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Review

Degradation of Concrete Structures in Nuclear Power Plants: A Review of the Major Causes and Possible Preventive Measures

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Abstract: Concrete, an integral part of a nuclear power plant (NPP), experiences degradation during their operational lifetime of the plant. In this review, the major causes of concrete degradation are extensively discussed including mechanisms that are specific to NPPs. The damage mechanism could be chemical or physical. The major causes of chemical degradation include alkali–aggregate reactions, leaching, sulfate attack, bases and acids attack, and carbonation. Physical degradation is a consequence of both environmental and mechanical factors combined. These factors are mainly elevated temperature, radiation, abrasion and erosion, salt crystallization, freeze–thaw distortions, fatigue and vibration. Additionally, steel reinforcements, prestressing steels, liner plates, and structural steel also experience degradation. The prospective areas in the structural components of the NPP where the degradation could occur are mentioned and the effective solutions to the causes of degradation are highlighted. These solutions are designed to enhance the physical and chemical characteristics of concrete. Some of the major recommendations include addition of mineral substitutes, use of low water-to-cement ratio as well as low water-to-binder ratio, use of low alkali cement, use of special aggregates and fibers, use of corrosion inhibitors, use of cathodic protection, etc. The review concludes with an overview of present methods and possible recommendations used to enhance the quality of concrete towards preventing concrete degradation and increasing the lifetime of NPPs.

Keywords: nuclear power plants; concrete; reinforcement structures; degradation; chemical attack; physical attack; mineral admixture; water-to-cement ratio; alkali-silica reaction; carbonation

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Citation: Rasheed, P.A.; Nayar, S.K.; Barsoum, I.; Alfantazi, A. Degradation of Concrete Structures in Nuclear Power Plants: A Review of the Major Causes and Possible Preventive Measures. *Energies* **2022**, *15*, 8011. https://doi.org/10.3390/en15218011

Academic Editor: Sung Joong Kim

Received: 15 September 2022
Accepted: 24 October 2022
Published: 28 October 2022

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1. Introduction

In nuclear power plants (NPPs), concrete structures are the main components used to support, contain, and protect the mechanical and electrical systems. Concrete structures are found in the primary containment building, the biological shield wall, secondary and internal containment as well as in cooling towers. The biological shield wall is the only structure expected to receive the radiation from the plant which is designed very close to the reactor vessel to absorb radiation and also acting as a load-bearing structure which supports the reactor vessel [1]. The concrete helps in preventing radiation releases, radiation attenuation (gamma radiation, neutron, and other irradiation), provide structural support for the nuclear steam system and different equipment in NPPs [2]. The degradation issues resulting from the nuclear power generation mainly occur in the containment building while other structures that surround the reactor building are not significantly affected by

the nuclear power generation process. Hence, different types of concretes have been used in NPPs according to the location and function of each structure in NPPs considering the safety, significance and environmental exposure.

From the NPP operational experience, it is obvious that concrete can be highly reliable without maintenance if it is properly designed for the exposed environment along with proper construction methods with high quality control [3]. In spite of all the understanding and consequent precautions, certain environments can damage the concrete either due to chemical or physical mechanism mainly by affecting the aggregates in the concrete or the performance of the cement-paste matrix [4]. As a result of this, these concrete structures in NPPs damage over time [5]. The locations of NPPs that are possibly vulnerable to different damage mechanisms are shown in Figure 1. Other than physical and chemical degradation, some other factors also contribute the aging process such as incorrect material selection, poor design, and exceptional environmental factors [4,6,7].

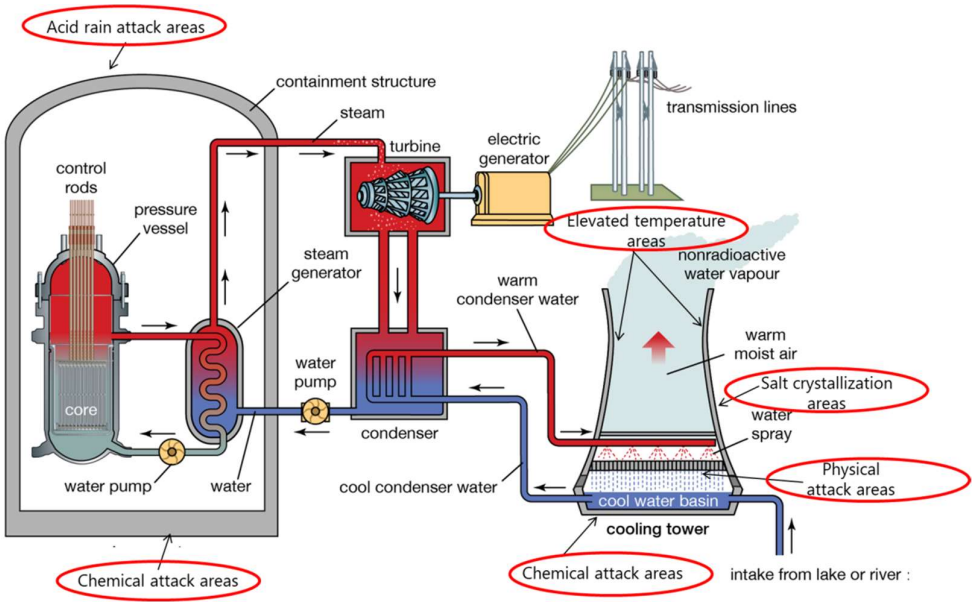


Figure 1. The structure of a NPP and different locations of the NPP which are potentially vulnerable to the degradation by chemical or physical mechanisms. The possible locations are marked in red circle. Reprinted with permission from [8]. @2013, Encyclopædia Britannica, Inc.

