# RADIATION SHIELDING POTENTIAL OF ULTRA-HIGH STRENGTH CONCRETE FROM AGRO-INDUSTRIAL WASTE

by

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**Ultra-high strength concrete produced with agro-residual wastes and industrial by-products were tested for radiation shielding capacity by measuring the linear attenuation coefficient, half value layer and tenth value layer. The linear attenuation test results, show that the ultra-high strength concrete with agro-residual and industrial wastes can be effectively employed in shielding the radiation. The half value layer results reveal that radiation shielding concretes can be produced using industrial and agro-residual wastes, by concentrating equally on the enhancement of both the homogeneity and density of the concrete matrix. The ultra-high strength concrete developed in this investigation registered a better radiation shielding properties than that of the conventional anti-radiation shielding concretes with high dense aggregates which are costlier and found to have environmental degradation along with the health hazards.**

*Key words: ultra-high strength concrete, radiation, linear attenuation coefficient, half value layer, tenth value layer*

## INTRODUCTION

In recent past, many researchers investigated the radiation shielding properties of various concretes. Sharma *et al*. [1] investigated the mechanical and radiation shielding properties of fibre reinforced concrete with steel fibres, lead fibres and a combination of the two (hybrid fibres). It was observed that the hybrid fibres showed a significant enhancement in both mechanical and radiation shielding properties. Demir *et al*. [2] investigated the concrete with different aggregates such as barite, colemanite and normal aggregate. It was concluded that the barite was effective for photon radiation absorption, while colemanite was good absorbent to prevent for neutron transmission. Similarly, Zaripova *et al*. [3] suggest that concrete with barite is effective in shielding material for nuclear power plants and medical centres. Korkut *et al*. [4] prepared four barite and four concrete samples with 0 %, 5 %, 10 %, and 15 % colemanite concentrations, and carried out neutron dose transmission measurements by using a source of mono-energetic neutrons. The study revealed that it is possible to enhance the neutron shielding property of barite and ordinary concrete by adding higher quantities of colemanite. Rezaei-Ochbelagh and Azimkhani [5] studied the gamma-ray shielding properties of concrete mixed with different percentages of lead used. The linear attenuation coefficient (LAC) of concrete with 90 % of lead was about 1.58 and 1.38 times higher than that of the concrete without lead. Mesbahi *et al*. [6] studied the effect of high-density concrete on photo neutron production in radiation therapy using Monte Carlo simulations. It has shown that the high-density elements such as iron and lead increase the photo neutron production in concrete walls of radiation therapy bunkers.

Ouda [7] analysed the effects of replacing sand by iron slag on the compressive strength, bulk density and gamma-ray radiation shielding properties. It was observed that the full sand replacement by iron slag has significant effects on shielding efficiency in thin shields. It reduces the captured gamma-rays better than the normal mortar. Ouda [8] investigated the air-cooled slag as an innovative substitute for natural coarse aggregate in high performance heavy density concrete. Concrete mixes containing air-cooled slag aggregate along with their fine portions and treated with 0.5 % borax showed the best ability to shielding against fast neutrons.

Elsharkawy and Sadawy [9] investigated the effect of gamma-ray energies and addition of nano-$SiO_2$ in cement on mechanical properties and mass attenuation coefficient (MAC). It was concluded that the addition of nano-$SiO_2$ articles improves mechanical and nuclear properties of concrete. Kumar and Singh [10]

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studied the effects of different percentages of bismuth-ground granulated blast furnace slag (Bi-GGBFS). It found that Bi-GGBFS concrete as gamma radiation shielding materials are good radiation shielding material. Yao *et al*. [11] investigated the mechanical performance and gamma-ray shielding by adding bismuth oxide. Concrete mixture with lead used for comparison. Concrete incorporated with the $Bi_2O_3$ additive offered slightly better radiation attenuation properties than those incorporated with the PbO additive. From the past literature studies, the ultra-high strength concrete (UHSC), a specialized type of concrete characterized by its high compressive strength, has not been tested for its radiation shielding ability by any of the researcher. To evaluate the radiation shielding capability, the UHSC is produced with sugarcane bagasse ash, rice husk ash, ground copper slag (GCS), and waste granite sand (WGS).

The basic mixture of concrete, composed of hydrogen and other light nuclei, helps it in acquiring the high atomic number, which makes concrete to effectively attenuate the radiation [7]. Further with the addition of natural heavy weight aggregates such as magnetite, hematite limonite, barite, bauxite, serpentine, and artificial aggregate additives like iron punching and lead shots, the attenuation properties of concrete can be improvised to a greater extent [12]. The concretes of such type are generally referred as high-density concrete (HDC) whose density varies from 2800 $kgm^{-3}$ depending on the type of coarse aggregate used in the production. The use of special aggregates has been proved to enhance the shielding characteristics of concrete, but the production process of these aggregates include some environmental degradation which causes health hazards due to the exposure to the toxic powders emitted from crushing of the heavy weight minerals needed to form aggregates [11]. Also, the cost of these materials is high and their availability is limited [13]. The use of environmentally friendly materials and industrial wastes for the concrete is in the current focus of research to produce economical products with good qualities and to find a way for disposing the wastes effectively. So far, in the research on radiation shielding concrete, the focus has been on developing HDC with different types of natural and artificial aggregates, filler materials and changing the material composition of the conventional HDC, with a main focus on increasing the density of the concrete.

