CHAPTER 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

With the advancement in science and technology, the scope of utility of gamma rays is widening. But before working with gamma sources in any field, they need to be kept under appropriate shielding. In the past, various materials have been tested for their shielding ability so as bring exposure of radiation under safe limits. But till date, concrete has outweighed any other material used in practical shielding situations.

It is requirement of the time to prepare cost effective, eco-friendly and better concretes which suits best for shielding gamma rays. The better concretes means those concretes which have desired strength, good radiation shielding ability and health physics characteristics in accordance with the set standards. When it is utilized for shielding humans from uncontrolled exposure, gamma radiation interacts with it and this interaction can be studied through different parameters.

In this chapter, the mechanical properties and gamma ray interaction parameters along with multiple scattering for shielding concretes have been reviewed. This review of literature is given in the following sections:

2.2 MECHANICAL PROPERTIES OF CONCRETES

Before preparing concrete with suitable mechanical properties and according to the given requirements, the proper selection of ingredients, water content, mixing of ingredients, compaction of concretes and curing after concrete has been set are the major factors to be kept in mind. The most important factor for having concrete with desired results is water to cement ratio, which later came to be known as water to cementitious ratio and is denoted by W/C. Water-cement ratio given by Abrams (1919) is the undisputed fundamental relation of concrete technology. He described a relation of the strength of concrete with W/C ratio and stated that strength of concrete decreases with an increase in W/C ratio. This inverse relationship has been experimentally verified by different workers in the past. Yeh (2006) tried to extend
applicability of Abrams’ law for practical applications by covering 3 to 365 days. He proposed two novel methodologies to extend this law and a power formula to any given age. The generalised formula agreed well with the experimental data.

The mechanical properties of different types of concretes including a variety of admixtures and superplasticizers have been studied by various workers. The following workers have investigated mechanical properties of concretes after giving due importance to W/C ratio and proportion of ingredients in concrete mixture.

Concrete is a structural material with adequate properties for diverse field applications. The concrete components, microstructure of concrete, mechanical properties with their significance and types of concretes and of admixtures are well explained by Mehta and Monteiro (2006). Also radiation shielding concretes are given due importance in their preparation process from suitable components.

Krishna and Jain (1993) specified the chemical requirements of cement in terms of lime and alumina, magnesia and sulphur content present. The concept and testing procedure for soundness of cement and mechanical properties of concrete in laboratory is well elaborated. The procedure of slump test of plastic concrete and significance of its results is explained for different requirements.

Jain (2002) stated three chief qualities required by good concrete and measures of determining each quality by testing in laboratory. The properties of flyash and its types, design of proportioning concrete mixture and different exposure conditions in which concrete can survive are analysed in terms of severity of environmental conditions.

Gambhir (2011) explained different chemical admixtures and mineral additives and importance of using them in concrete. He stated the testing procedure of basic properties of concrete as explained by Jain (2002). The importance of compaction of concrete and manual and vibrating method of compaction was also explained. The curing conditions are also stated as well as the effect of variation in temperature and age on concrete.

Bureau of Indian Standards (BIS) is the central authority of India which lays down norms, practices and methods for concrete in India. It recommended method of making and curing test samples as well as methods for testing compressive strength, flexural strength and

Basyigit (2006) investigated the physical and mechanical properties of 15 different types of concretes and also attempted to find an ideal water to cement ratio in concrete. He measured compressive strength of concretes at an age of 28 days and reported that W/C=0.51 is ideal for heavyweight concrete and W/C=0.43 gives highest compressive strength of concrete.

Kovler and Roussel (2011) studied various properties of fresh concrete and hardened concrete such as workability, slump, bleeding, segregation, compressive strength, shrinkage, etc. They attempted for modeling and prediction of mechanical properties of concretes, with special attention on lightweight concretes.

Zhutovsky and Kovler (2012) conducted durability tests through checking their resistance to chloride penetration, air permeability and drying shrinkage for high performance concretes. They reported there is lasting effect of internal curing on the durability aspect of concrete and studied it in terms of water to cement ratio.

Bouzoubaa and Fournier (2005) investigated the use of available supplementary cementing materials (SCMs) in Canada viz. flyash, ground granulated blast furnace slag and silica fume in cement and concrete. Their production, usage, success stories, guidelines and specifications are given in detail along with proposed solutions to the barriers faced by them. The under-utilisation of flyash available in large quantity in Canada can be overcome by citing its numerous benefits.

Oner (2005) investigated the efficiency and optimum usage of flyash in different 28 concretes prepared by different mix designs. Compressive strength of concretes at an age of 28 and 180 days was measured. He reported that as the cement content increases, the amount of lime in mixture increases and flyash will be used more efficiently. Also the optimum value of flyash for the test groups investigated was 40%.
The effect of mineral admixture on strength results vary significantly with its replacement levels as stated by Bharatkumar (2001). He presented modified mix design procedure, which utilises optimum water content and the efficiency factor of mineral admixture.

For effective utilization of flyash in concrete, Babu and Rao (1996) attempted to study efficiency of flyash in concrete for effective utilization of flyash. They proposed empirical relation for water to cementitious ratio for concrete mixture having slag and flyash. The results are helpful in evaluating the strength of flyash concretes at any age with any amount of replacement of cement by flyash.

Atis (2005) investigated the strength properties of high volume flyash concrete with 0, 50 and 70 % of Class F flyash replacing cement cured at moist and dry curing conditions. The compressive and flexural strength of the concrete samples were measured and their relationship was studied. They assessed the impact of curing conditions through a proposed efficiency factor. They reported that above concretes were more vulnerable to dry curing conditions than ordinary concretes.

Atis (2002) measured heat evolution of concrete from temperature increase in high volume flyash concrete under adiabatic curing condition. Characteristic of heat evolution of flyash concrete was found to be strongly dependent on the replacement level of flyash and dosage of superplasticizer used to maintain workability. Increasing the replacement level of flyash caused lower temperature rise in concrete.

Poon (2000) studied some parameters of concretes including compressive strength, heat of hydration, chloride diffusivity, degree of hydration and pore structures of flyash/cement concrete and corresponding pastes. With water to binder ratio of 0.24 and flyash content of 45%, the 28 day compressive strength obtained was 80 MPa. The study also quantified the reaction rates of cement and flyash in the cementitious materials. The results also demonstrated the dual effect of flyash in concrete: i) act as a micro-aggregate and ii) being a pozzolana.

Jiang (2000) investigated the water demand of the non-air-entrained concrete incorporating large volumes of Class F and C flyashes. The percentage replacement of flyash in concrete was 55 % by mass of Portland cement. The measured 28 day compressive strength of
the concrete ranged from 30.7 to 55.8 MPa. The investigated concrete mixtures had slumps ranging from 5.7 to 7.0 cm.

Bouzoubaa (2001) investigated mechanical properties and durability of concrete made with high volume flyash blended cement using a coarse flyash. The properties of fresh concrete (slump, air content, bleeding and setting time) and hardened concrete (compressive strength, flexural strength, drying shrinkage) were investigated and their results shows that studied concretes were better than concretes having unground flyash.

Siddique (2004a) studied the effect of three different replacements (35, 45 and 55 %) of cement by flyash and also san fibres on various mechanical properties. The usage of flyash in concrete increased the workability due to ball-bearing action of spherical particles of flyash, increased slump and decreased compressive strength and flexural strength.

