NOVEL APPROACH TO IMPROVED CONCRETE STRENGTH FOR ENHANCED SAFETY AND DURABILITY OF THE NUCLEAR POWER PLANT OPERATION

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Abstract

Concrete used in nuclear power plants is expected to last 40 years and from recently with renewed licenses even as long as 60 - 80 years. In general, the most influential time in determining concrete long-years durability is its initial curing phase. In this paper, we present a novel approach to concrete curing that examines its enhanced strength and durability (resistance to corrosion). Enhanced strength will increase the likelihood of concrete durability for the entire life cycle of a nuclear power plant years of operation. Such concrete may be considered a new nuclear material of interest to vendors building new conventional nuclear power plants and/or building advanced nuclear power plants, such as modular and medium size reactors or GenIV reactors. The curing of concrete in its first seven to 28 days of formation show to be crucial in its microstructure formation, leading to increased or deteriorated strength properties. We have examined the effects of gamma ray exposure to concrete during its first seven and 28 days of curing and tested it for its compressive strength in comparison to conventionally cured concrete. In addition, the microstructure of some of the samples is studied using Scanning Electron Microscope (SEM). The compressive strength tests and the SEM analysis provide preliminary conclusion that the gamma rays induce fast radiolysis of water in young concrete in thus resulting in its enhanced strength. Of particular interest is the formation of calcium-silicate-hydrate, a gel like structure formed during the curing phase that bonds aggregates within concrete, contributing to its overall strength. Statistical analysis and description of this novel approach of a concrete formation is detailed in showing the experimental and computational data.

1. Introduction

In current Gen II nuclear reactors concrete is used in containment domes, biological shields, as well as supporting infrastructure. The newest Gen III and other new reactor designs require a containment structure made of concrete. Its main purpose is to protect against a release of fission products into the environment. The containment structure also provides a radiation shield during normal operation of a nuclear power plant (NPP) [1]. In order for a containment structure to properly function it must be able to prevent the spread of radiation in many different adverse conditions including, severe accidents, weather and terrorist attacks [2]. Any imperfections in containment structures such as cracking or lower than expected compressive strength negatively impact its strength and durability. Usually small cracks develop during the plant lifetime that permit ingress of water and reinforcing steel can corrode, shortening the lifespan of the structure. The structure may also perform unreliably in severe accidents or under high pressure environments. While not much can be done to repair safety related concrete structures once they have begun to fail, as was recently demonstrated in the case of the Crystal River power generating station [3], an increased focus on enhancing overall safety of concrete structures is of interest for new NPPs under construction [1].

One method to improve the safety of containment structures is to increase the concrete strength. Common methods of increasing concrete strength may include using a high strength cement or admixtures to decrease the water to cement (w/c) ratio [4]. These methods may however have adverse effects: high strength cement is typically a much finer ground powder and its fineness causes for more rapid hydration. Because hydration of cement is an exothermic reaction [5] a high strength cement causes more expansion and contraction due to the heat of hydration, increasing the chances of unwanted cracking to occur in the structure.

The properties of concrete are most influenced during its early stages of curing. Concrete is composed of a mix of cement, water, and coarse and fine aggregates. After approximately 28 days of curing time, concrete achieves most of its compressive strength. A positive influence on concrete during its early stage curing will have lasting effects for decades in relation to its compressive strength as well as long-term durability. Improving curing also offers a means of improving compressive strength and reducing the overall curing time, without the downfalls of using cements or admixtures that may degrade concrete. An enhancement of these properties is expected to improve the safety and reliability of the concrete structures of interest to nuclear industry.

A substantial amount of literature shows that the high dose gamma ray exposure of concrete for long period of time has damaging effect [6]-[8]. However, in our previous studies we showed that if concrete is exposed to low dose gamma radiation during the first seven days of curing its compressive strength is increased [9]. In this paper, we show the experimental results of gamma radiation effect on concrete if it is exposed to low gamma dose during 28 days in comparison to seven days of curing time. In addition, by the time of the Conference, the effect of gamma exposure on concrete during its 14 days of curing will be presented. The final conclusion on the effects of "*gamma-curing*" of young concrete in increasing its overall comprehensive strength is expected to be developed in understanding if there is a threshold time beyond which the strength of concrete may decrease rather than increase.