Significant extension of the service life of NPPs is possible mainly by preventing the material degradation of the concrete elements, hence it is necessary to evaluate the major causes of degradation and its mechanism [9]. In general it is observed that the performance of concrete structures in the NPPs is fairly satisfactory during initial 40 years of service life, subsequently, the mechanical properties start diminishing, even at lower ranges of neutron fluence values (mostly E > 0.1 MeV) [10]. The performance sustained during the earlier service life could largely be attributed to the integrity of calcium–silicate–hydrate gel, mostly constituting the tobermorite mineral formed during the hydration of cement, resulting in the required strength characteristics. However, degeneration of the mineralogical structure of aggregtaes due to long-term irradiation and radiation-induced swelling leads to considerable degeneration of concrete structures. These factors which are specific to NPPs in combination with the general possibility of degeneration due to common physical and chemical attacks of concrete, lead to the general agreement that the service life of concrete structures in NPPs cannot extend beyond 40 years. However, a proper understanding of the various mechanisms including radiation-induced degradation mechanisms can help mitigate these and thereby result in the design of NPPs which can last much longer than stipulated today.

This article majorly presents a review of the general and specific degradation mechanisms of concrete used in NPPs. In addition to concrete degradation, degradation of mild steel reinforcement, liner plate, prestressing steel, and structural steel are also discussed. The commonly adopted mitigation strategies for each mechanism are also included in the discussions. An attempt has been made to emphasize the vulnerability of NPP structures to these degradation mechanisms. To increase the service life of NPPs, it is proposed that the concrete design should be optimized for long-term performance for each specific components based on the corresponding environmental factors and structural loads. Towards these aspects, some techniques employed to improve the properties of concrete are discussed which include modifying the cement with adequate hydration heat, use of supplementary cementitious materials, use of heavy coarse aggregates, and the careful choice of fine aggregates and chemical additives [11,12]. Finally, a conclusion and overview of the present methods and recommendations to enhance the quality of concrete towards preventing concrete degradation and increasing the lifetime of NPPs is presented.

2. Concrete Degradation by Chemical Attack

Chemical degradation on any concrete structure may originate from the chemical reactions between the cement paste/coarse aggregate and the environment. Although the chemical reactions generally occur at concrete surfaces and the areas between cracks, the entire cross-section of the concrete structure can be damaged after continuous exposure for a long time. The factors affecting the degree of chemical damage on the concrete materials are mainly the pH of the attacking fluid and the concrete's properties, such as alkalinity, permeability, and reactivity. The major mechanisms of chemical attack on concrete are alkali–aggregate reactions, leaching, effect of bases and acids, salt crystallization and sulfate attack.

2.1. Alkali–Aggregate Reactions

Portland cement contains large amounts of alkali ions and hence alkali–aggregate reactions occur in the presence of reactive silica, silicate, or carbonate in aggregate materials. Alkali–silica reactions (ASRs) cause the development of alkali–silica gel (e.g., calcium sodium silicate hydrate and calcium potassium silicate hydrate) which swells when in contact with water [13]. The mechanism of ASRs is given in Figure 2. A combination of reactive aggregate, high moisture levels and high alkalis can enhance this process. The reactivity of aggregates is closely related to the mineralogical evolution of the parent rock, whereas the presence of moisture and alkali is a consequence of the local environmental condition and the pore-solution characteristics of the concrete [14]. The amount of ASR gel mainly depends on the reactive nature of the silica, the amount of hydroxyl ions in the pore-solution, and the internal structure of the aggregate along with other factors such as gel composition, gradation of aggregates, reaction temperature, type and proportions of the reacting materials [15].

The swelling of alkali–silica gel can cause an increase in hydraulic pressure in the concrete which results in significant cracking of the concrete and loss of the mechanical properties (i.e., stiffness and tensile strength). This would in turn cause the reduction in the lifespan of NPPs. The primary structures susceptible to alkali–aggregate reactions are the concrete structures exposed to water (rain, cooling or ground water, or humidity inside containment areas. It is also found that neutron irradiation can enhance the reactivity of silica-rich aggregates leading to increased ASR gel formation [16,17]. The alkali-aggregate reactions cause damage to the concrete structures typically in the first 10 years of the NPP's lifespan. However, the presence of less reactive silica delays the concrete deterioration up to 20 years [18]. ASRs have been observed in NPP concrete structures in different countries, such as Belgium, Canada, the USA and Japan [3].

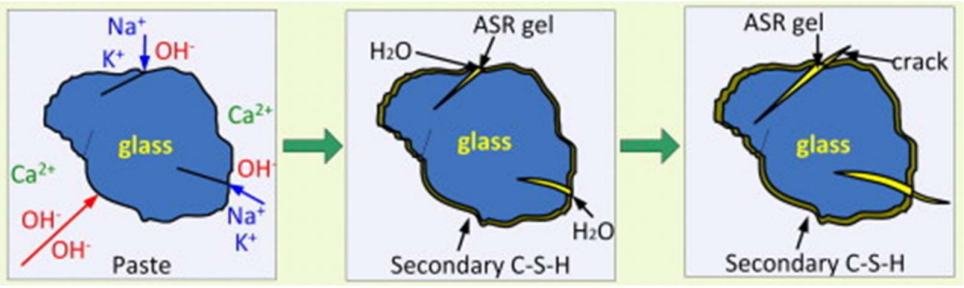


Figure 2. Mechanism of ASRs. Alkalis from cement react with silicaceous aggregates which result in gel formation. The formed gel absorbs moisture and expands followed by the formation of cracks. Reprinted with permission from Ref. [19]. Copyright © 2014 Elsevier Ltd.

The addition of mineral admixtures in concrete provides partial protection against ASRs (see Table 1). Ramlochan et al. examined the efficacy of highly reactive metakaolin towards the inhibition of ASRs and found that integration of 20% metakaolin reduced the long-term ion concentrations (OH^-, Na^+, and K^+) in pore solutions [20]. Another study showed that fly ash (FA) replacement (optimum level of 25–40%) changed the pore chemistry of the solution as well as lower the calcium and hydroxyl ion concentration; hence, this could be used for controlling the ASR mechanism [21]. However, these two studies used comparatively higher replacement levels of admixtures. It was found that metakaolin and FA help to reduce the expansion of interfacial transition zone between the alkali aggregates and cement paste, and hence they can control the ASR-related damages [4]. Boddy et al. found that 8% to 12% silica fume substitution was effective in controlling ASRs mainly due to the effect of the materials towards the composition of the pore solution and on the expansion due to ASR [22].

