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Review Article

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An overview of radiation exposure effects on concrete in nuclear power plants

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Abstract: This review summarizes the effects of radiation exposure on the properties of concrete, with a focus on the impacts on compressive and tensile strength, elastic modulus, weight loss, and dimensional changes. Ionising radiation, including neutron exposure, can significantly alter the mechanical and physical properties of concrete used in nuclear energy facilities. Recent advancements in developing ultra-high-performance concrete (UHPC) and radiation shielding concrete with heavy natural aggregates offer promising alternatives for radiation shielding. AI-driven models can support this by predicting material performance under irradiation.

Keywords: radiation, neutron exposure, concrete properties, nuclear energy facility, concrete biological shield

1. Introduction

Ionising radiation is a type of radiation that removes electrons from atoms or molecules, creating electric charges. The boundary between ionising and non-ionising radiation is set at the edge of the visible and ultraviolet light spectrum. There are four types of ionising radiation: alpha, beta, electromagnetic (such as X-ray or gamma), and neutron. Processes in radioactive materials at radioactive material repositories, during nuclear medicine procedures, or during energy production in a nuclear reactor produce ionising radiation. Figure 1 shows the different types of radiation and their penetration properties through different materials.

The least dangerous radiation is alpha radiation, produced by helium nuclei, which has an average range of 25 to 120 mm compared to beta, gamma, and neutron radiation. As the radiation passes through air or other media, the particles lose energy and are stopped, meaning that the radiation can be blocked by a sheet of paper. Beta radiation is a stream of electrons which, penetrating into biological tissue to a depth of about ten millimetres, can be stopped by a layer of thin metal. Another type is gamma radiation, which is electromagnetic in nature and has the highest energy at a wavelength of less than ten nanometres; it can penetrate the human body and is dangerous to humans. It can only be stopped by suitable layers of heavy materials with a high number of Z atoms or concrete of considerable thickness. During the production of electricity in nuclear reactors or in particle acceleration devices, such as cyclotrons, neutron radiation is generated, which does not occur naturally [1]. However, neutron radiation also occurs naturally, such as through cosmic ray interactions. Table 1 shows how neutrons are distinguished by their speed and energy.

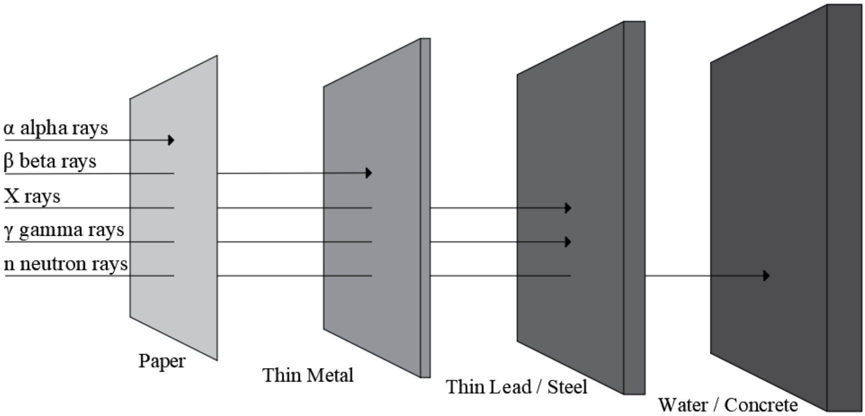

Fig. 1. Types of radiation and their penetration through different materials. *Source:* own study based on [2]

Table 1. Classification of neutrons according to their energy. *Source:* [3]

Neutrons	Energy [eV]
Cold	< 0.01
Thermal	0.01 – 0.3
Epithermal	$0.3 – 10 \cdot 10^3$
Fast	$10 \cdot 10^3 – 20 \cdot 10^6$
Relativistic	$> 20 \cdot 10^6$

Ionising radiation can harm living cells and cause health problems because of the energy it transfers to matter; therefore, protective shields are needed against this radiation [4]. Neutron radiation poses a risk in places such as nuclear power plants, research reactors, radioactive storage facilities, and medical centres. The main shielding material is concrete, which can also act as a load-bearing structure [5].

In the case of nuclear power plants, the area particularly susceptible to neutron radiation is the concrete biological shield (CBS), which surrounds the reactor pressure vessel (RPV). Concrete shields must meet a variety of requirements in terms of mechanical and physical properties, for example, mechanical strength, impermeability, and durability, as well as meeting the expected service life. There are also requirements for inhibiting gamma radiation and retaining neutron fluxes. Appropriate design and optimisation of the concrete composition, as well as protection of the reinforcement or prestressing of the concrete elements, are required to ensure structural durability and resilience in accident situations [1].