The research focusing on improving the homogeneity has not been carried out on concretes used for radiation shielding. As like normal strength concrete, high strength concrete has a reduced homogeneity among the binder pastes and at the zone between interaction of binder and aggregates. Still, the increased load carrying capacity of HDC, when compared to concrete with normal density, is credited to the high compressibility nature of heavy weight aggregates used in its production. The research concentrating on the influence of nature of the hardened binder structure on radiation shielding of is almost nil.

In the current investigation, the hypothesis is that the development of concrete by combining the concept of high homogeneity along with high density would result in a concrete product with enhanced radiation shielding. The choice of concrete type in the current investigation is UHSC, which has been proven by many researchers to have high homogeneity [14]. It is considered that high homogeneity of concrete would improve the radiation shielding property. When combined with high density industrial wastes as aggregates, the radiation shielding will further be enhanced. Therefore, the UHSC produced with agro-residual wastes such as treated bagasse ash (TBA) and treated rice husk ash (TRA) as replacement for cement and industrial wastes such as GCS and WGS as replacement for quartz sand was tested for the radiation shielding efficiency. The availability of literature on radiation shielding property of UHSC is almost nil and the current investigation is considered to be the first in this category.

## RADIATION SHIELDING CHARACTERISTICS OF UHSC

### Radiation attenuation test

In the present investigation, radiation shielding characteristics of UHSC was investigated using the facility available in Government Hospital at Madurai, Tamil Nadu, India. Radiation shielding test was performed using radioactive source of $^{60}Co$ with energy level of 1.173 MeV and 1.333 MeV which can be assumed as single source with average energy of 1.125 MeV with exposure rate constant of 127. The specimen was tested for counting time of 1 minute. The LAC ($\mu$) of the specimen was measured by ion chamber detector. The MAC of specimen ($\mu/\rho$) was calculated by density of specimen ($\rho$). The test set up for radiation attenuation test is shown in fig. 1.

## RESULTS AND DISCUSSION

The test for evaluating the radiation shielding capacity of UHSC was carried out on the samples with mix category that has proved to have better strength and durability properties. The UHSC produced individually with 15 % of TBA and TRA as partial replacement for cement has exhibited better strength and durability. In case of quartz sand replacement, UHSC having different proportions of GCS ranging from 10 % to 60 % and WGS ranging from 10 % to 40 % has shown better strength and durability enhancements. Hence in this investigation, the radiation shielding behaviour has been

**Figure 1. Test set-up for radiation attenuation**

evaluated for the above selected samples subjected to normal, steam and heat curing regimes. The samples were subjected to a radioactive source of $^{60}$Co with energy level of 1.173 MeV and 1.333 MeV which can be assumed as single source with average energy source of 1.125 MeV. The source exhibited an exposure rate constant of 127. The specimens were tested for counting time of 1 minute. The LAC $\mu$ of the specimens was measured by ion chamber detector. Using the linear coefficient values, the MAC, half value layer (HVL), and tenth value layer (TVL) were calculated. The test was carried out on UHSC samples of size 150 mm × 150 mm and 10 mm thick tile specimen as shown in fig. 2.

### Linear attenuation coefficient

The LAC indirectly measures the intensity of a photon beam as it passes through an absorber material, indicating the rate at which the beam attenuates while traversing the material. It depends not only on the intensity of the photon energy but also based on the type and density of the material. In general, it has been reported in various literatures that higher the LAC values of concrete better the radiation shielding. To investigate the influence of steel fibre on linear attenuation behaviour, control concrete sample without fibre was prepared and subjected to the radiation energy source. The LAC values for different samples of UHSC prepared in this investigation are given in tab. 1.


**Figure 2. Test sample for linear attenuation test**

**Table 1. The LAC of UHSC**

| Mix designation | LAC [cm$^{-1}$] | | |
|---|---|---|---|
| | Normal curing | Steam curing | Heat curing |
| CMWF | 0.074 | 0.095 | 0.107 |
| CM | 0.108 | 0.117 | 0.126 |
| TBA15 | 0.110 | 0.123 | 0.127 |
| TRA15 | 0.109 | 0.120 | 0.127 |
| GCS10 | 0.148 | 0.162 | 0.167 |
| GCS20 | 0.171 | 0.185 | 0.210 |
| GCS30 | 0.205 | 0.229 | 0.234 |
| GCS40 | 0.234 | 0.244 | 0.264 |
| GCS50 | 0.254 | 0.275 | 0.285 |
| GCS60 | 0.269 | 0.285 | 0.290 |
| WGS10 | 0.112 | 0.130 | 0.144 |
| WGS20 | 0.139 | 0.157 | 0.162 |
| WGS30 | 0.157 | 0.185 | 0.200 |
| WGS40 | 0.195 | 0.224 | 0.239 |

The LAC value in cm$^{-1}$ for the control mixture without fibre (CMWF) was 0.074, 0.095, and 0.107 for normal, steam and heat curing, respectively. Those values for the UHSC with the addition of steel fibre were 0.108, 0.117, and 0.126, respectively. Figure 3 presents the LAC values for control mix (CM) with and without steel fibres.