2. Concrete Strength Change Due to Exposure to Gamma Radiation During its Curing

A mix of cement with water initiates a hydration process that results in forming a gel known as calcium-silicate-hydrate (C-S-H). The structure of C-S-H is highly amorphous and is reflected by its general formula: $CaO_x \cdot SiO_2 \cdot H_2O_y$ where 'x' and 'y' vary with calcium to silica ratios ranging between 1 and 2 [4]. Several different forms of C-S-H may exist. One common C-S-H formation is the Jennite mineral, $Ca_9Si_6O_{18}(OH)_6 \cdot 8H_2O$. The formation of C-S-H is essential to both compressive strength as well as long term durability of concrete because it acts as a binder between the aggregates. Its formation is not instantaneous and concrete mix can take as long as 28 days or even longer, to reach the required strength [5]. When exposed to gamma radiation during the curing time, gamma rays interact with water molecules; several different interactions may take place, such as photoelectric effect or Compton scattering, leading to the formation of free radicals in a process known as radiolysis. The radiolysis is described as follows:

$$H_2O \xrightarrow{\text{ionizing radiation}} e^-_{aq}, HO, H, HO_2, H_3O^+, OH^-, H_2O_2, H_2 \qquad (1)^1$$

The products of radiolysis may interact with themselves to form water again, known as back reactions. They may also interact with other elements present in the aqueous solution of cement and water. The reaction of free radicals with the elements in solution may offer a means of both more rapidly increasing the production of C-S-H as well as a more complete formation of C-S-H. Our initial studies show that exposing concrete to a gamma radiation dose of 69.1 cGy on average during the first seven days of curing time increase its compressive strength by an average of 22% [9]. Because seven days represents the earliest stages of the curing, further experiments are

[1] The term e^-_{aq} refers to the initial free electron produced through the interaction of a gamma ray with a water molecule. This electron is captured by water molecule and becomes solvated being referred to as an aqueous or solvated electron. The solvated electron can react with H^+ to form the hydroxyl radical [10].

performed to assess the effects of gamma radiation on concrete during 28 days of curing time, as described in the following sections. By the time of the Conference, the effect of gamma dose on concrete during its 14 days of curing will be also presented. These data will provide additional information in concluding on the effect of "gamma-curing" of young concrete in increasing its overall comprehensive strength.

2.2. Description of the Experiment and Corresponding MCNP6 Model

Several batches of concrete were mixed in the laboratory at the Utah Nuclear Engineering Facility. The mix used for all concrete cubes is as follows: w/c ratio of 0.4, and s/c ratio of 2.75. The ASTM Standard C192/192M – *Making and Curing Concrete Test Specimens in the Laboratory* [11] is followed for mixing and casting the concrete cubes. The procedure is deviated from in that cubes are demolded after five hours of curing time rather than after 24 hours. To facilitate early exposure to gamma radiation the cubes are demolded as soon as they could hold their form. Once the cubes are demolded, half are placed in an irradiation chamber for seven (7) and 28 days with a 630 MBq ^{137}Cs source. In total 156 concrete cubes of 125 cm^3 in volume are cast, cured, and tested for compressive strength; 112 are tested after 7 days curing and 24 are tested after 28 days curing. Five separate batches of concrete are mixed for the seven days and two batches of cubes for the 28 days of curing. Of the 112 cubes cured for 7 days, 56 are cured using gamma radiation and 56 are cured conventionally. The same convention is followed for the 28 days cured cubes where 44 cubes are cast with half being cured with gamma radiation and the other half being cured conventionally. The experimental setup with cubes in the radiation chamber is shown in Fig. 1(a). The absorbed dose to the concrete cubes is calculated with the MCNP6 model as shown in Fig. 1(b) (F6 tally is specifically used to record the required data [9], [12]), and also is measured using a Landauer nanoDot system [13]. The absorbed dose was measured by placing two nanoDots on the side directly facing the ^{137}Cs source and two nanoDots on the rear face direct opposite. To obtain the absorbed dose the measured dose to the nanoDot on the rear face ^{137}Cs source on the cube is subtracted from the measured dose of the nanoDot on the side facing the ^{137}Cs source. As shown in Fig. 2, the dose range from 58.9 cGy to 98.0 cGy with an average value of 77.1 cGy. Cubes 1, 2, and 3 (Fig. 2) received doses higher than cubes 4, 5, and 6. The placement of the ^{137}Cs source in the experiment is slightly off center in the irradiation chamber, being closer to cubes 1, 2, and 3 while further away from cube 4, 5, and 6. The dose of cubes 5-10 most closely match the MCNP6 calculated dose as they most closely match the MCNP6 model source placement of 11 cm from the front face of each cube. Over seven days it is calculated with MCNP6 that each cube receives an absorbed dose of 0.66 Gy and 2.64 Gy (~0.66 Gy per week of exposure) over 28 days. The calculated dose is the same for each cube because the ^{137}Cs source is placed exactly center in the model. The absorbed dose over seven and 28 days fall well below the threshold dose values of 10^7-10^{11} Gy that have been shown to be necessary to cause radiation damage and consequently a reduction in concrete compressive strength [14], [15].