The design of the radiation shielding in nuclear reactors protects the pressure vessel, coolant loop, and inner shield from the high heat generated by the absorption of nuclear radiation. Another responsibility is to ensure operational safety for both personnel and the environment, as well as for Instrumentation and Control (I&C), particularly electromagnetic and electronic apparatus. The type of power plant and the fission technology determine the shape and thickness of the CBS. Due to technological differences, the nuclear reactor types, Pressurised Water Reactor (PWR) and Boiling Water Reactor (BWR), which are the most common types, require the design of additional CBSs. PWR reactors typically transfer loads from the pressure vessel support to the concrete CBS.

In addition, the concrete structures above it use the CBS structure as a base. Figure 2 shows a typical PWR reactor design. In a typical BWR reactor, a concrete biological shield wall surrounding the nuclear reactor pressure vessel provides the necessary radiation protection for the environment.

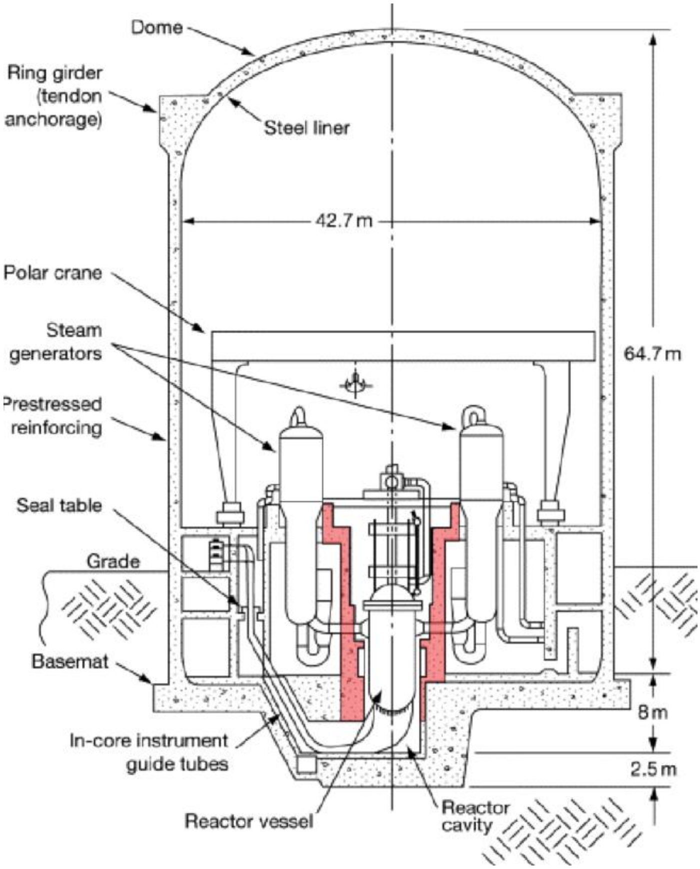

Fig. 2. Typical Pressurised Water Reactor with concrete biological shield (shown in red) *Source:* own study based on [6]

In many power plant designs, the biological shield wall also serves as a support structure for the reactor pressure vessel. This wall also supports other structures made of concrete, such as the operating floor and the reactor cavity [7]. A typical BWR reactor design is shown in Fig. 3.

The period of use of nuclear power plants, and especially the impact of long-term radiation on concrete for 60 years and longer, requires attention to the durability of the structure and the impact of neutron radiation on the properties of concrete [8]. This paper presents the results of a literature review on the influence of neutron radiation on the mechanical and physical properties of concrete. The paper aims to summarise the changes in material properties and to present the current directions of development in the protection of concrete.