The results show that the addition of steel fibres considerably increases the attenuation. The reason for this is the micro aggregate behaviour of micro steel fibres because of their dimension, which is 0.12 mm diameter and 10 mm length. It has been reported by Azeez *et al*. [15] and Maslehuddin *et al*. [13], in their research, that the addition of iron granules and steel shots have improved the radiation shielding, as the addition of these materials increased the density of the respective concretes, thereby improving the linear attenuation. The same can be related to the attenuation improvement of fibre reinforced UHSC specimens. The manufacturer of the fibre has reported in their datasheet, that one kilogram of fibres has approximately 11,32,000 individual fibres and these fibres act as micro aggregates to effectively attenuate the radiation. In the present investigation, LAC of CMWF sub-

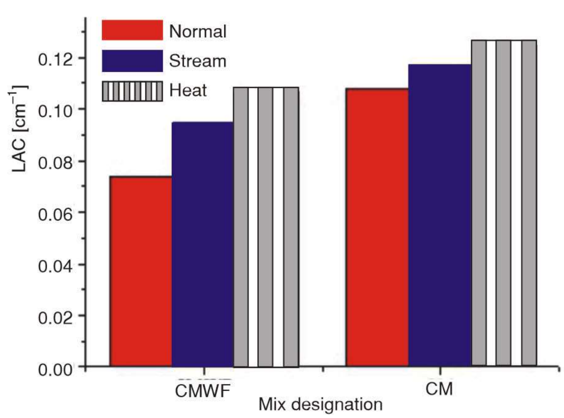


**Figure 3. The LAC for CM with and without fibre**

jected to normal curing was 0.074 $cm^{-1}$ with 10 mm thick sample and this value was almost twice that of HDC produced with magnetite as a coarse aggregate, as reported by Ouda [7], on testing a sample of 20 mm thick. This clearly shows that UHSC can be effectively used in shielding the radiation with minimum thickness when compared with HDC.

In the presence of TBA and TRA it has been registered an increase in resistance to radiation under different curing regimes and that is shown in fig. 4. It can be said that the addition of TBA and TRA in the UHSC mix has a positive effect on the attenuation performance of UHSC. This increase in attenuation is due to the incorporation of additional crystalline C-S-H [9]. A similar finding has been reported by Azeez *et al.* [15] based on their research on evaluating the influence of blast furnace slag on the linear attenuation of anti-radiation shielding concrete. The addition of supplementary cementitious materials will have significant improvement in the attenuation behaviour of concrete.

It has been emphasized in previous research works that the radiation shielding properties of concrete can be improvised considerably by making modification in the aggregates rather than on the binders. Similarly, the UHSC with aggregate replacement by industrial wastes has shown improvement in LAC values. Drastic increase in values of LAC was observed with the incorporation of GCS in UHSC matrix and the variation in LAC values with the GCS content is presented in fig. 5.

A significant increase in attenuation was observed even for a minimal replacement of 10 % of quartz sand with GCS and the percentage increase in attenuation was about 37 %, 32 %, and 39 % when compared with the corresponding CM for specimens subjected to normal, steam and heat curing respectively. An increasing trend in attenuation coefficient value was observed for all the mixes containing GCS as substitute for quartz sand, ranging from 10 % to 60 %. The highest LAC value was registered for GCS60 and the percentage increase in LAC values

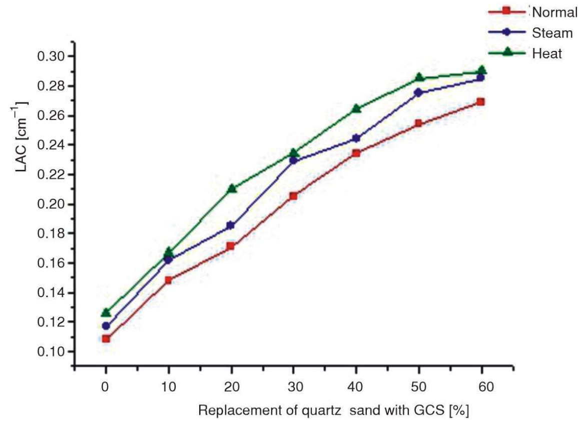


**Figure 5. The LAC of UHSC with GCS**

was 150 %, 130 %, and 144 % when compared with the corresponding CM for specimens subjected to normal, steam and heat curing respectively. Increase in LAC by more than 100 % was observed for UHSC specimens with GCS percentage ranging from 40 % to 60 %, when compared with the CM for all the curing regimes adopted in this investigation.