Siddique (2004b) further conducted extensive studies for increasing utilization of flyash in concretes by evaluating different mechanical properties of flyash concretes. He reported that although the compressive strength decreases at age of 28 days, but it increases significantly at age of 91 and 365 days. Other mechanical properties viz. flexural strength, modulus of elasticity, abrasion resistance of concrete improved with the age of concrete.

Siddique (2009) evaluated the utilization of flyash, bottom ash, spent foundary sand, cement kiln dust, wood ash and scrap tire rubber in making controlled low-strength materials (CLSM). He reported that flyash can be used up to 100% as replacement of cement and other materials can also be used as partial replacement of cement in CLSM.

Siddique (2014) further studied the utilization of industrial solid wastes from thermal power plants, iron and steel mills, non-ferrous industries and cement industry. He tested the materials for their physical, chemical and mechanical properties and also affect of their replacement with cement, sand and aggregates on concretes and controlled low-strength materials.

2.3 GAMMA RAY INTERACTION PARAMETERS

The knowledge of gamma ray interactions with matter is important in order to understand gamma ray detection and attenuation process. Various gamma ray interaction parameters such as linear and mass attenuation coefficient, mean free path, half value layer,
interaction cross section, effective atomic number, electron density etc. are required to characterize the penetration and diffusion of gamma rays in the absorbing material. Gamma ray shielding materials should be of high density and high atomic number so that they have a high total linear attenuation coefficient and a high photoelectric absorption probability. The requirements for a high performance shield material is to maximize the number of electrons per unit mass, maximize the nuclear interaction cross section per unit mass and minimize the production of secondary particles. Accurate values of these interaction parameters are required in many scientific and industrial applications. The review and measurements of gamma ray interaction parameters have been discussed in detail in the following sections.

2.3.1 Attenuation coefficients

The study of absorption of gamma radiation in shielding materials has been an important subject in the field of radiation physics. The knowledge of the linear attenuation coefficients is of prime importance in the scattering and absorption of gamma radiation. From the linear attenuation coefficient, a number of related parameters can be derived, such as the mass attenuation coefficient, total interaction cross section, effective atomic number, and electron density.

Many workers have determined and compiled the data of mass attenuation coefficients for different elements, compounds and mixtures at various X-ray and gamma ray energies. The work of mass attenuation coefficient measurements initiated by Barka and Sadler (1907, 1909) was continued in the following decades by Cork and Pidd (1944), Davisson and Evans (1951), Shimizu et al. (1952), Colgate (1952), Conner et al. (1970), Goswami and Chaudhari (1973), Millar (1975) and many more, who measured the attenuation coefficients for different elements in different energy regions.

For accuracy of attenuation results, sample size is an entity of concern as Gopal and Sanjeevaiah (1973) performed experiment for reporting the effect of sample thickness on attenuation results for elements C, Cu, Al, Sn and Pb. The measured gamma ray attenuation coefficient results were effectively improved for sample thickness (x) satisfying the criterion \( \mu x < 1 \) mean free path (mfp). Also following this criterion, the number of multiple scattered photons reaching the detector was minimized.
Similarly Varier et al. (1986) correlated the effect of longitudinal and transverse dimensions on the attenuation coefficients for Cu and Hg with energy 662 keV. He concluded that the criterion $\mu_x < 1$ mfp should be satisfied for both longitudinal as well as transverse dimensions of the target for accurate determination of attenuation coefficients.

For setting up the attenuation results database helpful in checking accuracy of transmission experiment for materials of different compositions, the initial major compilation work was done Allen (1935), Victoreen (1949) and Davisson and Evans (1952). The compilation work of attenuation measurement results reached a new high with the work of Hubbell (1982), who compiled the theoretically calculated attenuation coefficient for 40 elements ranging from hydrogen to uranium and 45 mixtures and compounds of dosimetric interest in the energy range of 1 keV to 20 MeV. Later on, Hubbell and Seltzer (2004) extended the tables of mass attenuation coefficients for elements, mixtures and compounds for energies ranging from 1 keV to 100 GeV.

With the growing attention of scientific world towards the ever expanding applications of gamma radiation to different fields, Berger and Hubbell (1999) developed a computer program, XCOM for calculating cross section and attenuation coefficient for elements, compounds and mixtures in the energy range of 1 keV to 100 GeV. Gerward et al. (2001) prepared database for mass attenuation coefficient in the windows version. XCOM, a computer program initially developed by Berger and Hubbell (1999) was transformed to windows platform, which is named as WinXCom.

Mudahar and Sahota (1988a) studied the effect of soil grain size and pressure on gamma ray attenuation coefficient in the energy region 279 to 1250 keV. They found attenuation coefficients vary with only change in soil grain diameter, not with chemical composition of soils. No significant effect in attenuation results was reported with change in pressure.

El-Kateb and Abdul-Hamid (1991) measured the mass attenuation coefficients of gamma rays in materials containing hydrogen, carbon and oxygen with hydrogen weight ratio ranging from 0.055 to 0.177 in the energy range of 54 to 1332 keV. They reported a relationship linear in nature of hydrogen weight fraction present in material with the experimental total attenuation coefficient results.
Mudahar et al. (1991a) computed total and partial mass attenuation coefficients of five different soils in the energy range from 10 keV to 100 GeV. They reported that no significant variation in mass attenuation coefficient with their chemical composition has been observed from 300 keV to 3 MeV. But there is considerable variation in it with photon energy below 300 keV and above 3 MeV.

Singh and Mudahar (1992) computed total and partial mass attenuation coefficients of various types of composite materials in a wide energy range of 10 keV to 100 GeV. For all types of materials investigated, a significant variation in the value of mass attenuation coefficient was reported in low and high energy regions but it remains constant in the intermediate energy region of 1.25 to 2.00 MeV.

Tajuddin et al. (1995) determined the mass attenuation coefficients for 12 particularly selected elements of moderate to high atomic number for source $^{241}$Am with good geometry conditions. Significant discrepancies (>10%) reported between measurement and theory for W at 59.5 keV was found in agreement with the reported measurements of others.

Abdel-Rahman et al. (2000) measured gamma ray attenuation coefficients of perspex, bakelite, paraffin, Al, Cu, Pb and Hg at energies 59.54, 661.6 and 1332.5 keV by using narrow beam transmission geometry. They reported that mass attenuation coefficient remains constant up to 3 mfp. Mass attenuation coefficient for Cu, Pb and Hg decreases with target thickness more than 3 mfp due to the increase in the number of coherent small angle scattering photons.

Turgut et al. (2004) measured X-ray attenuation coefficients for the elements Co, Mn and Co$_2$O$_3$, compounds CoCl$_2$.6H$_2$O, CoSO$_4$, CoSO$_4$.7H$_2$O, MnCO$_3$, KMnO$_4$, MnCl$_2$.2H$_2$O, and MnCl$_2$.4H$_2$O at different energies between 4.508 and 11.210 keV. It was observed that the mixture rule method is not suitable for the determination of the mass attenuation coefficients of compounds at energies near the absorption edges.

Singh et al. (2004b) measured mass attenuation coefficient of PbO–B$_2$O$_3$ and Bi$_2$O$_3$–PbO–B$_2$O$_3$ glass systems using narrow beam transmission method. The results were compared with theoretical values obtained by XCOM for shielding concretes. Effect of replacing lead by bismuth was analyzed in terms of mass attenuation coefficient and it was indicated that these glasses have good shielding properties.
Singh et al. (2006a) measured mass attenuation coefficient of PbO–BaO–B\textsubscript{2}O\textsubscript{3} glasses for energies 511, 662 and 1274 keV. Experimental results were compared with theoretical tabulations. They reported that on comparing half value layer results with shielding concretes indicates that these glasses possess good shielding properties.