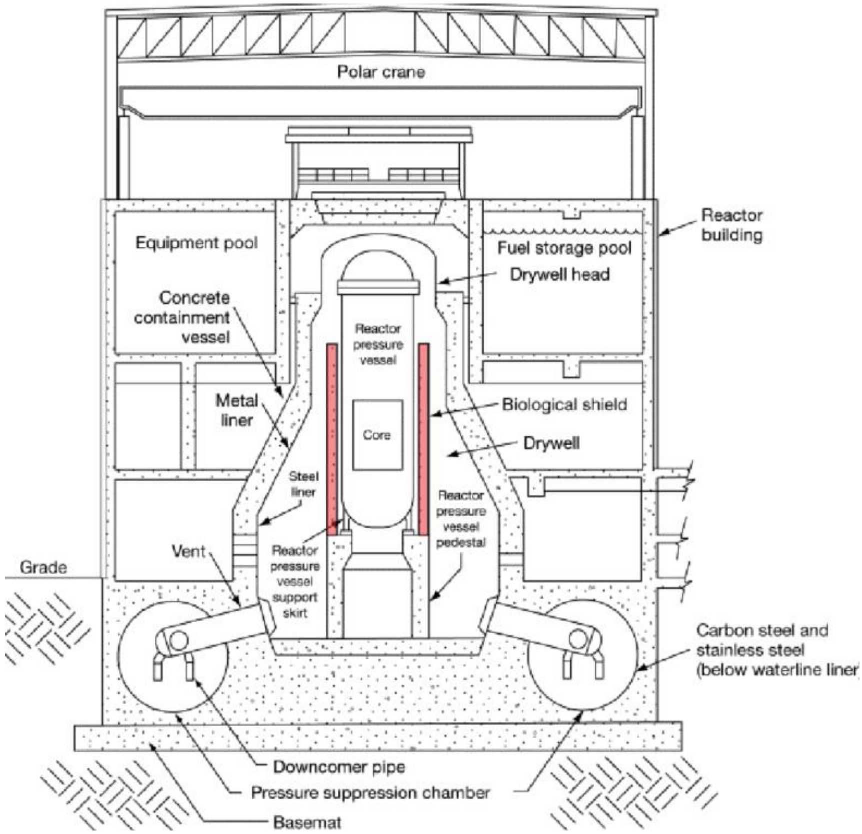

Fig. 3. Typical Boiling Water Reactor with concrete biological shield (shown in red). *Source:* own study based on [6]

The selection of specific concrete properties such as mechanical performance (compressive and tensile strength, elastic modulus) and mass or dimensional changes is driven by their direct implications for safety, durability, and structural integrity in nuclear energy facilities. Mechanical performance is a critical indicator because concrete structures in nuclear reactors must reliably sustain substantial mechanical loads and resist degradation over extended operational periods, often exceeding several decades. Mass and dimensional stability are equally important, as radiation-induced dehydration, internal expansion, and microcracking can compromise concrete's structural integrity, potentially leading to premature deterioration or failure. In nuclear power plants, concrete is frequently utilised as a filling material within various structural components, such as steel-plate composite walls [9]. These composite elements consist of steel plates filled with concrete, relying heavily on the mechanical integrity and dimensional stability of the concrete filler. Changes in the mechanical properties of concrete – especially radiation-induced losses in compressive and tensile strength, as well as volumetric expansions – can lead directly to excessive internal stresses, microcracking, or deformation. Such degradation in concrete performance significantly increases the risk of damage to the surrounding steel plates, compromising overall structural integrity. Consequently, understanding and accurately predicting concrete behaviour under radiation exposure is essential not only for concrete durability itself but also for ensuring the long-term safety and functionality of steel composite structural systems widely implemented in advanced nuclear facilities, i.e. shield buildings or structural module walls in AP1000® design. Thus, focusing on these properties aligns with broader research needs aimed at designing resilient materials capable of withstanding extreme radiation environments, ultimately contributing to safer and more durable infrastructure in nuclear energy applications.

2. Influence of neutron radiation on mechanical and physical properties of concrete

The concrete biological shield is typically made of Type II Portland cement, fine aggregates, water, and various mineral or chemical additives. The heavy aggregates most commonly used and occurring naturally are barite, magnetite, hematite, goethite, limonite, and ilmenite.

Neutron fluence and gamma-ray dose are typically described in terms of their effects on shielding materials and the potential damage caused by changes in material properties. Initial gamma-ray experiments indicated limited water decomposition solely by gamma-ray exposure and suggested little effect on the strength of concrete, as described by [10].

Several effects with varying intensities were observed, as gathered by [11]:

- Increase in temperature due to radiation..
- Activation of concrete, where radioactive isotopes created by neutron flux make the concrete radioactive.
- Increased dilatation coefficients of the aggregates, including barite, hematite, and magnetite.
- Changes in the permeability coefficients for air and water in concrete.
- Internal carbonation of the cement matrix under gamma radiation, leading to changes in microstructure and other properties.
- Radiolysis of interstitial or molecular water.

2.1. Compressive strength

The compressive strength of concrete depends on the quality of the hardened cement paste, the packing density of the aggregate, and the initial water-to-cement ratio. The water-to-cement ratio in ordinary concrete does not affect its shielding properties, but a higher ratio significantly reduces its strength [12]. Neutrons have a limited direct impact on the strength of the cement matrix, but other factors such as thermal damage, gamma irradiation, and aggregate-induced damage can weaken it. The results collected by [10] in the range of 2×10^{18} n/cm² to 1×10^{20} n/cm² indicate an inconclusive decrease in relative compressive strength, as presented in Fig. 4.

For their study, [13] gathered over 24 scientific articles that investigated the impact of radiation on the mechanical characteristics of concrete. The findings were reported as the relationship between relative compressive strength and neutron fluence, using a detailed analytical categorisation of aggregate type. In consideration of their mineralogical properties, aggregates were categorised into three groups: silicate, carbonate, and other (e.g. haematite, barite). Results indicate that concretes containing silicate aggregates exhibit a more significant decrease in strength compared to other types of aggregate. The majority of the studies documented findings within the range of 1×10^{14} n/cm² to 1×10^{22} n/cm².