The test results explain that with the addition of GCS, the ability of UHSC to shield the radiation enhances enormously and hence UHSC with GCS can effectively be applied in areas where shielding of radiation is mandatory. It has been reported, in a research to develop HDC with magnetite as aggregate, by Ouda [7] that the maximum LAC value was 0.205 $cm^{-1}$ for sample thickness of 100 mm. In another research, by Rezaei-Ochbelagh and Azimkhani [5], the maximum value of LAC was 0.21 $cm^{-1}$ for concrete produced with lead powder. But in the present investigation, the maximum value of LAC measured on sample of 10 mm thickness was 0.290 $cm^{-1}$ for specimen with 60 % GCS subjected to heat curing. In both the research stated above, the radiation energy source was same as that used in the present investigation.

The variation in LAC of UHSC produced with different proportions of WGS as substitute for quartz sand is presented in tab. 1 and fig. 6. An increasing trend was observed at all the replacement percentages considered in this study. For UHSC with WGS, the maximum value of linear attenuation was for WGS40 irrespective of the curing regimes. For WGS40, the percentage increase in the LAC was 81 %, 90 %, and 92 % for specimens subjected to normal, steam and heat curing, respectively, when compared with the corresponding CM. The WGS30 which has exhibited the highest strength and durability properties among the specimens produced with WGS, the percentage increase in LAC was only 46 %, 59 %, and 59% , respectively, for curing regimes listed in the previous order, which is lower than that of WGS40. Having the same binder content, fibre content and water cement ratio, the increase in LAC with increase in WGS is attributed to the enhancement in density due to the incorporation

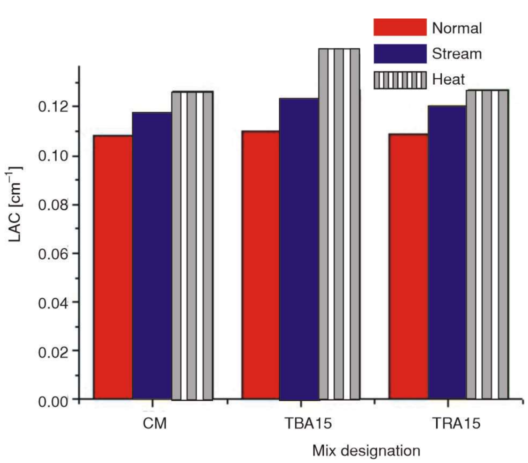


**Figure 4. The LAC for UHSC with TBA/TRA**

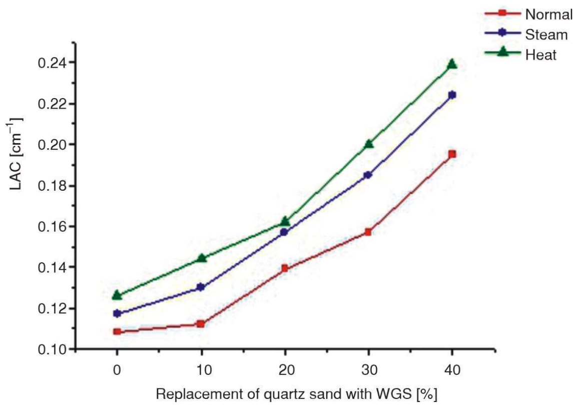


**Figure 6. The LAC of UHSC with WGS**

of more WGS. The stated reason is supported by the density determined for samples subjected to radiation as shown in tab. 2.

It is observed that the inclusion of WGS increases the density of the concrete and there by attenuating the radiation. The density of WGS40 is 2.83 gcm$^{-3}$, 2.92 gcm$^{-3}$, and 2.98 gcm$^{-3}$ for normal, steam and heat cured specimens respectively. The density values are much smaller when compared to the practically used HDC whose density starts from a minimum of 3.5 gcm$^{-3}$ [16]. As the specific gravity of both the quartz sand and WGS are almost the same, the better attenuation of UHSC with WGS is due to the improvement in packing density by addition of fine WGS and homogeneity enhancement. In previous researches on anti-radiation shielding concrete, the density was given the major consideration, but the LAC determined in this investigation suggests that in addition to density, homogeneity of the concrete matrix has to be given more consideration in producing a concrete with enhanced radiation shielding characteristics.

The attenuation property of the concrete depends on the thickness of the sample tested and it increases with the thickness of the concrete [7]. In the present investigation, the attenuation values were determined using specimens of 10 mm thickness and almost all the test specimens with GCS and WGS have LAC values greater than or, equal to that of HDC. Hence, it can be stated that UHSC with GCS and WGS can be effective in shielding the radiation and this can be further improved with the increase in the thickness, making it suitable for high energy radiation and neutron shielding. The increase in shielding resistance with use of GCS in UHSC is due to the higher density of CS, as its specific gravity is 3.52 equivalent to the high-density aggregates used in the production of HDC for shielding radiation and improvement in homogeneity due to the fine size of GCS with particle sizes less than 600 m.