Table 1. Important admixtures that can be used to prevent ASR damages in the concrete structures.

Mineral Admixture	Replacement Level	Results	Ref
High-reactivity metakaolin (HRM)	20%	Reduction in alkali concentration, Reduction in long term concentrations of OH^-, Na^+, and K^+	[20]
Fly ash (FA)	25–40%	Reduction in expansion and cracking	[21]
Silica fume	8% to 12%	Able to control ASR	[22]
Steel fibers	2%	Controls ASR expansion, mechanical properties can be restored	[23]

The introduction of steel fibers can reduce ASR expansion significantly and prevent the loss of mechanical properties due to ASR expansion [23]. Similarly, another study found that concrete incorporated with steel or synthetic macrofibers can minimize the ASR damage, preserving their original post-peak loading capacity during the ASR reaction [24]. Steel fibers can be used to reduce ASR expansion considerably; however, this does not mitigate ASR expansion completely [23]. In general it can be concluded that pozzolans at specific ratios can prevent ASR because their reaction products reduce free -OH ions by sequestering alkali available in the reaction mixture [25].

2.2. Leaching

Leaching is a diffusion–reaction phenomenon, which alters the cement paste matrix as a result of dissolving calcium-containing elements through hydrolysis. The leaching process results in an increase in pores and increases the permeability of the concrete thereby causing harmful effects on the long-term durability of the concrete. The concrete areas exposed to water are the most vulnerable to the leaching process. However, leaching can be seen even on dry surfaces of concrete structures of NPPs which might lead to a reduction in alkalinity of the concrete followed by corrosion of the reinforcements and

surroundings [26]. The leaching process lowers the compressive strength, increases the vulnerability to environmental attacks, and ends up in corrosion of the steel reinforcements due to chloride penetration.

Generally, leaching can be controlled by using a low water-to-cement (w/c) ratio thereby reducing the water leaching ratio, increasing the curing time, and by using cement with low alkali content [27–29]. The commonly used solution against leaching is the use of mineral admixtures in the concrete since the silica-rich mineral reacts with the calcium hydroxide which increases the formation of impermeable C–S–H gel [4].

The use of silica fumes and fly ash mixtures in the cement paste also favor the formation of stable C-S-H gel which can improve the leaching resistance. In addition, it has also been shown that a lower calcium-to-silica ratio decreases the porosity by forming additional C-S-H gels [30]. Another work demonstrated that cement pastes containing a small amount of FA were not affected by leaching while cement pastes with 65% of FA were damaged severely (Figure 3) [31]. However, they also found that the cement–slag pastes with less than 70% slag content showed promising long-term leaching resistance. Use of nano silica particles has also been shown to minimize the calcium-leaching rate in cement pastes by the formation of longer silica chains upon hydration which results in the formation of highly stable calcium–silicate–hydrate gels [32].

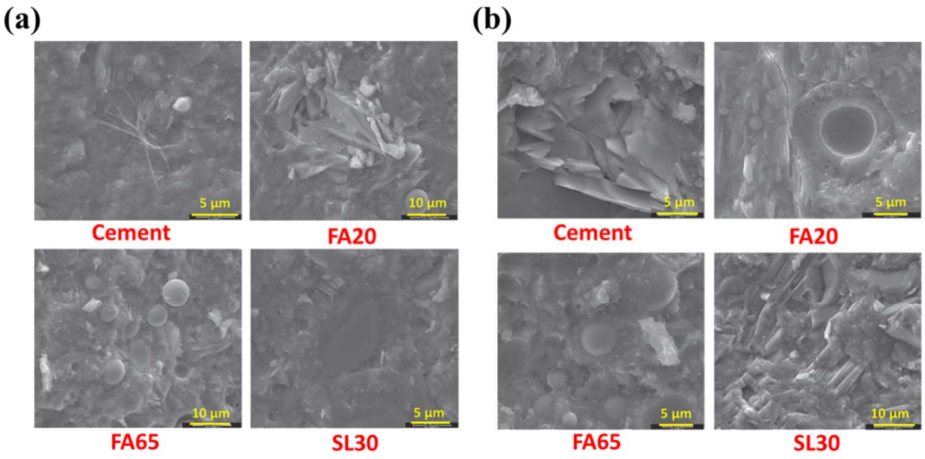


Figure 3. (**a**) Morphological characterizations of composite binder pastes. (**a**) before leaching, and (**b**) after leaching for 3 years for cement, FA20 and FA65 samples, and for 2 years for SL30 sample. FA20 stands for cements with 20% FA, FA65 stands for cements with 65% FA, and SL30 stands for cements with 30% slag. Reprinted with permission from [31]. Copyright © 2014 Elsevier Ltd.

2.3. Sulfate Attack

Exposure to sulfates present in the surrounding environment of NPPs leads to sulfate attack on concrete which is a major deterioration mechanism. Sulfate exposure is one of the major causes of the loss in compressive strength and expansion in volume of concrete [33]. Sulfates react with different concrete components in concrete to form ettringite and gypsum, which results in the expansion and disintegration leading to loss of strength [34]. The two main factors which affect the rate of sulfate attack are the concentration of sulfate and reactivity of the cement paste [35]. Anything above 1200 ppm (parts per million) concentration of sulfate in the environment can aggressively attack concrete in NPPs.