Midgley (2005) measured the X-ray linear attenuation coefficient for materials containing elements hydrogen to calcium for samples of six plastics, seven crystalline materials, three tissue substitute materials, three liquids and six salt solutions at 32–66 keV X-rays and 140 keV gamma rays using well collimated photon beam. The measured values were a few percent lower than values predicted by the tabulations with an uncertainty of less than 2%.

Turgut et al. (2005) measured the total mass attenuation coefficients for element Fe and compounds FeF\textsubscript{3}, Fe\textsubscript{2}O\textsubscript{3}, FeCl\textsubscript{3}4H\textsubscript{2}O and FeCl\textsubscript{3}2NH\textsubscript{4}Cl.H\textsubscript{2}O for different energies between 4.508–17.443 keV by using secondary excitation method. They again reported that the mixture rule method is not suitable for the determination of the mass attenuation coefficients of compounds, especially at energies near the absorption edge.

Kumar et al. (2006a) measured mass attenuation coefficient of some commonly used solvents (ethanol, methanol, propanol, butanol, water, toluene, benzene, carbon tetrachloride, acetonitrile, chlorobenzene, diethyl ether and dioxane) by using well collimated narrow beam transmission geometry with gamma energies of 279, 356, 662, 1173, 1252 and 1332 keV. From the obtained results, the molar extinction coefficients of these solvents were also determined.

Akar et al. (2006) determined half value thickness, linear and mass attenuation coefficient of biological samples (bone, muscle, fat and water) at 140, 364 and 662 keV gamma energies. The theoretical parameters were also computed for all samples for energies ranging from 0.001 keV to 20 MeV and good agreement between results was observed.

Singh et al. (2006b) measured the mass attenuation coefficient of lead and bismuth borate flyash glasses at 81, 356, 511, 662, 1173 and 1332 keV gamma rays using NaI(Tl) detector. A good agreement was reported between the experimental and theoretical results. Also glasses have ability of acting as shielding material for low energy gamma rays.
Ekinci and Astam (2007) measured the mass attenuation coefficients of some biological materials (cornea and soft contact lens, leiomyomata uteri and uterus) using energy dispersive X-ray fluorescence technique with SiLi detector at X-ray energy (5.9 keV).

Singh et al. (2008) measured attenuation coefficients of barium-borate-flyash glasses for gamma ray photon energies of 356, 662, 1173 and 1332 keV using narrow beam transmission geometry. These coefficients were then used to obtain values of mean free path, effective atomic number and electron density. From the obtained results, it was reported that barium-borate-flyash glasses better shields to gamma radiation in comparison to the standard shielding concretes.

Singh et al. (2009) determined experimentally the structural properties, gamma ray attenuation coefficients and half value layer of PbO-SiO$_2$ glasses using a narrow beam transmission method at 662, 1173 and 1332 keV photon energies. Also the results were compared with theoretical results obtained by mixture rule and XCOM software. Low values of HVL in PbO-SiO$_2$ glasses as compared to concretes were obtained.

Costa et al. (2013) evaluated soil bulk density ($\rho_s$) by using the soil mass attenuation coefficient ($\mu_s$). The variation in $\mu_s$ as a function of the sample thickness ($x$) and collimator sizes in $\rho_s$ measurements was analyzed. The results obtained with the $^{137}$Cs show that $\rho_s$ remained fairly constant for thicker samples ($x \geq 10$ cm) and smaller collimators (2 and 3 mm diameters). Regarding the $^{241}$Am source, the best $\rho_s$ values were obtained for samples smaller than 4 cm and with bigger collimator sizes (3 and 4 mm diameters).

Singh et al. (2014) investigated radiation shielding effectiveness of heavy metal oxide glasses. They calculated linear attenuation coefficients, effective atomic numbers and exposure buildup factors of silicate and borate heavy metal oxide glasses. It was reported that lead-free 70 Bi$_2$O$_3$: 30 SiO$_2$ is superior shielding glass than lead glasses.

Singh and Badiger (2014) studied gamma ray and neutron shielding effectiveness of some alloy materials, CS-516, SS-403, SS-410, SS-316, SS-316L, SS-304L, Incoloy-600, Monel-400 and Cupero-Nickel. They calculated mass attenuation coefficient, half value layer and exposure buildup factors of selected materials. It was reported that Cupero-Nickel and SS-316 are best shielding material for gamma rays and neutrons.
Costa et al. (2014) obtained physical properties of soils by gamma ray attenuation technique through accurate determination of linear attenuation coefficient ($\mu$). The effect of collimator size and target thickness on the experimental $\mu$ values of water and soils with different textures were investigated for $^{241}$Am and $^{137}$Cs gamma ray sources. Theoretical results were calculated using the program XCOM. It was observed that for the $^{137}$Cs the best agreements between theoretical and experimental linear attenuation coefficient were obtained for sample thickness greater than 10 cm also while for the $^{241}$Am, those were obtained for thickness less than 5 cm for small collimators.

Singh et al. (2015) calculated mass attenuation coefficients of some carbon steel and stainless steel alloys by using Geant4, MCNP simulation codes in photon energy range of 279.1-1332 keV. It was reported that both the simulation codes are suitable as an alternative method to experiment in determining gamma ray interaction parameters.

In addition to above listed elements and different composite materials, the most reliable shielding material tested for adverse radiation exposure conditions is concrete. It has been researched with different proportion of ingredients and admixtures.

Makarious et al. (1996) studied ilmenite concrete prepared from local materials as a radiation shield by calculating linear attenuation coefficients for wide energy range and compared the study results with the theoretical data. The study results stated that present ilmenite concrete under investigation is more effective for the attenuation of fast neutrons. Two empirical have also been derived for calculating total flux of gamma rays and neutrons at different thicknesses.

Bahster (1997) conducted theoretical study of attenuation for 7 different concretes in a wide energy range of 10 keV to 1 GeV. The calculated values of linear attenuation coefficient were compared with measured values in energy range of 1.5 to 6 MeV. It was reported that steel-magnetite concrete is most effective in shielding both gamma rays and neutrons.

El-Hosiny and El-Faramawy (2000) measured attenuation coefficient of Portland cement mixed 5 % lead for gamma rays emitted from $^{137}$Cs gamma source. Cement containing 5 % lead has higher attenuation coefficient value. Also the results were analyzed in terms of compressive strength of pastes.
Alam et al. (2001) measured the linear and mass attenuation coefficients of different types of soil, sand, building materials and heavy beach mineral samples with a high resolution HPGe detector for the photon energies of 276.1, 302.8, 356.0, 383.8, 661.6, 1173.2 and 1332.5 keV. They reported an exponential variation of the mass attenuation coefficient with change in gamma ray energy.

Singh et al. (2004a) generated data for total and partial mass attenuation coefficient of different building materials viz. glass, concrete, marble, flyash, cement and lime and studied as a function of chemical composition over a wide energy range of 10 keV to 100 GeV. It was reported that no significant variation is there in mass attenuation coefficient in the medium energy region.

Akkurt et al. (2004, 2006, 2007) computed the linear and mass attenuation coefficients for barite, concretes containing different amounts of barite, marble, limra and igneous rocks. The data was generated with a computer program, XCOM with energies ranging from 1 keV to 300 MeV.