After seven and after 28 days of curing both sets of concrete cubes (gamma-cured and conventionally cured) are tested for compressive strength in the University of Utah Structures Laboratory using an INSTRON universal testing machine [16] with a computer controlled loading rate. Testing for all cubes is in accordance with ASTM C109 – *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars* [17].

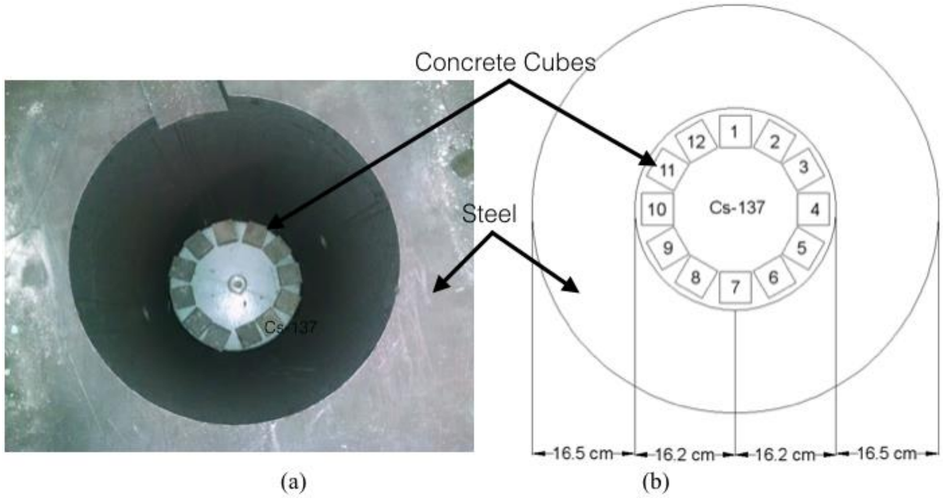


Figure 1. (a) Experimental setup for concrete cubes curing in gamma field (source placed in the center); (b) MCNP6 model for calculating absorbed gamma ray dose in concrete cubes [9]

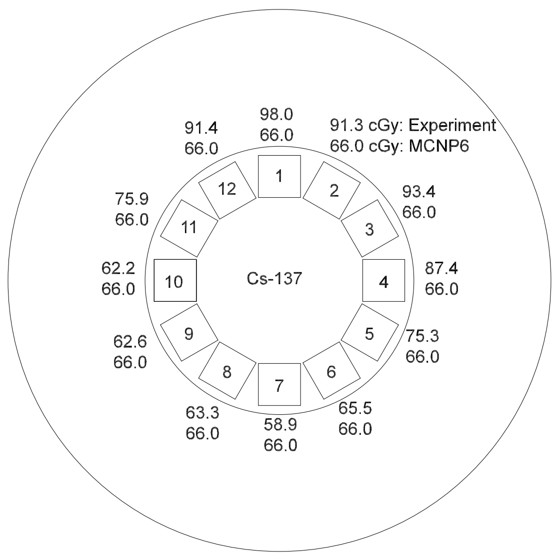


Figure 2. Experimental and MCNP6 absorbed dose values for gamma exposure to concrete cubes. The MCNP6 calculated values are the same for each cube because the ^{137}Cs source is placed exactly center whereas the experiment the source is located slightly off center varying the measured dose [9].