**Table 2. Density of UHSC specimens tested for radiation**

| Mix designation | Density [gcm$^{-3}$] | | |
|---|---|---|---|
| | Normal curing | Steam curing | Heat curing |
| CMWF | 2.43 | 2.52 | 2.66 |
| CM | 2.5 | 2.53 | 2.71 |
| TBA15 | 2.47 | 2.65 | 2.72 |
| TRA15 | 2.52 | 2.59 | 2.73 |
| Q90G10 | 2.54 | 2.66 | 2.75 |
| Q80G20 | 2.59 | 2.74 | 2.77 |
| Q70G30 | 2.57 | 2.76 | 2.83 |
| Q60G40 | 2.83 | 2.91 | 2.98 |
| GCS10 | 3.04 | 3.16 | 3.27 |
| GCS20 | 3.06 | 3.19 | 3.24 |
| GCS30 | 3.09 | 3.15 | 3.21 |
| GCS40 | 3.12 | 3.29 | 3.37 |
| GCS50 | 3.25 | 3.31 | 3.37 |
| GCS60 | 3.25 | 3.37 | 3.5 |

All the ingredients of UHSC being the same for any particular mix containing TBA, TRA, GCS, and WGS, the difference in LAC and density was observed among the samples subjected to different curing regimes. The density of specimens subjected to elevated temperature curing *i. e.* steam and heat curing is higher than that of normal curing. The increase in LAC and density under elevated curing is due to the formation of additional C-S-H, which goes on to fill the micro/nano pores present in the matrix and rapid crystallization of C-S-H. Among the three curing regimes considered in this study, heat cured specimens have shown better resistance against shielding because of the ability to produce crystalline C-S-H, followed by steam and normal curing.

The linear attenuation test results suggest that radiation shielding concretes can be produced using industrial and agro-residual wastes efficiently instead of conventional high dense aggregates which are costlier and causing some environmental degradation, by concentrating equally on the homogeneity and density of the concrete. Most of the HDC used practically have compressive strength ranging from 60 MPa to 100 MPa, whereas in the present investigation, the minimum compressive strength was above 180 MPa and the maximum was above 325 MPa. Ultra-high strength, along with the good radiation shielding properties, make UHSC produced in this investigation a favourable material for radiation shielding structures, with high load carrying capacity especially where structures with reduced structural component size are required as in high rise nuclear reactor constructions. Another major problem with HDC is its proneness to segregation in fresh state, but with UHSC the segregation problem is nil because of the size of the ingredients and the reduced water to cement ratio.

## Mass attenuation coefficient

The MAC of concrete is the measure of probability of interaction between the incident photon and the concrete and it used as an indirect measure of change in atomic number. The MAC values of conventional UHSC and UHSC produced with 15 % TBA and TRA as substitute for cement and GCS ranging from 10 % to 60 % and WGS varying from 10 % to 30 % as partial substitute for quartz sand, are presented in tab. 3.

**Table 3. The MAC of UHSC**

| Mix designation | MAC [$cm^2g^{-1}$] | | |
|---|---|---|---|
| | Normal curing | Steam curing | Heat curing |
| CMWF | 0.030 | 0.038 | 0.040 |
| CM | 0.043 | 0.046 | 0.046 |
| TBA15 | 0.044 | 0.05 | 0.05 |
| TRA15 | 0.044 | 0.05 | 0.05 |
| GCS10 | 0.049 | 0.051 | 0.051 |
| GCS20 | 0.056 | 0.058 | 0.065 |
| GCS30 | 0.066 | 0.073 | 0.073 |
| GCS40 | 0.075 | 0.074 | 0.078 |
| GCS50 | 0.078 | 0.083 | 0.085 |
| GCS60 | 0.083 | 0.085 | 0.083 |
| WGS10 | 0.044 | 0.049 | 0.052 |
| WGS20 | 0.054 | 0.057 | 0.059 |
| WGS30 | 0.061 | 0.067 | 0.071 |
| WGS40 | 0.069 | 0.077 | 0.080 |

The values presented in tab. 3 show the fractional resultant index obtained by dividing the LAC by the density of the samples, indicating the contribution made by the UHSC to resist the radiation irrespective of the density of the samples. The higher the MAC the better is the radiation shielding. From the results presented in tab. 3, it is observed that the replacement of Portland cement with 15 % TBA and TRA individually has yielded in MAC slightly higher than the CM. Like the LAC values, the replacement of quartz sand with GCS up to 60 % and WGS up to 40 % individually has yielded in higher MAC values. The maximum value of MAC was recorded for GCS60 and WGS40 with 0.083 $cm^2g^{-1}$ and 0.08 $cm^2g^{-1}$, respectively, for heat cured specimens. The MAC value for CM was only 0.046 $cm^2g^{-1}$ under heat curing.

## Half value layer

The HVL is defined as the thickness of material required to reduce the intensity of the incoming beam by one half, and these values are calculated using the LAC values of the samples. The lower the values of HVL the better is the performance of concrete against the radiation. The HVL values of UHSC specimens produced in the present investigation are presented in the tab. 4.