During the normal concrete curing process, ettringite is formed by the combining calcium aluminate with sulfate [36]. However, at higher curing temperatures, the ettringite formation can be inhibited. The reformation of ettringite in hardened concrete leads to the generation of extensive pressures, and cracking of the concrete in the presence of moisture, which is denoted by delayed ettringite formation (DEF). DEF is the result of high initial temperatures, more than 70–80 °C, in which the usual formation of ettringite is prevented or the decomposition of already formed ettringite. DEF can be enhanced by the use of

cements with high aluminate and sulfate content [36]. The degree of DEF also depends on the availability of water in concrete, presence of microcracks and the temperature.

Similar to the mitigation techniques for other deterioration mechanisms, the use of mineral admixtures has been effective in minimizing sulfate attack by reducing the mobility of water and dissolved ions as well as by varying the early hydration process. Table 2 shows some of the techniques adopted towards minimizing the effect of sulfate attack in concrete structures. Studies have shown that a lower water-to-binder ratio and moist-curing can reduce the sulfate attack as well as the presence of chloride ions can significantly minimize the sulfate attack with less expansion in specimens when the chloride concentration is higher [37,38]. Lee et al. proved that a low w/c ratio and a 5–10% silica fume replacement can be used to obtain good sulfate resistance [39]. Similarly, the replacement of cement with 5% volcanic origin pozzolan can be used to prevent sulfate attack owing to the enhanced pore structure of the concrete [40].

Another possible solution is the use of Type V cement with a lower C_3A content blended with natural pozzolan to protect against sulfate attack [41]. The same study also found that the resistance to sulfate attack increases when the C_3S/C_2S ratio increases. Diab et al. (2014) predicted the parameters for concrete with lower C_3A, for longer durations of exposure (200 years), using neural network-based modelling which was then verified experimentally, at least for shorter durations [33]. A study with different types of self-compacting concretes after exposure to sodium sulfate solution, the concrete integrating wastes from marbles and gravel tiles showed promising resistance to external sulfate attacks in comparison with ordinary vibrated concrete [42]. The degradation by sulfate is influenced by the amount of aluminates available in the concrete paste and the concrete containing wastes from marble and tile factories were significantly attacked by sulfate since these industrial wastes contain higher amounts of alumina. However, the sulfate ion penetration can be reduced by increasing the compactness of the concrete and reducing the pore interconnections.

The potential of mineral admixtures such as FA and slag in sulfate attack mitigation even in concrete with lower quality materials, such as recycled aggregates, has also been reported. However, the higher content of recycled aggregates may reduce the resistance of concrete against sulfates due to the high porosity and defects in recycled aggregates [43]. In addition, the replacement of a portion of cement with FA, slag or silica fume can significantly prevent DEF damage.

Table 2. List of measures/strategies to minimize the sulfate attack in the concrete structures.

Strategy	Results	Ref
Low water-to-binder (w/b) ratio + pozzolanic admixtures	The durability of concrete was enhanced significantly	[44]
Chloride in the presence of sodium sulfate	No deterioration was observed due to large fraction of ettringite	[37]
Low water-to-cement ratio and high concentration of chloride ions	Less expansion and less damage	[38]
Silica fumes (5–10% binder replacement levels)	Best resistance to sodium sulfate attack; however, a 15–20% strength loss can be expected	[39]
Natural volcanic pozzolan (5% binder replacement)	Improvement in sulfate resistance along with mechanical characteristics, and durability	[40]
Portland cement mortar with low C_3S content and natural pozzolana	Improved the sulfate resistance of low C_3A Portland cements	[41]
Marble, marble tiles and gravel tiles	Enhanced resistance to external sulfate attack for the sample containing marble	[42]
FA and granulated blast-furnace slag (GBFS) in 100% recycled coarse aggregate (RCA)	Better resistance against the sulfate attack and wetting-drying cycles	[43]

2.4. Bases and Acids Attack

Concrete structures are chemically attacked by acids and bases, in which acidic solutions are typically more reactive to the basic concrete/cement structures. The cement/concrete mixture may not react with other basic solutions since the mixture is highly alkaline with a pH of 12.5 or higher. However, when concrete is exposed to bases for a prolonged peior, deterioration can occur by chemical processes other than reacting with hydroxide ions. The possible acid solutions present in the NPP's surroundings are sulfuric acid, carbonic acid, phosphoric acid, acetic acid, etc. All these have a distressing effect on conventional as well as NPP concrete structures [4]. The rate of acid attack on concrete structures strongly depends on the pH of the surrounding fluid and the period of exposure. Acids reacts with the calcium components available in hydrated cement paste, such as calcium–silicate–hydrate, calcium hydroxide, and calcium aluminate hydrate, producing calcium salts which enhance the porosity and permeability of concrete [45–47].

It was found that the mineral admixtures can contribute positively against acid attack and Table 3 shows the effect of some admixtures against acid attack in the concrete structures. Mineral admixtures can reduce the permeability of concrete by enhancing the C–S–H content, followed by increase in the physical adherence at the cement–aggregate interfaces, which leads to stronger acid resistance. Roy et al. found that the incorporation of admixtures, such as metakaolin, silica fume, and low calcium FA in the concrete can be used to improve the acid resistance [48]. From a study it was found that the degradation process as well as the severity of the cracks in an acidic environment depends on the type of aggregates used, and concrete using limestone aggregates showed better resistance to acid attack [49]. They also found that using ternary cement containing FA and silica fume showed good resistance to the aggressive environment.

Aydın et al. observed that the incorporation of high-lime FA of up to 70% showed superior acidic resistance when it was made by steam curing [50]. Another study showed that concrete mixed with blast furnace slag exhibited a high resistance to the acidic environments [51]. However, there was only a slight increase in acid resistance when the replacement level changed from 50% to 85%. Makhloufi et al. evaluated the effect of the addition of slag, limestone filler, and natural pozzolan against a sulfuric acid environment and found that a blended mixture of slag and pozzolan exhibited good resistance to acid [52]. They concluded that cement replacement levels should be kept at around 30% for better sulfuric acid resistance. Similarly, another study found that the acid resistance was enhanced by the addition of natural pozzolan or limestone and the resistance varied depending on the proportion of admixtures [53]. The addition of pozzolanic materials can reduce the ratio of calcium-to-silicate, which can prevent the alkali entrapment and provide better acid resistance by densification and the formation of highly stable calcium–silicate–hydrate gels. It was observed that the incorporation of glass powder as a cement replacement (up to 45%) can enhance the mortar resistance to aggressive sulfuric acid attack [54]. Similarly, concrete with marble aggregates which is rich in calcium carbonate can improve the resistance to aggressive sulfuric acid attacks [45].