Salinas et al. (2006) determined the mass attenuation coefficient of building materials commonly used in Brazil such as asbestos, clay brick, concrete, bricks and wood, with photon energy of 662 keV. MCNP4B code was also used to compute mass attenuation coefficients and effective density for 21 different energies ranging from 50 to 3000 keV.

Basyigit (2006) prepared 15 different types of concretes for radiation shielding including ordinary, barites included concrete and mixture of them in different rate. The concretes were investigated against gamma radiation both theoretically and experimentally. Both calculated and measured linear attenuation coefficient increases with increase in concrete’s density and the w/c ratio of 0.51 is favourable for heavyweight concrete.

Yousef et al. (2008) measured linear attenuation coefficient for four types of concretes with changes in temperature between 20 and 800 °C. The effect of heat on strength and on gamma ray and neutron shielding properties of four types of local concretes were investigated. A Small loss in attenuation properties for gamma rays and neutrons at 100 °C, no significant loss in attenuation between 100 and 400 °C and loss in attenuation above 500 °C was observed.
Turkmen et al. (2008) measured the mass attenuation coefficients of cement, silica fume, blast furnace slag and zeolite using $^{241}$Am gamma ray source (59.5 keV gamma rays) and $^{133}$Ba gamma ray source (80, 302 and 356 keV gamma rays). It was observed that different percentages of constituents in cement and cement mixed with different additives such as zeolite, silica fume, and blast furnace slag lead to significant variations in total mass attenuation coefficients.

Kharita et al. (2008) measured attenuation coefficient of six types of concretes for gamma rays from $^{60}$Co and $^{137}$Cs and neutrons from $^{241}$Am sources. A reduction of about 10% in the HVL was obtained for the concrete from Damascus in comparison with that from Aleppo.

Kharita et al. (2009) further investigated the effect of addition of different percentages of carbon powder to shielding concretes made of hematite aggregates by measurement of attenuation coefficients. It was found that addition of carbon powder by 6% in weight of the concrete would increase the strength of concrete, but shielding effectiveness of concretes decreased for both gamma rays and neutrons which is within the limits of experimental errors.

Sharma et al. (2009) investigated the effect of inclusion of steel fibres, lead fibres and a combination of two fibres in fiber reinforced concrete on the mechanical and radiation shielding properties of concretes. The average attenuation provided by concrete with lead and steel fibres is up to 36 %, which is around 50 % more than the attenuation provided by plain or steel reinforced concrete.

Akkurt et al. (2010a) measured linear attenuation coefficient for concrete containing zeolite as an aggregate in different concentrations (0, 10, 30 and 50 %). It was confirmed that the linear attenuation coefficient is function of the photon energy due to the different photon absorption mechanism for different energy regions (Bashter, 1997). It decreased with increasing zeolite concentration and concretes containing zeolite as an aggregate are not suitable for radiation shielding.

Akkurt et al. (2010b) investigated the radiation shielding properties of barite and concrete produced with barite and the results were compared with standard shielding material lead. The linear attenuation coefficient and mean free path have been calculated for 1 keV to 1
GeV and compared with the measurements performed for energies 662, 1173 and 1332 keV. It was concluded that lead is an ideal shield, but barite can also act as alternate shielding material.

Kurudirek et al. (2010) compared the clinoptilolite-rich natural zeolite (CRNZ) with Portland cement with respect to the radiation attenuation properties. The mass attenuation coefficients were calculated by WinXCom program and the results indicate that Portland cement should be used rather than CRNZ for radiation shielding.

Akkurt et al. (2010c) investigated the photon attenuation coefficients of barite and concrete produced with barite using a gamma spectrometer for 662, 1173 and 1332 keV gamma energies. Also the half and tenth value layer values for the selected samples were measured and compared the results with that of lead.

2.3.2 Interaction cross section

The precise knowledge of photon cross sections is important because of their applicability in various fields such as radiation protection, crystallography, medical diagnosis, electron probe microanalysis, etc. Various tabulations of interaction cross sections for various elements and compounds of dosimetric and radiological interest have been published.

The first compilation of photon interaction cross sections due to White (1952) was extended by Storm and Isreal (1958) to include all elements from Z=1 to 100 and McGinnies (1959) further extended it by including energy region of 10-100 keV. Later Davisson (1965), Hubbell (1969, 1977, 1982), Storm and Israel (1970), Scofield (1973) and Chantler (1995, 2000) updated the cross section tabulations for all the elements in the wide energy range. Berger and Hubbell (1987) prepared a database of photon cross section for scattering, photoelectric absorption and pair production as well as total attenuation coefficient in any element, compound or mixture at energies ranging from 1 keV to 100 GeV.

Apart from the above conducted research, numerous investigations have been carried out to measure the photon cross sections at various energies in different composite materials.

Parthasaradhi et al. (1969) experimentally determined the total cross sections for elements Pb, Pt and Sn with energy of 280 keV. A satisfactory agreement between experimental and theoretical values computed with the latest data on photoelectric coherent and incoherent scattering cross sections was reported.
Prasad (1980) measured the total photon interaction cross sections for eight elements in the range Z= 20 to 60 for photon energies of 52.4, 60, 72.2, and 84.4 keV. The photoelectric cross section was obtained by subtracting the scattering cross sections from the measured values of total absorption cross sections and the results were compared with theoretical values.

Umesh et al. (1981) obtained incoherent-scattering cross sections from the total attenuation cross sections in elements Z=1 to 56 for photon energies of 279.2, 514, 661.6, and 1115.5 keV. The total attenuation cross sections in 26 solid chemical compounds were measured with help of mixture rule by gamma ray transmission experiments for good geometry conditions.

Smiles et al. (1982) calculated the total gamma interaction cross sections in O, F and Cl for photon energies of 59.54 keV, 122.06 keV and 136.47 keV by measuring the cross sections in boron trioxide, lithium fluoride and sodium chloride with HPGe detector. The reported results were in good agreement with the theoretical results.

Rao et al. (1985b) determined the atomic cross section for total photon interaction in bone, muscle, liver, spleen, fat and water. From the plot of cross section versus atomic number, the effective atomic number was also deduced.

Sasi et al. (1987) measured total gamma ray cross sections for Pd at 109.78 and 130.52 keV, for Pt at 109.78 keV and for tungsten-steel alloy at 276.4, 302.8, 356 and 383.8 keV with a good geometry setup by using HPGe detector. The reported results were highly accurate.

Jayaraman and Rao (1992) measured the total photon cross sections in 15 compounds and in 3 elements at 7 different photon energies in the range of 145–1120 keV by using a NaI(Tl) detector for good geometry conditions. The atomic cross sections in elements were obtained by using the measured total cross sections per molecule of the compound with the help of mixture rule. The atomic cross sections were compared with the theoretical values of Hubbell-Scofield and Storm and Israel. The results were in good agreement with theoretical results.

Gopinathan Nair et al. (1994) measured the total attenuation cross sections for several sugars and amino acids with gamma ray source $^{133}$Ba in a good geometry setup by HPGe.
detector. They observed these values to be in good agreement with the values calculated from the mixture rule on the basis of Hubbell’s data for the individual elements.

Gopinathan Nair et al. (1995) also measured total attenuation cross sections of several amino acids at 661.6, 1173 and 1332.5 keV gamma rays by HPGe detector and compared with the values calculated with the help of mixture rule from the data of Hubbell.

Kumar et al. (1996a) compared the photo effect cross sections of copper with recently published results of cross sections. It was found that these recently measured experimental cross sections are higher than both un-renormalised and renormalized values of Scofield.