Figure 7 presents the variations of HVL with the respect to the replacement of cement with TBA and TRA. It can be observed from the test results that the HVL values of UHSC without fibre were 9.43 cm, 7.30 cm, and 6.48 cm for normal, steam and heat cured specimens, respectively. These values are well below that of 17.32 cm for HDC produced with magnetite, calculated from the LAC value for a specimen of thickness 20 mm, as reported by Ouda [8]. This clearly shows the ability of UHSC even without fibre to attenuate the radiation with a thickness well below 10 cm. The review of previous literatures indicates that most of the tests to assess the LAC were carried out on specimens with minimum thickness of 10 cm, which will be yielding higher LAC values, because the LAC increases with the increase in thickness of the specimen and when HVL is calculated it will yield lower values. The ideal thickness for determination of LAC and hence the HVL is 10 mm. But it is not possible to produce specimen with a thickness of 10 mm using HDC, as they have mean aggregate size of 20 mm, whereas preparation of specimen with 10 mm thickness is possible using UHSC because of fine sized ingredients with maximum particle size of 600 μm.

**Table 4. The HVL of UHSC**

| Mix designation | HVL [cm] | | |
|---|---|---|---|
| | Normal curing | Steam curing | Heat curing |
| CMWF | 9.43 | 7.30 | 6.48 |
| CM | 6.42 | 5.92 | 5.50 |
| TBA15 | 6.30 | 5.64 | 5.46 |
| TRA15 | 6.36 | 5.78 | 5.46 |
| GCS10 | 4.67 | 4.28 | 4.16 |
| GCS20 | 4.05 | 3.75 | 3.31 |
| GCS30 | 3.39 | 3.03 | 2.96 |
| GCS40 | 2.96 | 2.84 | 2.62 |
| GCS50 | 2.73 | 2.52 | 2.43 |
| GCS60 | 2.57 | 2.43 | 2.39 |
| WGS10 | 6.17 | 5.32 | 4.82 |
| WGS20 | 4.98 | 4.40 | 4.28 |
| WGS30 | 4.40 | 3.74 | 3.47 |
| WGS40 | 3.55 | 3.09 | 2.90 |

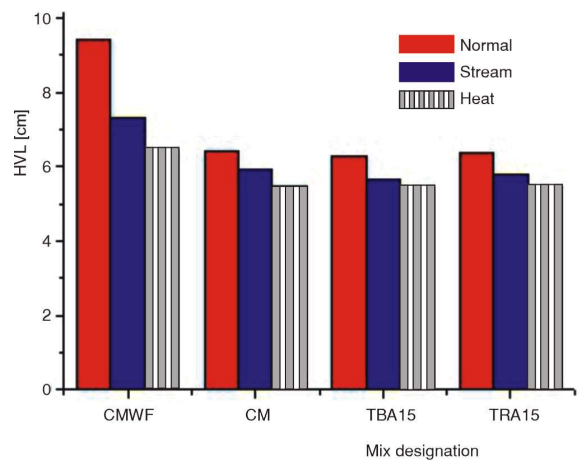


**Figure 7. The HVL of UHSC with TBA/TRA**

The HVL calculated in this investigation is based on the LAC obtained by testing 10 mm thick sample against the radiation source. Therefore, it is considered that the HVL values presented in the tab. 4 provide reliable data when compared with other researches on radiation shielding characteristics of HDC. The addition of steel fibres aids in reducing the HVL thickness of UHSC to 6.42 cm, 5.92 cm, and 5.50 cm for normal, steam and heat cured specimens. The percentage reduction in thickness is 32 %, 19 %, and 15 %, respectively, for normal, steam and heat cured specimens when compared with their counterparts without fibre. The presence of fibre has much influence on the specimens subjected normal curing than the steam and heat cured specimens.

The addition of GCS and WGS independently in the UHSC has positive impact in reducing the HVL thickness. The variation of HVL with GCS and WGS content is depicted in figs. 8 and 9 respectively.

The UHSC with GCS has yielded reduced HVL at all replacement percentages when compared with the CM. The maximum reduction is registered for GCS60 and the percentage reduction is 60 %, 59 %, and 57 % for the corresponding normal, steam and heat cured specimens, respectively. The HVL value reduces with increase in the WGS content in the mix for all the replacement percentages considered for assessing the radiation attenuation of UHSC, and the maximum reduction was for UHSC with 40 % WGS, with a percentage reduction of about 44 %, 47 %, and 48 % in the order of normal, steam and heat cured specimens, respectively.

The lowest HVL value among all the UHSC specimens is for GCS60 subjected to heat curing having a thickness of 2.39 cm, which is sufficient to reduce the radiation by 50 % of its original intensity. This value of HVL is lesser than 2.49 cm for heavy weight concrete produced with Colemanite-Galena as aggregate with a