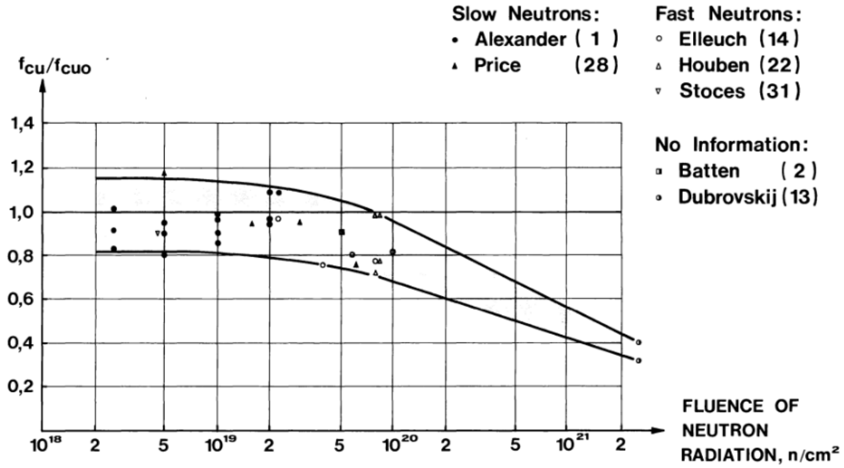

Fig. 4. Compressive strength of concrete exposed to neutron radiation. *Source:* [10]

The compressive strength of neutron-irradiated concrete decreases as neutron fluence increases. This reduction is most significant at fluence values over 1.0–2.0×10^{19} n/cm², with residual strength dropping to about 50% of the initial strength at around 10^{20} n/cm² in [13] studies. Most data over 2.0×10^{19} n/cm² is derived from the use of siliceous concretes and mortars, which are the foundation for the downward sloping trend. Accordingly, multiple data points of various aggregates (such as haematite and chromite) seem to support the suggested declining trend. However, the apparent slope seems to be smaller for miscellaneous aggregates compared to silica-based aggregates. Various damage mechanisms that can impact the deterioration of concrete strength were also addressed, including internal damage to the cement paste resulting from gamma radiation and high temperature, as well as damage associated with the aggregate, such as variations in thermal expansion or distortion produced by radiation-induced swelling. While cement pastes traditionally exhibited less vulnerability to structural alterations, empirical evidence has demonstrated their susceptibility to degradation under specific circumstances, therefore impacting the overall strength of the concrete composite.

2.2. Tensile strength

The tensile strength of irradiated concrete is more crucial than its compressive strength for structural performance under shear loading. The research gathered by [13] demonstrates that the impact of neutron irradiation on the tensile strength of concrete surpasses its influence on the compressive strength.

The most significant reductions in strength were observed when irradiation was conducted at temperatures over 100 °C, consistent with prior findings that higher temperatures lower the tensile strength of silicate concrete. The analysis highlights the significant variation and dispersion in tensile strength data compared to compressive strength. This may be attributed to variations in mix composition, such as aggregate size and constituent proportions, which are highly responsive to variations in tensile strength. The scarcity of data on post-irradiation tensile strength hinders the ability to conduct comparisons among various aggregate types. The primary cause of strength deterioration is the irradiation itself. This means that concrete and mortar exposed to neutron irradiation above 10^{19} n/cm² could experience a significant decline in structural performance, as presented in Fig. 5. The shaded polygon in the drawings indicates the prediction interval of 90%. The analysis indicates that the compressive strength remains nearly constant at the reduced fluence level.

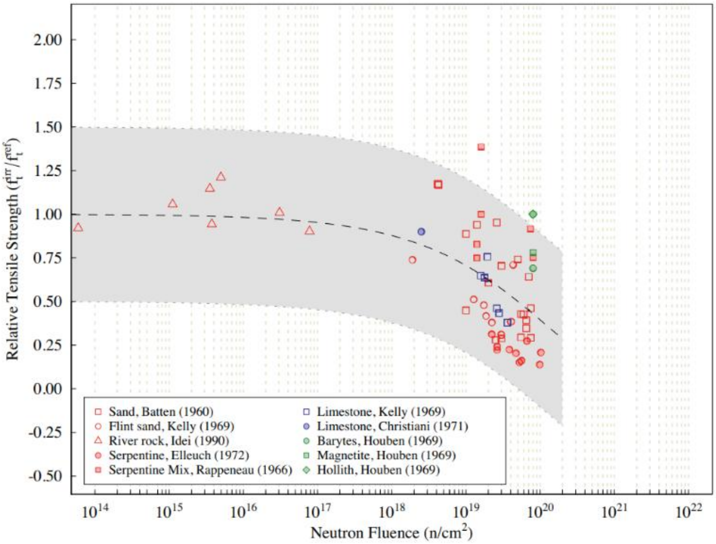

Fig. 5. A plot of concrete relative tensile strength versus neutron fluence Source: [13]

2.3. Modulus of elasticity

Increased neutron exposure reduces the elastic modulus of concrete. The impact of neutron irradiation on the elastic modulus is comparatively smaller than its influence on the compressive or tensile strength. Nevertheless, there is a progressive decline in the elastic modulus when the fluence exceeds 2.0×10^{19} n/cm², irrespective of the concrete's aggregate type. The most significant reductions, reaching almost 60%, were observed in tests conducted at temperatures up to 100 °C, specifically for silicate concrete.