Kaur et al. (2000) measured the total interaction cross section of aqueous solutions of alkali metal chlorides (LiCl, NaCl and KCl) having different concentrations for 81, 356, 511, 662, 1173 and 1332 keV gamma rays. These results were compared with the theoretical values obtained by using mixture rule.

Abdo (2002) calculated the total mass attenuation coefficients for gamma rays and the effective removal cross sections for fast neutrons for four different types of concretes. The theoretical calculations for gamma rays were performed by using XCOM computer program. The calculated results were compared with previously measured values and a reasonable agreement was reported.

Singh et al. (2002b) measured the total interaction cross section of selected amino acids in aqueous solutions at 81, 356, 511, 662, 1173 and 1332 keV gamma rays and the obtained results were compared with the theoretical values.

Gowda et al. (2005) measured the total attenuation cross sections and then calculated effective atomic numbers and electron densities of amino acids and sugars at the energies 30.8, 35.0, 81.0, 145, 276.4, 302.9, 356, 383.9, 661.6, 1173 and 1332.5 keV. The interpolation of total attenuation cross sections was performed using the logarithmic regression analysis of the XCOM data in the photon energy region 30–1500 keV. These values are found to be in good agreement with the theoretical values calculated based on XCOM data.

Kumar et al. (2006a) calculated the total gamma ray interaction cross sections for some commonly used solvents at different gamma ray energies with a narrow beam transmission
geometry set up. A good agreement was reported between the experimental and theoretical results.

Kaewkhao et al. (2007a) determined the total interaction cross sections of the Cu and Zn alloy at 356, 511, 662, 835 and 1275 keV gamma ray energies using NaI(Tl). They observed a good agreement between experimental and theoretical values as calculated through WinXCom.

Kaewkhao et al. (2008b) determined the total interaction cross sections of the Cu and Zn alloy on the basis of the mixture rule at 356, 511, 662, 835 and 1275 keV gamma ray energies by using NaI(Tl) scintillation detection system. It was observed that the mixture rule is a suitable method for determination of radiation interaction parameters.

Han et al. (2009) measured the total mass attenuation coefficients for SiO$_2$, KAlSi$_3$O$_8$, CaSO$_4$.2H$_2$O (gypsum), FeS$_2$ (pyrite) and Mg$_2$Si$_2$O$_6$ (pyroxene) natural minerals for 22.1, 25.0, 59.5 and 88.0 keV photon energies. Atomic and electronic cross sections were determined by using the obtained mass attenuation coefficient values for the investigated samples.

Han and Demir (2009a) measured the total atomic and electronic cross sections for Ti, Ni and Ti$_x$Ni$_{1-x}$ (x = 0.7, 0.6, 0.5, 0.4, 0.3) alloys at photon energies of 22.1, 25.0, 59.5 and 88.0 keV. The total atomic and electronic cross sections were calculated theoretically also and the obtained results for all samples were compared with experimental values.

Han and Demir (2009b) measured total atomic and electronic cross sections from total mass attenuation coefficients for pure Ti, Co, Cu and Ti$_x$Co$_{1-x}$ and Co$_x$Cu$_{1-x}$ (x = 0.8, 0.7, 0.6, 0.5, 0.4, 0.3 and 0.2) alloys for 22.1, 25.0, 59.5 and 88.0 keV photon energies. The X-rays and gamma rays were counted by a Si(Li) detector.

Un and Sahin (2011) determined the total mass attenuation coefficients for PbO, barite, colemanite, tincal and ulexite for 80.1, 302.9, 356.0, 661.7 and 1250.0 keV photon energies by using NaI(Tl) scintillation detector. Total atomic cross section and total electronic cross section were determined experimentally and theoretically. The calculated values were compared with the experimental values for all samples.

El-Khayatt et al. (2014) investigated interaction cross section of some heavy metal oxide glasses, using the MCNP-4C code. By changing the photon energy and chemical composition of glasses, an appreciable variation is noted in interaction cross section. Good
agreement between simulated results and the experimental data was reported. It was indicated that Monte Carlo Method is quite useful for making calculations of different glass systems.

2.3.3 Effective atomic number

Hine pointed out that for photon interactions in the composite materials composed of several elements, the atomic number cannot be represented uniquely by a single number across the entire energy region, which is there always in the case of pure elements. This statement is in resonance with the findings of Spiers (1946) and Hine (1952) who proposed the concept of “effective atomic number” \( (Z_{\text{eff}}) \) to be used for composite materials in various applications. For each of the different processes, by which X-rays and gamma rays can interact with matter, the various atomic numbers in the material has to be weighted differently. Also Murty (1965) concluded that different effective atomic numbers for different gamma ray processes might be required for a heterogeneous material. Accordingly, the effective atomic number is not a constant for a given material. It varies with photon energy depending upon the interaction processes involved. Only in the case of Compton scattering, \( Z_{\text{eff}} \) is constant over a wide energy range. Effective atomic number is a useful parameter for characterizing the X-ray and gamma ray response of multi-element materials. Among early applications one may mention the detection of slight differences in the effective atomic number of bone and soft tissues and the measurement of the fat content of liver.

Sastry and Jnanananda (1958) calculated the effective atomic number for total and partial photon interaction processes by interpolation method. The generated numbers for the total photon interaction process were greater for photoelectric interaction and lesser for pair production than that for the total interaction.

Parthasaradhi (1968) determined \( Z_{\text{eff}} \) of some alloys for partial as well as total interaction process in the energy range of 100–662 keV from the plot of experimental cross section versus atomic number of individual elements.

Yang et al. (1987) later introduced a new method in which the total photon interaction cross section per electron is used to derive the effective atomic number. They showed that \( Z_{\text{eff}} \) of soft human tissues, such as blood, brain, heart, liver, etc. are equal from 10 to 200 keV within 4 % variation, whereas large variations are observed for bones of different chemical composition.
Mudahar and Sahota (1988b) computed the $Z_{\text{eff}}$ of twelve different soils for the total photon interactions in the energy range of 10 keV to 5 MeV. They reported the change in effective atomic number in different energy regions due to dominance of different interaction processes.

El-Kateb and Abdul Hamid (1991) measured $Z_{\text{eff}}$ in the energy range from 54 to 1332 keV for 13 different materials containing hydrogen, carbon and oxygen. They suggested that $Z_{\text{eff}}$ of these low-Z materials is independent of energy, provided the contributions from the photoelectric effect and pair production are negligible.

Mudahar et al. (1991a) calculated the $Z_{\text{eff}}$ for 5 different soils for different interaction processes in the energy region 10 keV to 100 MeV. They reported that $Z_{\text{eff}}$ first increases with increase in energy to 30-40 keV, decreases up to 2 MeV and then continuously increases with energy up to 100 MeV.

Mudahar et al. (1991b) studied the variation of $Z_{\text{eff}}$ of eight different alloys for the total and partial photon interaction processes in the energy region 10 keV to 100 GeV. It was reported that in all alloys, $Z_{\text{eff}}$ initially increases to the maximum value and then decreases to the minimum value with increase in energy, after which $Z_{\text{eff}}$ again starts increasing with further increase in energy. It was further reported that maximum and minimum values of $Z_{\text{eff}}$ are at different energies for different alloys.

Bhandal et al. (1992) determined the effective atomic number of some fatty acids in the energy range of 356–1116 keV. $Z_{\text{eff}}$ for each sample was found to be independent of energy in line with the results of El-Kateb and Abdul Hamid (1991).