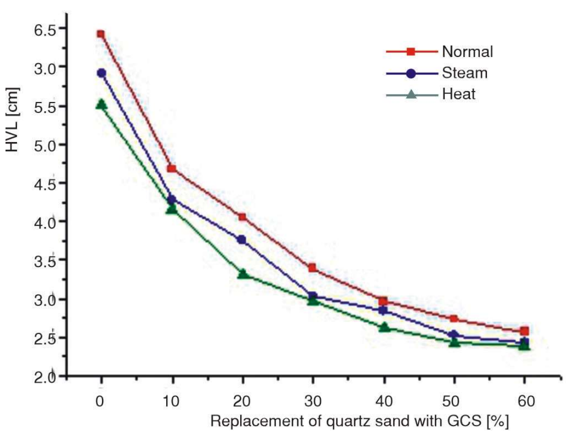


**Figure 8. The HVL of UHSC with GCS**

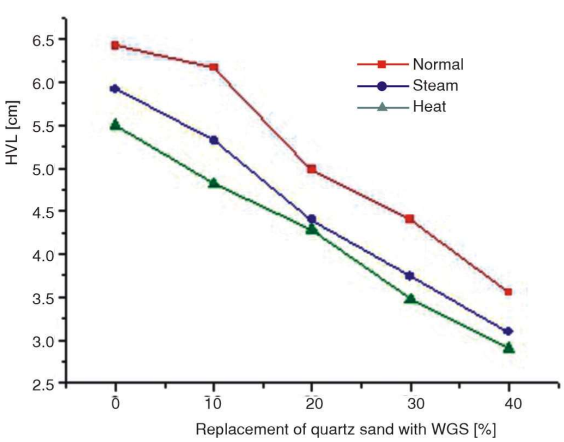


**Figure 9. The HVL of UHSC with WGS**

maximum concrete density of 4.65 $gcm^{-3}$, developed by Mortazavi *et al*. [16] and 3.6 cm for heavy weight concrete produced with bismuth oxide, developed by Yao *et al*. [11]. It is interesting to note that density of UHSC with 60 % GCS was 3.48 $gcm^{-3}$, well below the density mentioned in both the previous reports. Thus, it is evident that UHSC can effectively be utilized in shielding the radiation.

### Tenth value layer

The TVL is defined as the thickness of material required to reduce the intensity of the incoming beam by one tenth and these values are calculated using the LAC values of the samples, similar to HVL. The reduced values of TVL indicate the increased resistance in shielding the radiation. The TVL values for UHSC samples tested for radiation attenuation efficiency are presented in tab. 5. Similar to HVL, GCS60 and WGS40 have topped the table because of their improved density and homogeneity.

### SUMMARY

The study highlights the significant radiation shielding capabilities of UHSC compared to conventional HDC. The inclusion of steel fibers and supplementary cementitious materials such as TBA and TRA significantly improved shielding efficiency, as evidenced by the increased LAC and MAC and reduced HVL and TVL. Optimal replacement levels of 15 % TBA or TRA enhanced radiation resistance across all the curing regimes.

Furthermore, GCS and WGS played a crucial role in improving attenuation properties. A 60 % GCS mix demonstrated the highest LAC, with a substantial 150 % improvement under normal curing, compared to the control. Similarly, 40 % WGS substitution yielded significant gains in attenuation, primarily due to increased material density. The reduction in HVL and

**Table 5. The TVL of UHSC**

| Mix designation | LAC [cm] | | |
|---|---|---|---|
| | Normal curing | Steam curing | Heat curing |
| CMWF | 31.33 | 24.26 | 21.52 |
| CM | 21.31 | 19.68 | 18.27 |
| TBA15 | 20.93 | 18.72 | 18.13 |
| TRA15 | 21.12 | 19.19 | 18.13 |
| GCS10 | 15.53 | 14.21 | 13.81 |
| GCS20 | 13.47 | 12.45 | 10.99 |
| GCS30 | 11.25 | 10.05 | 9.84 |
| GCS40 | 9.84 | 9.44 | 8.71 |
| GCS50 | 9.06 | 8.38 | 8.08 |
| GCS60 | 8.54 | 8.08 | 7.93 |
| WGS10 | 20.49 | 17.69 | 16.02 |
| WGS20 | 16.54 | 14.62 | 14.21 |
| WGS30 | 14.62 | 12.41 | 11.52 |
| WGS40 | 11.81 | 10.27 | 9.63 |

TVL thickness across all the mixes highlights the effectiveness of these waste-based materials in radiation shielding applications.

Among the curing methods, heat curing exhibited superior shielding performance, achieving maximum reductions in HVL and TVL. Additionally, while traditional HDC typically range from 60-100 MPa, UHSC mixes in this study achieved decisive compressive strengths between 180 MPa and 325 MPa. The combination of superior strength and radiation resistance positions UHSC as an ideal material for high-load radiation shielding structures, such as nuclear reactors, where reduced structural component size is essential.

Based on the exhaustive experimental investigation carried out on UHSC with effective utilisation of agro-residual and industrial wastes, it is strongly concluded that it is practically possible to produce UHSC with excellent radiation shielding capability, thereby making it a sustainable construction material.

## AUTHORS' CONTRIBUTIONS

D. Rajkumar – conceptualization, investigation, writing – review and editing; A. Rajasekar – data curation, methodology, software, supervision, validation; K. Arunachalam – conceptualization, formal analysis, methodology, validation, writing original draft, review and editing.