The largest decrease is seen in studies conducted above 100 °C, while studies below 100 °C show a limited decrease. The reduction in elastic modulus for neutron fluence above 1.0×10^{19} n/cm² might be due to the combined effect of high temperature and radiation exposure, or it could be a methodological flaw in the research because of the high temperature used in these studies. The authors reference [10], who indicate that a reduction in elastic modulus beyond a fluence of 1.0×10^{19} n/cm² could be attributed to the combined influence of high temperatures and neutron radiation. The relationship between temperature and the modulus of elasticity of concrete is extensively studied and often exhibits a trend of decreasing values as temperature increases. Effectively, the reduction in modulus of elasticity is contingent upon the specific type of aggregate used; thus, concrete incorporating silicate aggregates exhibits more significant reductions compared to concrete containing other forms of aggregate.

2.4. Weight change

Most studies reporting weight loss in concrete used a mix design with 7–8% free water by weight and involved either long-term ageing in a controlled environment or pre-drying specimens before irradiation. The weight loss in irradiated concrete is likely due to the dehydration of the cement paste and can be attributed to the irradiation environment or how the samples were handled. The investigation struggled to identify distinct patterns linked to the various forms of aggregates, and the findings indicate significant diversity.

Research on pure cement has consistently revealed a linear relationship between shrinkage and weight loss at specific fluence levels. Additional evidence supporting this observation is derived from reports of gas production during concrete irradiation, primarily composed of hydrogen and oxygen, due to the processes of radiolysis and drying of free water. Nevertheless, the absence of in situ evaluations of gas production in connection with mass loss poses a challenge in ascertaining whether radiation expedites the drying process of cement paste.

Furthermore, several investigations have been carried out employing low neutron fluxes, leading to the prolonged exposure of samples to elevated temperatures beyond the necessary duration for complete dehydration of the cement paste, potentially influencing the obtained outcomes. The observed correlation between mass change and fluence, both within individual trials and across multiple investigations, indicates that the decrease in mass is mostly caused by the drying of the cement paste. However, the possible impact of accelerated neutrons or gamma radiation has not been extensively studied [13].

2.5. Dimensional changes

Irradiated concrete undergoes dimensional changes in both the aggregate and cement paste, including drying shrinkage and neutron effects. The volumetric expansion observed in irradiated concrete is greater than that caused by other factors. Limestone aggregates in concrete show limited dimensional changes of around 5% compared to flint aggregates at over 9%, while the cement paste contracts. The expansion results from various factors, including irradiation temperature and neutron-induced changes in materials. It was also noted that the cement paste (ordinary Portland cement) exhibited shrinkage, suggesting that while the cement paste tends to shrink, the concrete as a whole tends to expand after high fluence irradiation.

Swelling in aggregates, particularly in complex minerals irradiated at 3.0×10^{20} n/cm², likely indicates the overall expansion of concrete and mortars.

High thermal expansion of concrete can cause permanent deformation of components when exposed to radiation. Aggregates constitute almost 70% of the overall volume of concrete, thereby indicating that the thermal expansion of concrete is significantly influenced by the specific type of aggregate used. The observed expansions for both silicate and limestone concrete above 1.0×10^{19} n/cm² are larger than the usual irreversible expansions caused by thermal effects. This indicates that neutron irradiation has a substantial impact on the volumetric expansion of concrete. A hypothesised relationship exists between irradiation-induced aggregate expansion and the resulting expansion of concrete and mortar.

The observed association implies that the expansion of aggregates can serve as a credible indicator of the expansion of concrete and mortar, thus providing further confirmation of the impact of neutron radiation on these materials. The restricted expansion of aggregates at fluences below 1.0×10^{19} n/cm² (at all temperatures) suggests that this phenomenon is caused by neutron transmission. The phenomena responsible for this increase and their correlation with the deterioration of irradiated concrete structures are referred to as Radiation-Induced Volumetric Expansion (RIVE). Under high neutron fluences, neutron irradiation induces amorphisation of aggregates, resulting in a reduction in density and volumetric swelling. The largest volumetric expansion observed is between 14% and 15% [13]. This expansion is permanent and compromises the integrity of the concrete, resulting in the formation of tiny fissures in both the cement paste and the aggregates. Disparities in deformation between the cement paste and the aggregate give rise to microcracks in the cement paste, whereas microcracks in the aggregates arise from anisotropic swelling of the various phases within them.