Singh and Mudahar (1992) calculated $Z_{\text{eff}}$ for low-Z materials (water, perspex, polyethylene, polystyrene and bakelite) for total and partial interaction processes in the energy range 10 keV to 100 MeV. They reported that $Z_{\text{eff}}$ decreases with increase in energy from 10 keV to 150-200 keV, constant in the energy range 200 keV to 2.3 MeV and increases with further increase in energy.

Kumar et al. (1996b) calculated effective atomic numbers of different clay minerals for total photon interaction in the energy region of 10 keV to 10MeV. Its variation with energy was compared with similar studied made for alloys and compounds.
El-Kateb et al. (2000) determined effective atomic numbers of some alloys such as brass, bronze, steel, aluminium-silicon, lead-antimony for 81, 356, 511, 662, 835, 1274 and 1332 keV gamma ray energies using NaI(Tl) detector. The results confirmed the validity of the mixture rule for alloys.

Gagandeep et al. (2000) determined the effective atomic numbers for glucose, maltose monohydrate, and sucrose for 81, 356, 511, 662, 1173, and 1332 keV in a good geometry set up. They reported that the experimental results are in line with their theoretical values computed with the help of a piece wise interpolation computer program.

Shivaramu (2002) computed the $Z_{\text{eff}}$ for some human organs and tissues such as cortical bone, ovary, eye lens, testis, breast tissue, adipose tissue, lung tissue, soft tissue, soft tissue (4-component), blood (whole), brain (grey/white matter), skeletal muscle in the energy region of 1 keV to 20 MeV. The effect of absorption edge and its variation with photon energy were also investigated.

Gowda et al. (2004) determined mass attenuation coefficients of some thermoluminescent dosimetric (TLD) compounds viz. LiF, CaCo$_3$, CaSO$_4$, CaSO$_4$.2H$_2$O, SrSO$_4$, CdSO$_4$, BaSO$_4$, C$_4$H$_6$BaSO$_4$ and 3CdSO$_4$.8H$_2$O for energies 279.2, 320.07, 514.0, 661.6, 1115.5, 1173.2 and 1332.5 keV with well collimated narrow beam good geometry setup using a high resolution, hyper pure germanium detector. The values of the effective atomic numbers of TLD compounds were in agreement with the already available data.

Icelli et al. (2005) measured effective atomic numbers for CuCoNi alloys against changing Ni contents in the X-ray energy range from 15.746 to 40.930 keV. Also, the total effective atomic numbers of each alloy were estimated using mixture rule and these were compared with the measured values.

Singh et al. (2006b) calculated the effective atomic number of lead and bismuth borate flyash glasses from the measured values for mass attenuation coefficient at gamma ray energies of 81, 356, 511, 662, 1173 and 1332 keV.

Manohara and Hanagodiamth (2007) calculated the effective atomic number of some amino acids viz. histidine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine for partial and total photon interactions in wide energy range of 1 keV-100 GeV.
The variation of effective atomic numbers with change in energy was studied for all photon interactions.

Singh et al. (2007) determined the effective atomic number for some commonly used solvents such as acetonitrile, butanol, chlorobenzene, diethyl ether, ethanol, methanol, propanol, water in the energy range 10 keV to 100 GeV. Effective atomic number was reported to be constant in the intermediate energy region (0.1-5 MeV) and significant variation in lower (10-100 keV) and upper (5MeV-100GeV) energy regions.

Cevik et al. (2008) measured mass attenuation coefficients for Cd, Se, Te in elemental state and semiconductor CdSe, CdTe at different energies from 9.7 to 87.3 keV by using the secondary excitation method. These energies were obtained using secondary targets such as Br, Sr, Mo, Cd, In, Sn, Sb, La, Eu, Tb, Yb, W, Au, Hg, Tl, Pb, and Bi. The variation of effective atomic numbers with photon energy in CdSe and CdTe semiconductors was explained.

Manohara et al. (2008) gave a comprehensive and consistent set of formulas for calculating the effective atomic number and electron density for all types of materials and for energies greater than 1 keV. The formulas used were derived from first principles using photon interaction cross sections of the constituent atoms. The theory was illustrated by calculations and experiments for molecules of medical and biological interest, glasses for radiation shielding, alloys, minerals and liquids.

Ozdemir and Kurudirek (2009) determined effective atomic numbers for 21 different compounds at 59.54 keV using a narrow beam good geometry setup. The effective atomic numbers determined on the basis of mixture rule were compared with the calculated ones from theory. Also, the obtained values of effective atomic numbers have been compared with the ones calculated according to a different approach proposed by Hine (1952).

Bastug et al. (2010) measured effective atomic numbers for PbO, Na₂B₄O₇·10H₂O, (UO₂(NO₃)₂ and Na₂B₄O₇·10H₂O mixtures against changing contents of PbO, Na₂B₄O₇·10H₂O, and UO₂(NO₃)₂ in the X-ray energy range from 25.0 to 58.0 keV. The total effective atomic numbers of each mixture were estimated by using the mixture rule. The measured values were compared with estimated values for the mixtures.
Kurudirek and Topcuoglu (2011) calculated the effective atomic numbers and electron densities of human teeth for total photon interaction in the energy region of 1 keV–20 MeV. Effective atomic numbers of human teeth were calculated using different methods. Discrepancies were noted in $Z_{\text{eff}}$ between the direct and interpolation methods in the low and high energy regions where absorption processes dominate while good agreement was observed in intermediate energy region where Compton scattering dominates.

Chanthima et al. (2012) calculated the effective atomic number of $xR_mO_n: (1-x)\text{SiO}_2$ glass system (where $R_mO_n$ are $\text{Bi}_2\text{O}_3$, $\text{PbO}$ and $\text{BaO}$) by theoretical approach using WinXCom program in the energy region from 1 keV to 100 GeV. It has been observed that the value of $Z_{\text{eff}}$ changed with energy and composition of the silicate glasses.

Latha et al. (2012) measured effective atomic numbers of various combinations of elements with $13 \leq Z \leq 50$ and the results compared with the theoretical values obtained using XCOM and the values calculated with an empirical formula. The coherent and incoherent scattering contributions were subtracted from the measured total cross section to obtain the photoelectric cross section and corresponding effective atomic numbers were also determined. The results were in good agreement with empirical estimations.

Chanthima and Kaewkhao (2013) calculated the radiation shielding parameters of $(50-x)\text{SiO}_2: 15\text{B}_2\text{O}_3: 2\text{Al}_2\text{O}_3: 10\text{CaO}: 23\text{Na}_2\text{O}: x\text{Bi}_2\text{O}_3$ glass systems (where $x = 0, 5, 10, 15$ and 20 mol%) by using WinXCom program. For the medium energy region, the effective atomic number obtained was close to the mean atomic number dominated by Compton scattering process.

Kurudirek (2014a) calculated the effective atomic numbers of different types of materials such as tissues, tissue equivalents, organic compounds, glasses, dosimetric materials for total proton interactions in the energy region of 1 keV–10 GeV. Some human tissues were investigated in terms of tissue equivalency by comparing $Z_{\text{eff}}$ values. The values of $Z_{\text{eff}}$ were found to be constant for photographic emulsion after 1 GeV, for calcium fluoride between 1 MeV and 1 GeV and for silicon dioxide, aluminum oxide and Teflon between 400 keV and 1 GeV.