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## REFERENCES

[1] Sharma, A., *et al*., Experimental Investigations on Mechanical and Radiation Shielding Properties of Hybrid Lead-Steel Fiber Reinforced Concrete, *Nuclear Engineering and Design, 239* (2009), 7, pp. 1180-1185

[2] Demir, F., *et al.*, Radiation Transmission of Heavyweight and normal-Weight Concretes Containing colemanite for 6 MV and 18 MV X-Rays Using a Linear Accelerator, *Annals of Nuclear Energy, 37* (2010), 3, pp. 339-344

[3] Zaripova, Y., *et al*., Investigation of Gamma Radiation Shielding Features for Modified Structural Materials for Nuclear Energy and Nuclear Medicine, *Nucl Technol Radiat, 38* (2023), 2, pp. 108-115

[4] Korkut, T., *et al*., Neutron Dose Transmission Measurements for Several New Concrete Samples Including colemanite, *Annals of Nuclear Energy, 37* (2010), 7, pp. 996-998

[5] Rezaei-Ochbelagh, D., Azimkhani, S., Investigation of Gamma-Ray Shielding Properties of Concrete Containing Different Percentages of Lead, *Applied Radiation and Isotopes, 70* (2012), 10, pp. 2282-2286

[6] Mesbahi, A., *et al*., Photoneutron Production and backscattering in High-Density Concretes Used for radiation Therapy Shielding, *Annals of Nuclear Energy, 38* (2011), 12, pp. 2752-2756

[7] Ouda, A. S., Development of High-Performance Heavy Density Concrete Using Different Aggregates for Gamma-Ray Shielding, *Progress in Nuclear Energy, 79* (2015), Mar., pp. 48-55

[8] Ouda, A. S., Estimation of Radiation Properties of High-Performance Concrete for Use in Nuclear Installations, *Journal of Materials in Civil Engineering, 28* (2016), 11, 04016121

[9] Elsharkawy, E. R., Sadawy, M. M., Effect of Gamma-Ray Energies and Addition of Nano-$SiO_2$ to Cement on Mechanical Properties and Mass Attenuation Coefficient, IOSR *Journal of Mechanical and Civil Engineering, 13* (2016), 6, pp. 17-22

[10] Kumar, S., Singh, S., Study of Some Health Physics Parameters of Bismuth-Ground Granulated Blast Furnace Slag Shielding Concretes, *AIP Conference Proceedings, 1728* (2016), 1, 020484

[11] Yao, Y., *et al*., Investigation of Gamma-Ray Shielding Efficiency and Mechanical Performances of Concrete Shields Containing Bismuth Oxide as an Environmentally Friendly Additive, *Radiation Physics and Chemistry, 127* (2016), Oct., pp. 188-193

[12] Al-Humaiqani, M. M., *et al*., $\gamma$-Radiation Shielding Properties of High-Strength High-Performance Concretes Prepared with Different Types of Normal and Heavy Aggregates, *Asian Transactions on Engineering, 3* (2013), 2, pp. 18-28

[13] Maslehuddin, M., *et al*., Radiation Shielding Properties of Concrete with Electric Arc Furnace Slag Aggregates and Steel Shots, *Annals of Nuclear Energy, 53* (2013), Mar., pp. 192-196

[14] Richard, P., Cheyrezy, M., Composition of Reactive Powder Concretes, *Cement and Concrete Research, 25* (1995), 7, pp. 1501-1511

[15] Azeez, A. B., *et al*., The Effect of Various Waste Materials' Contents on the Attenuation Level of Anti-Radiation Shielding Concrete, *Materials, 6* (2013), 10, pp. 4836-4846

[16] Mortazavi, S. M. J., *et al*., High-Performance Heavy Concrete as a Multi-Purpose Shield, *Radiation Protection Dosimetry, 142* (2010), 2-4, pp. 120-124

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**Деивендиран РАЏКУМАР, Ајалусами РАЏАСЕКАР, Калидас АРУНАЧАЛАМ**

## ПОТЕНЦИЈАЛ ЗАШТИТЕ ОД ЗРАЧЕЊА БЕТОНА УЛТРАВИСОКЕ ЧВРСТОЋЕ ОД АГРОИНДУСТРИЈСКОГ ОТПАДА

Бетон ултрависоке чврстоће произведен од агрозаосталих отпадака и индустријских нуспроизвода тестиран је на капацитет заштите од зрачења мерењем коефицијента линеарног слабљења, слоја полудебљине и слоја слабљења на десетину интензитета. Резултати теста линеарног слабљења показују да се бетон ултрависоке чврстоће са агрорезидуалним и индустријским отпадом може ефикасно користити у заштити од зрачења. Резултати за слој слабљења откривају да се бетони за заштиту од зрачења могу производити коришћењем индустријског и пољопривредног отпада, тако што ће се подједнако концентрисати на повећање хомогености и густине бетонске матрице. Бетон ултрависоке чврстоће развијен у овом истраживању регистровао је боља својства заштите од зрачења од конвенционалних бетона за заштиту од зрачења са агрегатима високе густине који су скупљи и за које је утврђено да имају деградацију животне средине заједно са опасностима по здравље.

*Кључне речи: бетон ултрависоке чврстоће, зрачење, коефицијент линеарног слабљења, полудебљина, слој слабљења на десетину интензитета*