2.3. Comparison of the Compressive Strength Values between Gamma-Cured and Conventionally Cured Concrete Cubes

Our initial studies of concrete comprehensive strength after exposing it to gamma radiation for seven days with 630 MBq ^{137}Cs source show an increased strength by 22% compared to cubes that are conventionally cured, [9]. Figure 3 summarizes these values. The compressive strength of the gamma-cured cubes ranges from 48 to 73 MPa resulting in an average value of 61 MPa. The conventionally cured cubes have compressive strength from 24 to 65 MPa resulting in an average value of 49 MPa. A t-test was performed with a resultant p-value of 1.26×10^{-12}, indicating that the two data sates are dissimilar. The overall compressive strength of the gamma-cured cubes is higher than in the conventionally cured cubes. However, those benefits are lost if concrete is exposed to gamma radiation during its first 28 days of curing.

Figure 4 summarizes the comprehensive strength values for gamma-cured and conventionally cured cubes after 28 days of curing time. The gamma-cured cubes have comprehensive strength ranging between 25 to 58 MPa, with the resulting average value of 50 MPa; while the comprehensive strength of the conventionally cured cubes varies from 26 to 68 MPa, with an average value of 51 MPa. A statistical t-test is performed and the p-value is equal to 0.82 representing 82% probability that the gamma-cured and conventionally cured concrete practically have the same compressive strength values. From Fig. 4 it can be seen that the sample batch A of the conventionally cured cubes has a high standard deviation compared to sample batch B of the conventionally cured cubes. This is because the first conventionally cured cube had visible surface cracking not present in any of the other concrete cubes resulting in a compressive strength value lower than for the rest of the cubes. Therefore, based on the results as shown in Fig. 4 and the t-test that is showing sameness in data, the benefits of gamma curing diminish with 28 days of exposure. By the time of the Conference, the compressive strength testing will be completed for 14 days curing to determine at what point the benefits of gamma curing are diminished.