The extent of RIVE is influenced by the matrix, meaning that silicate aggregates exhibit more expansion than carbonate aggregates. This is attributed to variations in crystal structure and the characteristics of the chemical bonds. The process of aggregate amorphisation results in substantial reductions in the mechanical characteristics of concrete. This is especially important when considering the extended operation of nuclear power plants, where neutron fluences may exceed 1.0×10^{19} n/cm².

The relationship between ion irradiation-induced amorphisation and volume expansion in quartz and feldspar aggregates has been studied [14], highlighting that volume expansion persists even after post-irradiation annealing, due to permanent amorphisation and vitrification of quartz. This supports previous findings indicating a complex relationship between amorphisation and expansion, suggesting that volumetric changes may continue even when minerals become fully amorphous. Understanding defect density and associated mechanical changes is essential, especially given the critical role aggregates play in maintaining structural integrity under neutron irradiation in nuclear reactor environments.

A recent mesoscale numerical study [15] investigated the effects of RIVE on concrete behaviour, taking into account not only the expansion of aggregates but also associated temperature rise, drying, and damage development in the mortar matrix and interfacial transition zones. Finite element simulations of 3D cylindrical concrete specimens, composed of mortar, polyhedral aggregates, and interfaces, showed good agreement with experimental data for residual Young's modulus, compressive strength, and macroscopic expansion at neutron fluences exceeding 6×10^{19} n/cm². The study emphasised the necessity of including RIVE effects in the mortar phase, justified by the high-volume fraction of embedded sand grains, and revealed significant desaturation of the material due to irradiation-induced heating.

2.6. Limitations

Several key limitations have been identified across recent research on concrete used for radiation shielding in nuclear facilities. A critical issue noted by [10] is the scarcity of reliable experimental data, with only a portion of reviewed publications providing usable results due to inconsistencies in testing methods, materials, and conditions. [13] also emphasised limitations related to data normalisation, particularly regarding neutron fluences exceeding 1.0×10^{19} n/cm², which often lack relevant temperature and neutron energy cut-off data, reducing practical applicability to real nuclear environments.

Research by [12] indicated that although variations in the water-to-cement (W/C) ratio minimally influence radiation attenuation, significant reductions in mechanical strength occur with increased W/C ratios, complicating mix optimisation.

Early works by [1] and [11] further revealed that long-term radiation exposure and environmental conditions – such as freezing and thawing – are insufficiently considered in experimental protocols, resulting in limited predictive capability for real-world performance. High radiation doses can significantly degrade mechanical properties due to aggregate swelling and matrix shrinkage, but the lack of standardised testing across laboratories complicates accurate assessments of long-term degradation trends.

In summary, despite extensive research, critical limitations related to experimental data consistency, long-term durability assessments, material optimisation, and realistic testing conditions remain significant obstacles in developing reliable radiation shielding concrete for nuclear applications. Addressing these limitations through standardised procedures, advanced material formulations, and comprehensive long-term studies is essential for improving safety and durability in nuclear power plants.

3. Recent trends and developments in radiation shielding concrete

Recent research has explored the development of ultra-high-performance concrete (UHPC) with radiation shielding properties. UHPC is very strong due to its high density, but its gamma attenuation is lower than that of high-strength concrete with the same type of heavyweight aggregate at the same energy exposure. A new type of concrete, radiation shielding concrete (RSC), has been developed as a superior alternative to many traditional concretes for radiation shielding, as gathered and described by [16]. RSC, frequently referred to as nuclear protection concrete or heavyweight concrete, is a cement-based composite composed of water, cement, and heavyweight aggregates. Concrete made with magnetite aggregates can have a density of 3.2–4 t/m^3, significantly higher than that of concrete made with ordinary aggregates.

The increasing occurrence of industrial waste has led to interest in its potential use in the production of radiation-shielding concrete, as it is readily available and inexpensive compared to the limited resources of haematite or magnetite. Table 2 shows potential alternatives to heavy natural aggregates [17].

Table 2. Alternative materials used in RSC. *Source*: [17]

Mines wastes	Lead and zinc mines Borax Barite Fluorspar mines
Industrial wastes	Ferrous slag Non-ferrous slag Fly ash and red mud Silica fume
Commercial wastes	Polymers Marble wastes Cathode ray tube funnel glass
Virgin materials	Fibres Artificial aggregates Powder Nano-particles

Due to the long life cycle of shielding concretes in nuclear facilities, there is a growing trend of research into the selection of mineral admixtures for radiation shielding in concrete at the decommissioning stage of a nuclear power plant after 60 years of operation. The most common admixtures, such as Portland cement, granulated blast furnace slag, and fly ash, were investigated, and it was found that concrete with ash admixtures has 9% higher radioactivity than with the other admixtures [18].