Kurudirek (2014b) calculated effective atomic numbers of 107 different materials of dosimetric interest for total electron interactions in the wide energy region of 10 keV to 1 GeV.
The tissue equivalent materials have been compared with the tissues and dosimetric materials in terms of $Z_{\text{eff}}$ to reveal their ability to use as tissue substitutes.

Yasaka et al. (2014) investigated the radiation shielding properties of zinc bismuth borate (ZBB) glasses of the composition $10\text{ZnO}: x\text{Bi}_2\text{O}_3: (90-x)\text{B}_2\text{O}_3$ (where $x = 15, 20, 25$ and $30 \text{ mol\%}$). The results indicated a decrease of the effective atomic number and effective electron density values with increasing of gamma ray energies and good agreements between experimental and theoretical values was reported.

### 2.3.4 Electron density

The scattering and absorption of gamma rays is directly concerned with electron density of the material. Electron density, defined as the number of electrons per gram of material, is another important parameter for understanding the interaction of photons with the composite materials.

El-Kateb and Abdul Hamid (1991) calculated electron densities for different substances containing C, H and O in the energy range of 54 to 1333 keV. A relationship, linear in nature was obtained for electron density and weight fraction of hydrogen, but not for weight fractions of carbon and oxygen.

Sandhu et al. (2002) determined electron densities in some fatty acids viz. formic acid, acetic acid, propionic acid, butyric acid, $n$-hexanoic acid, $n$-caprylic acid, lauric acid, myristic acid, palmitic acid, oleic acid, stearic acid with narrow beam transmission geometry for photon energies of 81, 356, 511, 662, 1173 and 1332 keV. The results were compared with their theoretical values.

Singh et al. (2002a) calculated electron densities in bismuth borate glasses at five different concentrations of Bi$_2$O$_3$ and B$_2$O$_3$ for gamma ray energies of 356, 662, 1173 and 1332 keV. A good agreement was reported for the obtained values of electron densities with the theoretical values.

Singh et al. (2002c) measured electron densities of bakelite, black cement, white cement, plaster of paris, concrete and glass having oxides of B, Cd, Pb, and Bi at gamma energy of 662 keV. A good correlation between the calculated and experimental values was reported by them.
Singh et al. (2003a) determined the electron densities for the varying concentration of ZnO, PbO and B$_2$O$_3$ in ZnO-PbO-B$_2$O$_3$ glasses at the incident photon energies of 511, 662, 1173 and 1332 keV. A very little variation of electron density was observed change in photon energy.

Singh et al. (2006b) measured mass attenuation coefficient of lead and bismuth borate flyash glasses for 81, 356, 511, 662, 1173 and 1332 keV gamma rays. They reported that for a particular energy, the value of calculated electron density shows a linear decrease with an increase in the heavy-metal oxide content. For a particular composition, the electron density decreases with increase in the incident gamma ray photon energy.

Cevik and Baltas (2007) determined the electron densities for Bi, Pb, Sr, Ca, Cu metals, Bi$_2$O$_3$, PbO, SrCO$_3$, CaO, CuO compounds and solid state forms of Bi$_{1.7}$Pb$_{0.3}$Sr$_2$Ca$_2$Cu$_3$O$_{10}$ superconductor for 57.5, 65.2, 77.1, 87.3, 94.6, 122 and 136 keV energies and studied effect of absorption edges on it. They reported that electron density increases linearly with an increase in Z$_{eff}$.

Baltas and Cevik (2008) calculated the electron densities of YBa$_2$Cu$_3$O$_{7-\delta}$ superconductor at 59.5, 65.2, 77.1, 94.6, 122 and 136 keV by using the measured mass attenuation coefficients. Measurements were made by performing transmission experiments in a well collimated narrow beam geometry setup with Si(Li) detector. The experimental results indicated good agreement with the theoretical values.

Ozdemir and Kurudirek (2009) determined effective electron densities for 21 different compounds at 59.54 keV using a narrow beam good geometry setup. The electron densities have been determined on the basis of mixture rule using the values of total mass attenuation coefficients and compared with the calculated ones from theory.

Onder et al. (2012) determined the effective electron density experimentally and theoretically for some thermoluminescent dosimetric (TLD) compounds at 8.04, 8.91, 13.37, 14.97, 17.44, 19.63, 22.10, 24.90, 30.82, 32.06, 35.40, 36.39, 37.26, 43.74, 44.48, 50.38, 51.70, 53.16, 80.99, 276.40, 302.85, 356.01, 383.85 and 661.66 keV photon energies by using an HPGe detector. The theoretical mass attenuation coefficients were estimated using mixture rule. The calculated values were compared with the experimental values for all compounds.
Un and Sahin (2012) calculated effective electron numbers for Earth and Martian soils in the energy range from 1 keV to 100 GeV. The values of mass attenuation and absorption coefficients used in calculations are taken from the WinXCom program and data base.

Pawar and Bichile (2013) measured the effective electron densities ($N_{\text{eff}}$) of some amino acids, such as glycine, DL-alanine, proline, l-leucine, l-arginine, l-arginine monohydrochloride at 122, 356, 511, 662, 1170, 1275 and 1330 keV photon energies using a well collimated narrow beam good geometry setup. It was obtained by using the experimental attenuation coefficients of amino acids. The results indicated that the experimental values of effective electron densities were in good agreement with the theoretical values.

Un and Demir (2013) calculated the effective electron numbers values for different 16 heavy-weight and normal-weight concretes in the energy range from 1 keV to 100 GeV. The values of mass attenuation coefficients used in calculations were taken from the WinXCom computer program. The results of heavy weight concretes fairly differ from results for normal-weight concretes.

Ahmadi et al. (2013) calculated electron densities of bacteriorhodopsin, a proton pump protein in cell membrane of Halobacterium salinarium and its comprising amino acids by using theoretical values of mass attenuation coefficients obtained from WinXCom program for photon energies from 1 keV to 100 GeV.

Kurudirek (2014c) calculated the electron densities for some human tissues and dosimetric materials such as adipose tissue, bone cortical, brain grey/white matter, breast tissue, lung tissue, soft tissue, LiF TLD-100H, TLD-100, water, borosilicate glass, PAG, fricke and OSL using mean photon energies of various radiation sources. Different calculation methods for $Z_{\text{eff}}$ such as the direct method, the interpolation method and Auto-$Z_{\text{eff}}$ computer program were used and agreements and disagreements between the used methods were reported.

Kore et al. (2014) measured the electron densities of some amino acids, such as dl-aspartic acid-LR, l-glutamine, creatine monohydrate, creatinine hydrochloride, l-asparagine monohydrate, l-methionine for 122, 356, 511, 662, 1170, 1275 and 1330 keV photon energies using a well collimated narrow beam good geometry setup. It was observed that the effective atomic number ($Z_{\text{eff}}$) and effective electron densities ($N_{\text{eff}}$) initially decrease and tend to be
almost constant as a function of gamma ray energy. Their results showed good agreement with the theoretical values.

Un and Caner (2014) developed the Direct-Z\textsubscript{eff} software for the computation of the effective electron number per unit mass (N\textsubscript{eff}) in the energy range 1 keV–100 GeV. The values of the N\textsubscript{eff} can be determined for total photon interaction with and without coherent interaction as well as partial photon interactions such as coherent scattering, incoherent scattering, photoelectric absorption and pair production by using the Direct-Z\textsubscript{eff} software. The accuracy of the Direct-Z\textsubscript{eff} software was demonstrated by comparing the calculated data and the experimental values for the various materials.