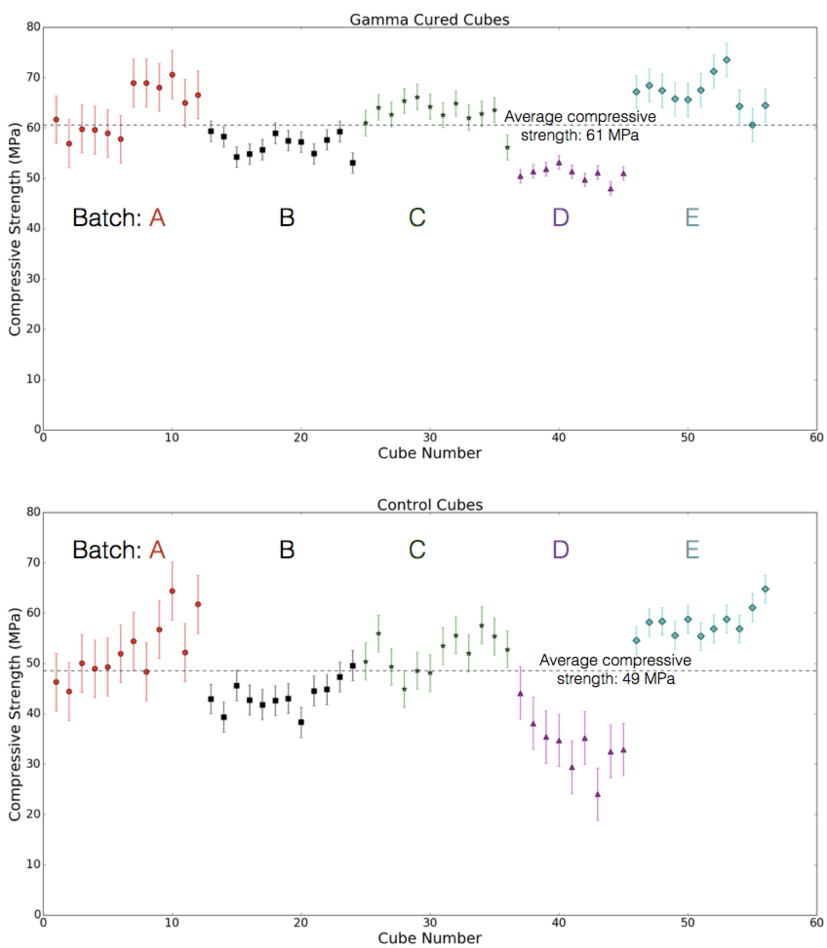


Figure 3. Compressive strength of gamma cured (top) and conventionally cured (bottom) concrete cubes. The five batches, A-E are mixed and cured for 7 days after which compressive strength is tested.

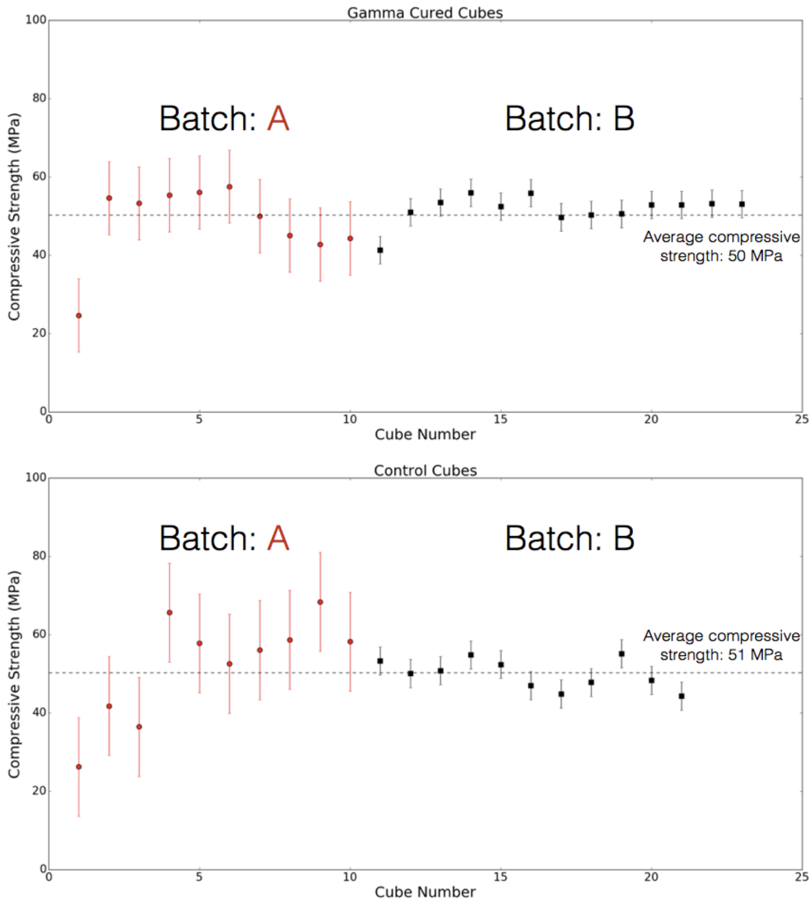


Figure 4. Compressive strength of gamma cured (top) and conventionally cured (bottom) concrete cubes. The two batches, A-B are mixed and cured for 28 days after which compressive strength is tested.