Table 3. The list of relevant studies with admixtures with positive effect against acid attack in the concrete structures.

Mineral Admixture	Replacement Level	Results	Ref
Silica fume, FA, metakaolin	0–30%	Chemical resistance was higher for silica fume followed by metakaolin and FA. The 0–10 wt.% replacement level showed high resistance for all the admixtures	[48]

Table 3. *Cont.*

Mineral Admixture	Replacement Level	Results	Ref
Limestone aggregates and ternary cement containing FA and silica fume	7% silica fume and 33% FA	The acid resistance was higher for concrete with limestone aggregates and ternary cement (with 33% FA and 7% silica fume) compared to other tested samples with different replacement levels	[49]
FA	0–70%	Strength loss decreased to 21% from 58% for 70% replacement level from 0% replacement level. Similarly, weight loss decreased to 3.3% from 5% for standard curing concrete and 8.3% to 1.1% for steam-cured concrete.	[50]
Blast furnace slag	50%	High resistance to the acidic environments	[51]
Slag and pozzolan	30% each	Good resistance to acid attack	[52]
Natural pozzolan and limestone fine	-	The acid resistance was improved; however, the rate of resistance varied depending on the proportion of supplementary cementitious materials	[53]
Glass powder	45% replacement level of cement	Enhanced mortar resistance against sulfuric acid attack.	[54]

2.5. Carbonation

Carbonation is the rarest degradation issue in NPPs, which is a chemical degradation process as a result of the reaction between Ca^{2+} and CO_3^{2-} ions [55]. In addition, the diffusion of CO_2 from the surrounding environment is the driving force behind carbonation. Carbonation results in the reduction of pH which may accelerate the corrosion of reinforcing bars in the concrete through the dissolution of the protective thin oxide passive layer. On the contrary, it is known that carbonation refines pore structures, decreases transport properties, and increases the strength of cement-based materials. The carbonation process increases with increasing temperature since penetration of CO_2 occurs at high temperature.

Presence of water/moisture is essential for the carbonation process. The water can act as a catalyst for this reaction; however, the carbonation reaction releases water which can prevent CO_2 gas penetration into the concrete network by filling the pores. Radiation can accelerate the carbonation of concrete due to the higher temperatures, and this process is called radiation-induced carbonation [56]. As discussed, the normal carbonation of concrete increases the strength of the concrete while radiation-induced carbonation decreases the strength of the concrete as a result of a series of chemical reactions [57].

To protect concrete structures from carbonation, different methods can be adopted such as increasing the CO_2 binding capacity, increasing capillary condensation and applying surface coatings [58,59]. Portland cement has the highest resistance to carbonation due to its high CO_2 binding capacity [58]. The CO_2 binding capacity can be increased by increasing the available CaO in Portland cement with a low level of binder replacement and using a higher binder-to-aggregate ratio. Other than CO_2 binding capacity, capillary condensation and porosity are additional parameters determining the carbonation rate [58]. It was found that porosity can be reduced by using a lower water-to-binder ratio, and a higher binder-to-aggregate ratio to increase capillary condensation [60]. Lowering the diffusion of CO_2 can be accomplished by increasing the relative humidity. Surface coatings can prevent carbonation by reducing the air permeability, hence reducing the diffusivity of CO_2 in concrete [61]. It was found that organic polymer coatings with at least 200 µm thickness were effective against carbonation [62]. Organic surface coatings reduce the permeation and diffusion coefficient of carbon dioxide and acrylic coatings were the most effective coatings among organic coatings [59,63].

3. Concrete Degradation by Physical Attack

Concrete can be damaged by physical attack mainly due to mechanical and environmental effects. Most of the prominent degradation mechanisms in NPPs are due to physical attack. The different processes causing physical damage to concrete materials are elevated temperature, irradiation, abrasion and erosion, freeze–thaw distortion, and salt crystallization.

3.1. Elevated Temperature

Generally, the exposure of the majority of concrete structures is limited to a maximum temperature of 65 °C based on their NPP specifications. However, the temperature can be raised up to the temperature of the steam system coolant in certain areas. The heat transfer medium, liquid sodium, may undergo accidental leakage in NPPs leading to a high temperature when it comes into contact with water [64]. The concrete performance at elevated temperatures depends on the temperature and duration of exposure, moisture content of the concrete, type of cement aggregates, and size of the structural elements. [65]. Usually, at higher temperatures the cement paste shrinks, while the aggregate mostly expands and this causes thermal stresses at the interface which results in cracking [66].

The concrete may lose its compressive strength and modulus of elasticity at 90 °C, and the loss will be higher when the temperature reaches 200 °C. The breakdown of cement gel starts at 180 °C since the free water is expelled by the dehydration process at this temperature [67]. At temperatures of around 400 °C, the decomposition of calcium hydroxide to quick lime and water happens, which induces secondary internal stresses [68]. At temperatures above 430 °C, the loss of strength is greater in concrete comprising siliceous aggregates compared to concrete with light-weight aggregates [69]. Sancak et al. observed that concrete loses its strength by approximately 50% after exposure to temperatures of 600 °C and it further degenerates to 80% at a temperature of 800 °C [69].

Chan et al. found that a significant increase in the pore size of concrete happened at higher temperatures [70]. It was also identified that the radiation in NPP reactors can cause the increase in the temperature of concrete components and structures [71]. For example, neutron and gamma radiation may increase the temperature of up to 250 °C and the rise in the temperature has major impacts on the mechanical and radiation-shielding properties of concrete [72]. From these studies, it was revealed that the heat generated by NPPs definitively reduces the strength of concrete components progressively [73]. Specific effects due to irradiation are discussed later.