2.3.5 Multiple scatter peak

The shielding used for protecting humans from harmful effects of radiation can lead to buildup of photons due to multiple scattering of photons inside the thick shielding material. It has been experimentally found with any material of thickness greater than 1 mean free path (mfp), attenuation results vary from theoretical results. This may be due to multiple scattering of photons. A medium having longitudinal thickness large or simultaneous large longitudinal and transverse dimensions can lead to multiple scatter peak of photons in soft part of transmitted photon spectrum.

Alberg et al. (1967) reported a distinct energy line of low energy in the continuous spectrum of the air-like medium. It is because of gamma photons multiple scattered by the medium.

Swarup and Ganguly (1975) studied skyshine spectra from a 650 Ci \textsuperscript{60}Co source placed at the center of gamma irradiation field of radius 90 m surrounded by stone wall. They found that spectrum has a pronounced peak at 72 keV for all distances and no evidence was there in the spectra for the presence of primary gamma photons. It was reported that this 72 keV peak is a property of the scattering medium and not of incident photon energy.

Swarup and Ganguly (1977) also reported observations of counts-spectra of gamma rays backscattered by infinite air, measured with NaI(Tl) collimated detector pointing vertically upwards at different distances from the source.
Hydo (1962) studied the background radiation spectra measured by scintillator spectrometer from semi-infinite slabs of paraffin, aluminium, iron, tin and lead. The measurements were conducted by placing point sources of $^{60}$Co and $^{137}$Cs in close contact with the scattering slabs. The background radiation was measured through angle between the normal to the plane face of the slabs and the detector axis. No perturbing effect was produced by the detector or source collimating shields.

Smith and Scofield (1972) calculated the gamma ray backscattering results for semi-infinite media of aluminium and iron by using the moments method. From the experimental results and calculated albedo spectra results, it was clear that the calculated albedo distributions were higher in the multiple scattering area for angles greater than 130°.

Burst (1972) reported that multiple scatter peak appears at different energies for different atomic number media.

Minato (1973) used Monte Carlo method for obtaining energy spectra of scattered gamma rays. The spectra were obtained with different collimation conditions. From low energy components of spectra, it was reported that these are affected mainly by the atomic number of sample used for scattering. He developed theory by considering homogeneous medium of infinite thickness and that photons slow down continuously. The relation between the position (energy) of multiple scatter peak as appeared in spectrum and effective atomic number of sample (scatterer) was given by:

$$E = 9.09 \times (Z_{\text{eff}})^{0.899} \times 10^{-3} \text{MeV}$$

This relation was given after experiments with different source energies for different target thicknesses.

Bishop (1979) has reviewed energy and angle spectra of gamma ray penetration through different media. Miyasaka et al. (1978) and Nason et al. conducted studies for air-scattered spectra and concluded that spectra has a maxima between 50 and 90 keV.

Swarup (1979a) obtained skyshine spectrum from 650 Ci point source of $^{60}$Co backscattered by infinite air. The spectrum shows a peak at around 70 keV. This peak is a property of the infinite scattering medium.
Swarup (1979b, 1980) conducted study for gamma photons backscattered in the vertical direction by infinite air. From the spectra obtained by Gold’s iterative technique, it was reported that a peak appeared at 72 keV due to multiple scattered photons. He explained the peak due to balance of photoelectric and Compton cross sections for the multiple scattered photons. The absorbed dose measurements in the nuclear installations should be sensitive to respond to 72 keV gamma photons along with general considerations of radiation.

Swarup and Minato (1983) used Monte Carlo method to obtain multiple scatter spectra of gamma radiation of 1250 keV energy in infinite air, air over ground and infinite ground media. The scattered spectra, in air and ground, calculated with respect to number of scatterings in the media show that a maxima is obtained between 47 and 95 keV energy after five scatterings. It was concluded that the scattered flux can be represented by the diffusion equation.

Swarup et al. (1983) measured the transmitted spectra of $^{241}$Am, $^{57}$Co, $^{203}$Hg, $^{137}$Cs and $^{60}$Co point sources through several mean free path thickness of water. It was reported that spectra show a peak at 60 keV due to multiple scattering of gamma rays. It is independent of the energy of source used in study. They also concluded that it is not a single peak but a band of continuous energies with maximum intensity at 60 keV.

Swarup and Peshori (1985) reported that a multiple scatter peak in water is observed at energy below 100 keV where Compton scattering is not effective in degradation of photon energy and photon cross section is negligible. Also the energy of peak does not depend on the thickness and physical state of the medium from the results of transmitted photon spectra for water and ice. The intensity of the peak decreases with increase in thickness of the medium.

Swarup and Peshori (1986a) measured the gamma ray spectra of point sources $^{241}$Am, $^{57}$Co and $^{203}$Hg for different thicknesses of nuclear grade graphite and unfolded these spectra by iterative technique. The spectra show multiple scatter peak at energy of 50 keV and it does not depend on the photon energy of source. The intensity of the peak decreases exponentially increase in thickness of the medium.

Swarup and Peshori (1986b) gave a relation for the transmitted gamma ray flux in water and graphite for sources $^{241}$Am, $^{57}$Co and $^{203}$Hg for the total and multiple scatter peak spectra.
The representation is suitable for the studied target thicknesses and is in good agreement with Lambert-Beer law.

Singh et al. (1993) studied the transmitted spectra of gamma sources $^{133}\text{Ba}$, $^{137}\text{Cs}$ and $^{60}\text{Co}$ for different thicknesses of soil. They reported that multiple scatter peak at around 100 keV, which is independent of photon energy and medium thickness. A relationship, linear in nature, was observed between energy of multiple scatter peak and the effective atomic number of medium.

Bhandal et al. (1994) studied transmitted photon spectra of $^{133}\text{Ba}$, $^{22}\text{Na}$, $^{137}\text{Cs}$, $^{54}\text{Mn}$ and $^{60}\text{Co}$ through different thicknesses of materials. They reported multiple scatter peak of water, concrete and sand at 60, 90 and 100 keV respectively. The energy of multiple scatter peak is independent of thickness of the medium. The calculated values of multiple scatter coefficients decrease with increase in incident photon energy.

Swarup (1994) investigated the effect of transverse dimensions on the multiple scattering for $^{203}\text{Hg}$ source through graphite medium. He reported that intensity of multiple scattered part increases with transverse thickness and reaches a maximum for 5 mean free path thickness of the material.

Sidhu et al. (2000) studied the transmitted photon spectra of $^{133}\text{Ba}$ as a function of soil medium dimensions (longitudinal and transversal) and a multiple scatter peak is reported in the soft part of the spectrum. They reported that the variation in longitudinal thickness of soil medium affects only intensity of peak while variation in transverse thickness affects both intensity and energy of peak.

Singh et al. (2005) measured the transmitted photon spectra of $^{60}\text{Co}$ through the longitudinal and transverse dimensions of soil medium. They reported that intensity of peak decreases exponentially with increase of longitudinal thickness and a reversal trend of exponential decrease in multiple scatter peak intensity with transverse thickness is observed. Also this behaviour becomes clearer with increase in longitudinal thickness.

Sidhu et al. (2006) again measured the transmitted photon spectra through the longitudinal and transverse dimensions of soil medium, but for $^{137}\text{Cs}$ gamma source. The multiple scatter peak behaves in a similar manner as in the case of findings of Singh et al.
(2005), irrespective of the gamma ray source used in study. From the study results, it is clear that soil medium takes part as a whole in multiple scattering of transmitted photons.