2.4 Analysis of the Gamma Ray Effects on Concrete Microstructure using the Scanning Electron Microscope (SEM) Images

A cement hydration is an exothermic reaction. Excessive heat during curing may cause undesirable effects such as expansion, contraction, and excessive cracking. Such effects may cause an overall reduction in long term strength and durability of concrete. Exposing concrete to a high dose of radiation has also been shown to cause radiation heating, resulting in both shrinkage, expansion, and a reduction in strength [8]. To ensure that no gamma heating was occurring or damaging its microstructure the concrete cubes from batch E (Fig. 3) were analyzed using SEM (Hitachi S-4800 SEM in the Crus Advanced Materials Technology Center at the University of Utah). Figure 5 shows detailed compressive strength values of each cube (related to Fig. 3).

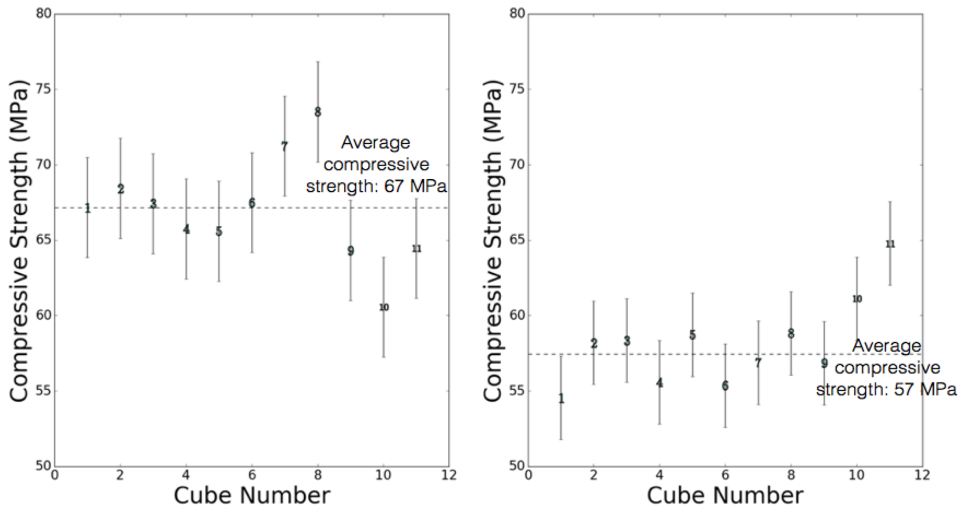


Figure 5. Detailed view of the compressive strength of Batch E (Fig. 3) of (7-days) gamma cured (left) and conventionally cured (right) concrete cubes

It can be seen from Fig. 5 that among all tested cubes, a gamma-cured cube 8 and conventionally cured cube 11 each has the highest compressive strength of 74 MPa and 65 MPa, respectively. The SEM images of these two cubes are shown in Fig. 6. Both cubes show similar characteristics of low void ratio, represented by dark areas. A low void ratio is indicative of well-developed contact between C-S-H and aggregates. Increased contact between C-S-H and aggregates increases the strength due to greater bonding surface area. The SEM images of cube 10 and cube 1 with compressive strength of 58 MPa and 52 MPa, respectively, are shown in Fig. 7. These cubes have the lowest compressive strength in the batch E, and show similar features to the cubes with the highest compressive strength having low void ratios and well developed C-S-H (Fig. 6). If damage from gamma heating is present, a greater void ratio would be observed in the gamma cured cubes. The increase in void ratio would be a result of the expansion and contraction separating the particles and decreasing the bonded surface area. These SEM images provide information that no gamma heating is occurring that could potentially lead to detrimental effects. This leads to a conclusion that the gamma curing may be safely used for a period of seven days. Additionally, SEM analysis of 14 and 28 days cured cubes will be completed by the Conference and presented in comparison to seven day cured concrete cubes microstructure.