A recent study [19] evaluated the gamma-ray and neutron shielding efficiency of fourteen concrete formulations containing varying proportions of boron carbide, iron, and iron boride. Results showed that a composition of 20% iron and 80% concrete provided the most effective neutron shielding, while boron carbide significantly enhanced the material's stiffness, as reflected by an increase in elastic modulus. These findings demonstrate that tailored concrete mixes can offer optimised combinations of mechanical strength and radiation protection, with the 20% Fe mix standing out as a promising material for nuclear shielding applications. The combined influence of aggregate type (magnetite, amphibolite, serpentinite) and cement type (ordinary Portland and slag cement) on gas permeability and gamma-ray shielding performance of concrete has been thoroughly examined by [20]. The research revealed that magnetite aggregates significantly improve radiation attenuation and reduce gas permeability, making them highly suitable for shielding applications. In contrast, serpentinite aggregates resulted in lower density, reduced compressive strength, and increased permeability due to microstructural defects at the interfacial transition zone. The use of slag cement generally reduced gas permeability and water absorption compared to ordinary Portland cement, although the latter offered better gamma attenuation. Research performed by [21] on barite concrete has been conducted to evaluate its effectiveness in gamma radiation shielding using both linear and environmental ^{60}Co irradiation methods. The results showed that barite concrete improved the linear attenuation coefficient by 13–18% compared to normal concrete, with the environmental method offering a more accurate representation of γ diffusion in nuclear engineering contexts.

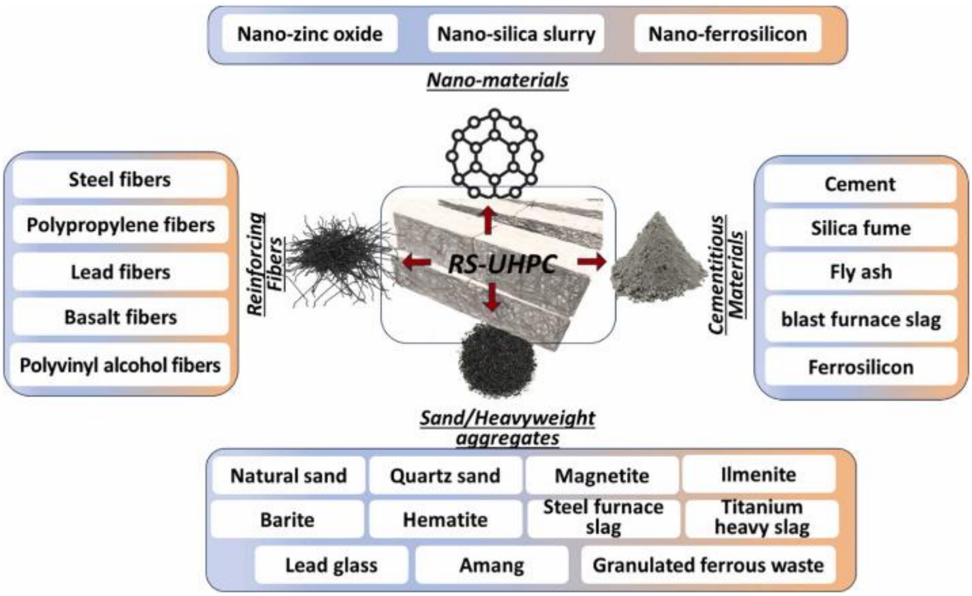

Fig. 6. Diagram illustrating the various materials influencing the design of Radiation Shield – UHPC. *Source:* [22]

A comprehensive review by [23] and [24] highlights key research gaps, including the need to investigate material behaviour under extreme conditions (e.g. temperature, moisture, radiation), the limited understanding of radiation interaction with concrete microstructure, and insufficient data on the long-term durability, mechanical performance, and environmental impact of RSC. Studies performed by [25] and [17] noted that using dense aggregates or industrial wastes (IWs) can lead to segregation or durability issues due to impurities, ultimately affecting concrete performance and structural integrity over time. Furthermore, [18] discussed barriers to implementing ultra-high-performance concrete (UHPC), citing limited standardisation and affordability concerns. Polymer-based composite shielding materials were similarly found to have substantial drawbacks, including poor thermal stability, low neutron attenuation efficiency, and challenging compatibility at interfaces [26].

Future research is needed on the influence of binding materials, particularly active mineral additives, on radiation shielding characteristics. Nanotechnology has enabled the development of materials specifically engineered for effective radiation shielding, which can be integrated into existing structures without extensive modifications. Figure 6 shows the factors affecting the properties of UHPC concrete.

