.7%, 0.219 cm^{-1} and 3.055 cm respectively. Further, for Mix c the experimental values of GAF, LAC and HVL are 96.8%, 0.233 cm^{-1} and 3.028 cm respectively. From the experimental results, it can be inferred that IF steel slag incorporated concrete

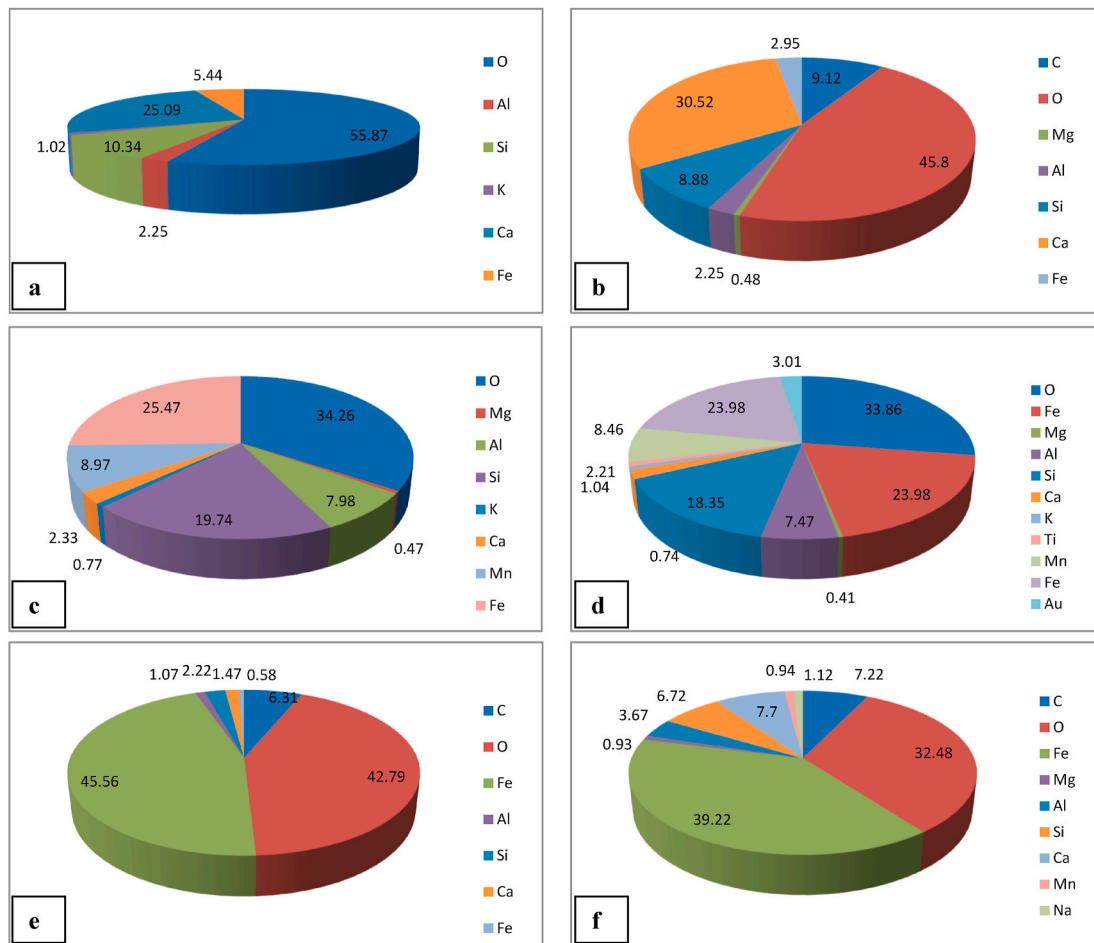


Fig. 10. EDAX analysis of concrete specimens.

a) and b) Mix a before and after irradiation respectively; c) and d) Mix b before and after irradiation respectively; e) and f) Mix c before and after irradiation respectively.

specimens showed higher gamma attenuation than conventional concrete specimens. Hematite and other mineralogical phases of iron (isocorite and almandine) present in IF steel slag would have enhanced the radiation shielding effect of concrete specimens. Also, concrete with hematite can be used in high temperatures, since hematite is not affected by heat [40] and hence IF steel slag incorporated concrete specimens withstand the formation of heat when photons of gamma rays penetrate into matter. Among the different concrete specimens prepared complete replacement (100%) of IF steel slag as fine aggregate and 40% as coarse aggregate shows better gamma attenuation. The source strength of Co-60 (1.5 mCi) and Cs-137 (10 mCi), which is very low and primarily used to study the gamma attenuation [50].

3.4. X-ray diffraction studies

XRD analysis of concrete specimens before and after irradiation is shown in Fig. 8(a–c). The peak intensity of mineralogical phases present in the concrete decreased significantly or shifted slightly and even disappeared due to the interaction of photon with the concrete matrix. XRD pattern of conventional concrete specimens (without slag replacement) before and after irradiation is shown in Fig. 8a. Calcite mineralogical phase of CaCO_3 in rhombohedral shape with plane 1 0 4 corresponding to the 2θ value of 29.4 (JCPDS 05-0586) is shifted to 29.6 with less peak intensity. Portlandite mineral of Ca(OH)_2 in hexagonal shape with plane 1 0 1 corresponding to the 2θ value of 34.02 (JCPDS 04-0733) is disappeared. Quartz mineralogical phase of SiO_2 in hexagonal shape with plane 1 0 1 corresponding to the 2θ value of 26.7 (JCPDS 46-1045) has a

moderate shift to 26.9 with less peak intensity.