Since the concrete temperature can be increased by both heat and radiation, concrete with low radiation penetrability can be used for better performance at high temperatures in NPPs. Sakr et al. found that the concrete with ilmenite aggregates exhibited an improved mechanical performance compared with concretes containing barite or gravel [74]. The concrete attenuation coefficient of ilmenite concrete was higher than gravel and baryte concrete by 39.8% and 8%of ^{60}Co at laboratory temperatures, respectively. Horsczaruk et al. showed that the compressive strength of the concrete with magnetite aggregate initially increased up to 300 °C and then reduced when the temperature reached 450 °C, followed by a gradual decrease in compressive strength at 800 °C [73]. Here, the use of magnetite aggregate in concrete significantly enhanced the mechanical properties when the temperature goes up to 450 °C. Although the mechanical properties diminish at higher temperatures, the performance was better than the concrete containing normal aggregates. To reduce the radiation effect towards heat production, hematite and barite aggregates can be used due to the radiation-shielding effect which is discussed in the next section [4].

Concrete containing OWA (olive waste ash) showed good performance at elevated temperatures compared to control concrete [75]. In addition, the performance of OWA concrete was diminished when the OWA content was increased from 7% to 22% and the performance of OWA concrete containing tuff aggregate was better compared to OWA concrete containing basalt aggregate. They also found that the OWA concrete with a w/c ratio of 0.5 was more resistant than a w/c ratio of 0.7, and an air entrained OWA concrete

was better than non-air entrained OWA concrete. The concrete containing palm oil fuel ash (POFA) showed no change in compressive strength up to 400 °C and a substantial strength loss beyond 600 °C [76]. In addition, they reported that the performance was better at higher replacement levels of POFA of up to 70% at elevated temperatures.

Li et al. reported that concrete containing ground granulated blast furnace slag (GGBFS) at a 10% and 30% replacement level were able to resist mass loss at up to 400 °C [77]. The relative compressive strength of concrete with 0%, 10%, 30% and 50% GGBFS was decreased with the increase in GGBFS content while the relative modulus of elasticity increased with GGBFS content. However, the degradation of concrete was greater at above 600 °C. Another study evaluated the performance of high-performance concrete (HPC) made with metakaolin and FA at higher temperatures [78]. The results showed that concrete with 20% FA displayed better performance while concrete containing metakaolin (10 and 20%) showed higher degradation in terms of durability and mass loss at temperature above 400 °C. Another study showed that concrete with a high volume of FA (70% replacement level) exhibited a higher fire resistance than concrete containing less than 70% FA and concrete containing slag [79]. The important admixtures that can be used to reduce the effects of elevated temperature in concrete structures are listed in Table 4.

Table 4. The list of important admixtures that can contribute towards the positive effects against elevated temperature in concrete structures.

Mineral Admixture	Replacement Level	Results	Ref
Ilmenite concrete	-	The concrete attenuation coefficient of ilmenite concrete was higher than gravel and baryte concrete by 39.8% and 8% of ^{60}Co at laboratory temperatures, respectively.	[74]
OWA	22%	The resistance of OWA concrete to elevated temperature was high at 22% compared to 7% and 15% at a w/c ratio of 0.5. The resistance was less for OWA concrete at a w/c ratio of 0.7.	[75]
GGBFS	10–50%	The relative compressive strength of concrete with 0%, 10%, 30% and 50% GGBFS was decreased with an increase in GGBFS content while the relative modulus of elasticity increased with GGBFS content.	[77]
High-performance concrete (HPC) made with metakaolin and FA	20% FA 10–20% metakaolin	The result showed that concrete with 20% FA displayed better performance while concrete containing metakaolin (10 and 20%) showed higher degradation in terms of durability and mass loss at temperatures above 400 °C	[78]
FA	70%	Concrete with a high volume of FA (70% replacement level) exhibited a higher fire resistance.	[79]
Palm oil fuel ash (POFA)	70%	The concrete containing palm oil fuel ash (POFA) showed no change in compressive strength up to 400 °C and a significant strength loss beyond 600 °C. At elevated temperatures, a better performance was obtained for a higher replacement level of POFA of up to 70%.	[76]
Magnetite	2300 kg/m^3	Enhanced the mechanical properties significantly up to a temperature of 450 °C.	[73]

3.2. Abrasion and Erosion

Abrasion is observed in the areas of cooling water intake and discharge, and floor elements in NPP structures. The abrasion–erosion damage is usually observed in spillway aprons, stilling basins, and tunnel linings [80]. Abrasion–erosion damage results from the friction between particles and the components at the concrete's surface during hydraulic structure operation and leads to the loss of material at the concrete's surface [81]. By enhancing the quality and compressive strength of the concrete, the abrasion–erosion resistance can be improved [82]. The abrasion–erosion resistance of NPP concrete can be enhanced by adding mineral admixtures, such as FA, using low w/c ratios and appropriate aggregates [82].

It was found that abrasion resistance increased with an increase in the percentage of FA content and achieved 40% enhancement with 40% replacement of fine aggregates with FA. In another work, it was found that waste foundry sand (WFS) can be used as the replacement for sand towards enhancing the abrasion resistance of the concrete [83]. The abrasion resistance increased with an increase in the amount of WFS and concrete containing 15% WFS was found to be effective compared to 0, 5, 10 and 20%. The depth of wear for mixtures containing 0, 5, 10, 15 and 20% WFS was found to be 2.84, 2.6, 2.5, 2.28 and 2.4 mm, respectively.