Additional investigation is required into the durability and self-healing capabilities of UHPC, especially its potential for crack-sealing, which offers a significant advantage in resisting ageing and extending its service life as a shielding structure [25].

The integration of artificial intelligence (AI) and nanotechnology in the development of radiation shielding materials represents a highly promising advancement in nuclear applications. A notable research direction involves the use of AI techniques to predict the mechanical and physical characteristics of nuclear concretes, akin to applications in other types of concrete [27,28], or to support decision-making in concrete mix design [29]. AI techniques, such as Support Vector Machines (SVM) and Artificial Neural Networks (ANN), have demonstrated impressive accuracy, reaching up to 92% and 89% in property prediction, respectively. These tools also optimise synthesis processes, enhancing material performance by up to 35% and improving energy efficiency by approximately 40% through methods such as Genetic Algorithms and Particle Swarm Optimisation [30]. Moreover, AI technologies are revolutionising computational simulations in radiation shielding. The MCShield programme, for example, incorporates Auto-Importance Sampling (AIS) to significantly enhance accuracy and computational efficiency, especially in complex shielding scenarios [31]. ANN-based approaches further streamline the design of thermal neutron shielding compositions, reducing the need for time-consuming simulations [32]. Simultaneously, nanotechnology is contributing to the development of innovative shielding materials. Polymer composites enhanced with nanoparticles – such as graphene and carbon nanotubes – are being engineered to match the gamma attenuation performance of traditional heavy metals while exhibiting lower toxicity and environmental impact [33]. High-entropy alloys and composite materials also demonstrate strong shielding capacity across various radiation types [34]. Nanomaterials, including polyimides and fluorinated hyperbranched polymers infused with functional nanoparticles, offer lightweight, flexible solutions suitable for high-demand environments like aerospace applications [35]. The synergy of AI-driven optimisation and nanotechnological innovation enables the design of high-performance, environmentally sustainable shielding materials, tailored to specific operational conditions [36].

Concrete remains the most widely used material for radiation shielding in nuclear facilities due to its effective neutron and gamma-ray attenuation, affordability, and adaptability in formwork. While theoretical models exist to estimate shielding thickness, they remain limited in scope and often neglect the effects of radiation-induced degradation. This underscores the need for more sophisticated and unified modelling approaches that integrate material physics with structural mechanics to accurately predict long-term performance [37].

Current material solutions for shielding concrete remain vulnerable to degradation caused by changes in mechanical and physical properties. However, emerging trends in the development of advanced shielding concretes aim to address these challenges. Given the rapid development of nuclear energy, plans for new nuclear units across Europe, and the rising interest in Small Modular Reactors (SMRs), there is a clear opportunity to enhance nuclear power plant design. This can be achieved by engineering concrete materials with improved radiation resistance and extending reactor service life well beyond 80 years.

4. Conclusions

- Ionising radiation in nuclear power plants poses a risk to personnel, equipment, and other nuclear structures and components. The Concrete Biological Shield has different designs depending on the type of power plant and is the main radiation barrier. Maintaining the physical and mechanical properties of concrete under irradiation is critical to the operational safety and viability of nuclear facilities.
- The Concrete Biological Shield is typically made from Type II Portland cement and heavy aggregates such as barite and magnetite. Radiation and long-term exposure in nuclear facilities cause a loss of the physical and mechanical properties of concrete through temperature increase, radiation activation of concrete, permeability changes, and internal carbonation.
- Although neutron radiation has a limited direct effect on the strength of the cement matrix, other factors such as heat damage, gamma irradiation, and damage associated with aggregates contribute to the weakening of concrete. Empirical evidence consistently shows that the compressive strength of concrete exposed to neutron radiation decreases as the neutron fluence increases, with significant reductions in strength at higher fluence levels.
- Irradiation with neutrons reduces the tensile strength of concrete significantly more than its compressive strength. This is particularly dangerous because the tensile strength of irradiated concrete is more critical than its compressive strength for structural performance under shear loading.
- Increased neutron exposure reduces the elastic modulus of concrete, especially at temperatures above 100 °C, due to the combined effects of high temperature and radiation.
- Dehydration of the cement paste, influenced by irradiation, is probably responsible for the 7–8% weight loss reported in irradiated concrete.
- Irradiated concrete undergoes significant dimensional changes, with aggregate expansion and cement paste shrinkage, particularly after high neutron fluence, with limestone aggregates showing less expansion (~5%) compared to flint aggregates (~9%).
- Current research on UHPC focuses on the integration of industrial waste, active mineral additives, and nanotechnology, polymers, and composites into concrete mixes, to enhance concrete properties and improve durability and radiation absorption in nuclear applications.
- With Small Modular Reactor technologies advancing towards deployment, research into radiation-resistant concrete is crucial. AI-driven models can support this by predicting material performance under irradiation, helping to design safer and more durable shielding tailored to nuclear conditions.

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