XRD analysis of Mix b concrete specimen before and after irradiation is shown in Fig. 8b. Quartz mineralogical phase of SiO_2 in hexagonal shape with plane 1 0 1 corresponding to the 2θ value of 26.7 (JCPDS 46-1045) has a shift to 26.9 with less peak intensity. Presence of CaCO_3 as calcite mineral with the plane 1 0 4 of 2θ value 29.4 (JCPDS 05-0586) has been disappeared after the irradiation process. Ferroactinolite mineralogical phase of $\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ is in monoclinic shape with plane 3 1 0 corresponding to the 2θ value of 28.01 (JCPDS 23-0118) has appeared with the same 2θ value and peak intensity after the irradiation. Portlandite mineralogical phase of Ca(OH)_2 is in hexagonal shape with plane 1 0 1 corresponding to the 2θ value of 34.2 (JCPDS 04-0733) has been disappeared due to the photon interaction with the concrete matrix.

XRD pattern of Mix c concrete specimen before and after irradiation is shown in Fig. 8c. Presence of SiO_2 (quartz) is in hexagonal shape with plane 1 0 1 corresponding to the 2θ value of 26.5 (JCPDS 46-1045) shifted to 26.8 with less peak intensity. Calcite mineralogical phase of CaCO_3 in rhombohedral shape with plane 1 1 3 corresponding to the 2θ value of 39.4 (JCPDS 05-0586) is disappeared due to the strong interaction of photon with the concrete matrix. In the XRD pattern, babingtonite mineralogical phase of $\text{Ca}_2\text{FeSi}_5\text{O}_{14}(\text{OH})$ (anorthic) is in lattice-primitive shape and the 2θ values before irradiation are 26.5 and 29.3 is in the plane of 0 0 2 and 2 1 0 respectively (JCPDS 45-1387). After irradiation with gamma rays the 2θ values shifted to 26.7 and 30.7 respectively. $\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ is in monoclinic shape of ferroactinolite mineralogical phase with plane 3 1 0 corresponding to the 2θ value

of 28.2 (JCPDS 23-0118) appeared with the same 2θ value and peak intensity after the irradiation.

3.5. Surface morphology and EDAX analysis

Field Emission Scanning Electron Microscope (FE-SEM) analysis of concrete specimens before and after gamma irradiation is shown in Fig. 9. Surface morphology of concrete specimens without steel slag replacement (Mix a) before and after irradiation is shown in Fig. 9 a and b respectively. Surface morphology of Mix b concrete specimen before and after irradiation is shown in Fig. 9 c and d respectively. Fig. 9 e and f represents the SEM analysis of Mix c concrete specimens before and after irradiation respectively. Among the three mixes tested for SEM analysis after gamma irradiation, concrete specimens with IF steel slag 100% as fine aggregate and 40% as coarse aggregate (Mix c) shows less disruption in surface morphology (Fig. 9 f) compare to conventional concrete (Mix a - Fig. 9 b) and concrete specimens with 40% steel slag as coarse aggregate replacement (Mix b - Fig. 9 d).

Elemental composition of prepared concrete specimens Mix a, Mix b and Mix c before and after irradiation with gamma rays is shown in Fig. 10. From the EDAX results silicon (Si), iron (Fe), aluminum (Al), Calcium (Ca), Manganese (Mn) and Oxygen (O) are the elements occurred predominantly in the prepared all three mixes along with trace elements such as Magnesium (Mg), Potassium (K), Sodium (Na) and Titanium (Ti). Concrete specimens without steel slag replacement (Mix a - Fig. 10 a) have 5.44% of Fe content which is less compared to the other two mixes prepared with IF steel slag replacement. Fig. 10 c represents the EDAX analysis of concrete specimens prepared with 40% steel slag as coarse aggregate replacement (Mix b), in which the percentage of Fe content is 25.47% and causes more attenuation towards gamma radiation than conventional concrete. EDAX analysis of concrete specimens with 100% steel slag as fine aggregate and 40% steel slag as coarse aggregate (Mix c) is shown in Fig. 10 e, in which the percentage of Fe content is 45.56% causes maximum gamma ray attenuation compared to other two mixes prepared (Mix a and b). The presence of hematite, iscorite and almandine mineralogical phases of iron in IF steel slag makes the material suitable for gamma radiation shielding. The SEM and EDAX results infer that, maximum replacement of IF steel slag (100% as fine aggregate and 40% as coarse aggregate - Mix c) shows better gamma radiation shielding properties of concrete.

4. Conclusions

The present study highlights the development of radiation shielding composite by using IF steel slag in concrete as effective radiation shielding material.

- Concrete specimens prepared with IF steel slag composite as 100% fine aggregate and 40% coarse aggregate show better density, compressive strength and radiation shielding properties. Complete replacement of fine aggregates without affecting the strength of the concrete is the major outcome of the study.
- The gamma radiation shielding factors such as GAF, linear attenuation co-efficient and HVL for ^{60}Co and ^{137}Cs gamma source of energies in this study is better than conventional concrete. The radiation shielding materials in concrete presently used in nuclear industries include barite, magnetite, hematite, serpentine, etc. and are obtained from natural resources.
- IF steel slag in concrete can be an alternative and cost effective material in nuclear industry for spent fuel storage areas and hot cells application.

Author contribution

VGK and JB conceived the idea of utilizing IF steel slag in developing radiation shielding concrete and studied it. BV guided and validated the

entire experimental studies. SC and SB carried out the radiation shielding studies. RP and VKB assisted in mix design & mechanical properties of concrete. VGK, JB and SC prepared the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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