The incorporation of basalt fibers (0.14% by volume) was also found to significantly improve abrasion resistance at a 0.6 w/c ratio [84]. However, the addition of basalt fibers may decrease the compressive strength while the use of longer fibers at a high-volume fraction can decrease the abrasion resistance. In addition, the use of rubber at a 20% replacement level significantly improved the abrasion resistance although it reduced the strength of the concrete [85]. The increase in the rubber content from 0% to 20% led to an enhancement in the abrasion resistance by the fiber holding effect of rubber particles which kept the integrity of cement paste. The depth of wear decreased (abrasion resistance increased) from 0.91% to 0.17% when rubber was replaced by 20%.

3.3. Radiation-Induced Degradation

The degradation mechanisms induced by the irradiation of concrete is specific to NPPs, especially in containment vessels and waste storage facilities. Concrete structures of NPPs, especially the biological shields and radioactive waste storage facilities, are exposed to gamma and neutron radiation [57]. It was observed that the interaction of concrete with nuclear radiation caused aggregate expansion by geometric changes of solid phases and phase transformations which led to changes in the properties of concrete [86,87]. The compressive strength and stiffness of concrete diminished after exposure to the neutron irradiation due to the expansion of aggregates called radiation-induced volumetric expansion (RIVE) and internal damage in the concrete material which affected the transport properties of the degraded concrete [88,89]. Gamma rays can decompose water content in the concrete to hydrogen, oxygen, and hydrogen peroxide by radiolysis, and the by-product of radiolysis may react with cement paste [90]. This also leads to shrinkage of cement paste and subsequent damage to the concrete depends on the exposure temperature.

The irradiation behavior of concrete will be different for concrete with different types of aggregates. Additionally, the concrete containing the same aggregate can behave differently to radiation with respect to their microstructures [4]. Silva et al. evaluated radiation-induced changes in quartz which is considered a mineral analog of NPP concrete aggregates [91]. They found that the lattice parameters of quartz increased with neutron flux and amorphous content had been formed with a neutron irradiation of 4×10^{19} n/cm^2, reaching a maximum at a fluence of 2×10^{20} n/cm^2. It has been reported that minimum 1×10^{19} neutrons/cm^2 or 10^{10} rads for gamma radiation are required to have measurable damage in concrete [67]. Pomaro et al. showed that the mechanical properties of concrete degraded when exposed to irradiation above the threshold level [92].

Recently, the Japanese nuclear regulatory authority (NRA) found that concrete structures in NPPs were degraded due to neutron irradiation through reduction in the density

of the minerals [93]. In addition, the large volume expansion of aggregates results in severe degradation of concrete structures by forming many cracks around aggregates and results in a ~50% reduction in compressive strength of the concrete and ~70% reduction in Young's modulus. Radiation can induce the reactivity of aggregates towards ASRs depending on the composition of the cement in the concrete [94]. It was also found that radiation induced accelerated carbonation which can go into the depth of the concrete structure [95]. In conclusion, excessive irradiation of concrete results in cracks and spalls at exposed surfaces as well as losses in mechanical strength [2].

The damage due to radiation may be diminished by introducing insulation and air gaps. It was reported that high-performance concrete with the incorporation of magnetite was capable of enhancing the shielding efficiency against γ-rays in comparison to barite and goethite aggregate-based concrete. However, barite aggregates enhanced the radiation resistance in comparison with marble and limra due to the higher photon linear attenuation coefficients as reported by Akkurt et al. [96]. In another study, they evaluated the radiation-shielding property of zeolite aggregate and found that there was no radiation-shielding effect from this material [97]. Kharita et al. used 15% carbon powder to enhance the radiation-shielding property of hematite-containing concrete and found that the strength of the concrete increased while the shielding property against gamma rays and neutrons remained unchanged [98].

Heavy-density concrete made with air-cooled slag and fine aggregates of ilmenite can be used to enhance the shielding properties against gamma rays [99]. In the same study, they found that the crushed air-cooled slag can be used to develop concrete with high-mechanical strength compared with corresponding concrete made with crushed hematite and ilmenite. Thomas et al. investigated the possibility of building protective walls against neutron radiation using various specialized concrete skins [100]. They used a neutron absorber by incorporating natural limestone aggregate, boron carbide, and polyvinyl alcohol fibers.

The effects of hematite on the physical and mechanical properties of concrete have been evaluated by Gencel et al. [101]. They used 10 to 50% volume of hematite at a unique water-to-cement ratio of 0.42 kg/m^3. The results showed that the addition of hematite aggregates increased the density such that the thickness of the concrete required to obtain radiation shielding can be minimized. In addition, the composite with 10% hematite lost only 7.8% of the compressive strength while the plain concrete lost 21.3% of its compressive strength after 30 freeze–thaw cycles. Masoud et al. investigated the effects of barite/hematite on the radiation-shielding properties of serpentine concrete by partially replacing serpentine concrete with either hematite or barite aggregate at 25% and 50% [102]. They found that the incorporation of hematite or barite enhanced the attenuation properties of the serpentine-based concrete and 50% barite was found to be the best ratio in enhancing the shielding of gamma-rays and fast neutrons. The important admixtures that can be used against radiation effects in the concrete structures are listed in Table 5.

Table 5. The list of important admixtures can contribute towards positive effect against radiation in the concrete structures.

Mineral Admixture	Replacement Level	Results	Ref
Magnetite	1457 kg/m^3	Concrete made with magnetite aggregate enhanced the shielding efficiency against γ-rays	[103]
Barite aggregates	-	The photon linear attenuation coefficients were higher for barite aggregate than marble and limra	[96]

Table 5. *Cont.*

Mineral Admixture	Replacement Level	Results	Ref
Carbon powder	15%	The strength of concrete increased while the shielding property against gamma rays and neutrons remained unchanged	[98]
Limestone aggregate, B_4C and PVA	350, 120 and 7 kg/m^3	At high temperatures, compressive strength increased by 15% at temperatures between 20 °C and 200 °C and reached 18% while severe losses in the compressive strength (90% loss) were observed at 1000 °C.	[100]
Hematite	10%	The composite with 10% hematite lost only 7.8% of the compressive strength while the plain concrete lost 21.3% of its compressive strength after 30 freeze–thaw cycles	[101]
Barite/hematite	50%	The incorporation of hematite or barite enhanced the attenuation properties. The best ratio found was 50% barite	[102]

3.4. Freeze–Thaw Distortions

Freeze–thaw distortion is a fundamental issue of NPPs in cold climates in which moisture accumulates on the surfaces leading to degradation of concrete structures [104]. The water in the concrete expands as it freezes which results in an increase in hydraulic pressure in the concrete and ends up in cracking of the concrete especially when repeated freeze–thaw cycles occur. Hence, proper evaluation of the effect of freeze–thaw cycles must be taken into account before designing the lifetime of NPPs in locations where this could be critical. The freeze–thaw damages are visible on the outer surfaces of NPP components; hence it can be identified before the loss of the concrete's structural properties. Freeze–thaw distortions are the most commonly reported degradation issue in NPPs.