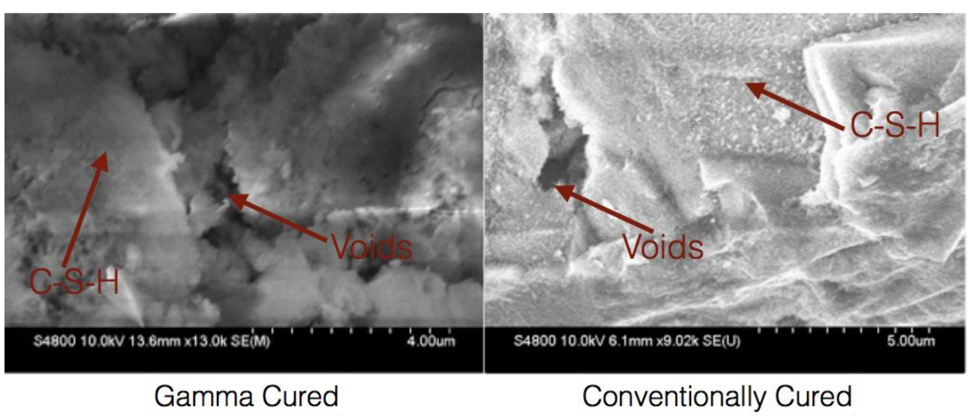
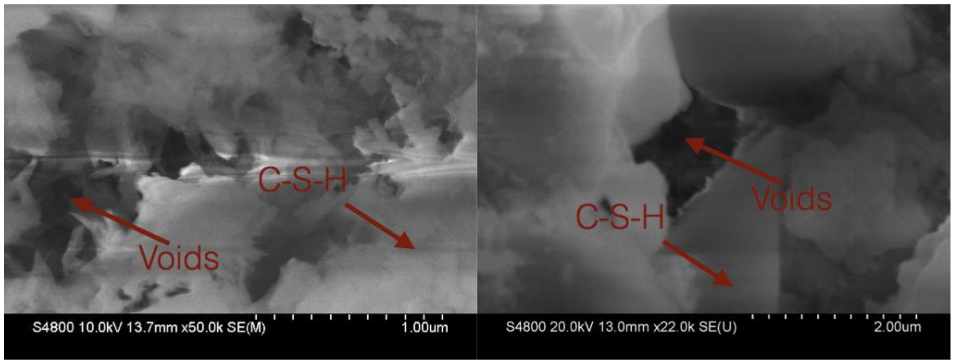


Figure 6. SEM images of gamma cured cube 8 of Fig. 4 and conventionally cured cube 11 of Fig. 4. Both cubes had the highest compressive strength of their batch.



Gamma Cured   Conventionally Cured

Figure 7. SEM images of gamma cured cube 10 of Fig. 4 and conventionally cured cube 1 of Fig. 4. Both cubes had the lowest compressive strength of their batch.

3. Conclusion

Concrete plays an important safety role in all facets of the nuclear industry. Concrete structures, such as containment domes are expected to last for 40 (or doubled) years. The most influential time affecting properties of concrete such as strength and durability is the initial curing phase, lasting approximately for standardized 28 days. Increasing compressive strength is a common approach to improving safety of concrete. Conventional methods of increasing compressive strength such as decreasing w/c ratio or using high strength cements may decrease safety related properties over the decades. A novel approach presented in this paper show an improved /increased compressive strength while curing for only seven (7) days.

A total of 156 concrete cubes of 125 cm3 in volume are cast and tested for compressive strength. For seven days, 112 cubes are cured with half of them being exposed to continuous gamma radiation and the other half are cured conventionally. Additionally, 44 cubes are cured for 28 days with half cured with gamma radiation and half cured conventionally Compressive strength is tested after seven and 28 days of curing for concrete exposed to gamma radiation as well as conventionally cured concrete. Exposure of concrete to gamma radiation during the first seven days of curing increases compressive strength while the 28 days gamma cured concrete shows no improvement. Future experiments to be finished by the time of this Conference will include 14 days gamma curing in order to determine at what point the benefits of gamma cured concrete are maximized. The concrete microstructure is analyzed using SEM on concrete cubes cured for seven days. The SEM analysis shows that the microstructure of the gamma cured and conventionally cured cubes is practically the same, ensuring that no damage is occurring at the microscopic level that could have negative effects on safety of the concrete structure. Statistical analysis shows that gamma curing for seven days increases compressive strength while 28 days of curing shows no added benefit to compressive strength.

4. References

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