Freeze–thaw can reduce the concrete's resistance to the entry of harmful chemicals. The prevention of such chemical diffusion can be done by using mineral additives or kaolinite clay in the cement. Chung et al. found that both FA- and silica fume-enriched concrete at lower water-to-cementitious ratios with proper curing showed resistance to freeze–thaw damage [105]. Additionally, the use of these materials can significantly reduce the ion diffusion into concrete, improve the pore structure, and hence lead to better resistance.

Fan et al. evaluated the effects of nanokaolinite clay on the freeze–thaw behavior of concrete and found that the nanokaolinite clay enhanced the resistance to freeze–thaw owing to its smaller particle size and denser microstructures causing less damage [106]. The 5% nanokaolinite clay additive in concretes enhanced the compressive strength by up to 34% compared to the control samples. In addition, nanokaolinite clay enhances the electrical resistivity and reduces the chloride diffusion in the concrete samples due to its lower porosity. The 5% nanokaolinite clay additive achieved a 64% increase in the electrical resistivity and achieved a 59% reduction in the chloride diffusion coefficient compared to the control samples, after 75 freeze–thaw cycles.

In general, it has been well demonstrated that improvement in the ductility of concrete contributes positively to reducing the damage due to freeze–thaw. The use of rubber crumps, and fibers of different materials have all been commonly investigated as methods for achieving this. A study demonstrated that the use of rubber enhanced the freeze–thaw resistance with an increase in rubber content until 180 freeze–thaw cycles; however, it reduced the strength of the concrete [85]. Until 180 freeze–thaw cycles, concrete with 20% rubber had low mass loss than compare with concrete with 10% rubber, while after 180 cycles, concrete with 10% rubber showed lower mass loss than concrete with 20% rubber content.

Jang et al. found that the use of polyvinyl alcohol (PVA) fiber-reinforcement improved the freeze–thaw resistance owing to the interfacial bond between the cement matrix and the fiber [107]. They also showed that the addition of PVA enhanced the fatigue resistance of concrete in the freeze–thaw cycles. Similarly, the addition of waste crumb rubber to the concrete can enhance the resistance to freeze–thaw damage with a 0.6% optimal crumb rubber percentage and a particle size of less than 0.5 mm compared to the larger sized particles [108]. There was no absolute correlation between the particle size and compressive strength and the rubberized concrete lost its strength by 5.24% after 28 days. The smaller sized particles have a greater surface area and thus the greater the opportunity to entrain air, and this provides freeze–thaw protection. Another study compared the effect of the addition of steel and polypropylene fiber on the freeze–thaw cycle damage, and found that the freeze–thaw damage to concrete with steel fibers was lower than with polypropylene fibers [109].

3.5. Salt Crystallization

Salt crystallization is another issue in NPPs especially when they are located in rural/coastal areas and use sea water as a coolant. The water containing dissolved salts can permeate the concrete and salt crystallization occurs within the concrete pores when it evaporates. This salt deposit increases the stress enough to create micro-cracks in the concrete and hence causes a substantial threat for NPP concrete.

The use of low-permeability concrete can reduce the salt crystallization damage when exposed to water containing dissolved salt. Maes et al. found that the chloride penetration increased with more sulfate content at short immersion periods, except for high-sulfate-resistant concrete [37]. Different coating methods can be used to prevent chloride penetration, such as silane, polyurethane and acrylic coatings [110,111]. Other than coatings, different admixtures have also been used against salt crystallization damage. Lubelli et al. used sodium ferrocyanide as a salt crystallization inhibitor by mixing in a lime–cement mortar and found that the addition of the inhibitor enhanced the resistance of the mortar to salt crystallization [112]. In addition, the cross-sectional surface of the specimens showed that the sodium ferrocyanide inhibited the formation of specific crystal faces. Similarly, another study showed ferrocyanide decreased NaCl supersaturation in salt mixtures and changed the crystal morphology [113]. There is a formation of loosely bound dendritic crystals from the reaction between ferrocyanide and salt mixtures which promotes efflorescence so that some amount of structural damage occurs.

Chahal et al. proposed that that inclusion of S. asteurii in concrete with silica fume can reduce the chloride permeability of concrete due to calcite deposition as a result of bacterial activity [114]. They found that the inclusion of S. pasteurii in concrete reduced the porosity and improved the compressive strength owing to the bacterial cell deposition within the pores. Here, the bacteria acted as nucleation sites during the mineralization process as evidenced by the presence of calcium carbonate crystals (Figure 4). A study on replacing cement content with rice husk ash (RHA) at a 15% replacement level demonstrated that there was decrease in micro-pores which provided a dense and impermeable membrane which blocked the entry of chloride ions.

3.6. Fatigue and Vibration

Fatigue and vibration are mechanical causes of damage to concrete structures due to the fluctuations in loading, moisture content and temperature. The damage by fatigue in concrete structures starts from small cracks in the cement paste near to reinforcing steel, in large aggregate particles, or in defective areas. This will lead to large scale concrete failure when excessive cracking/deflections, or brittle fractures occur. So far, there are no significant fatigue-related concrete failures that have been reported in NPPs.

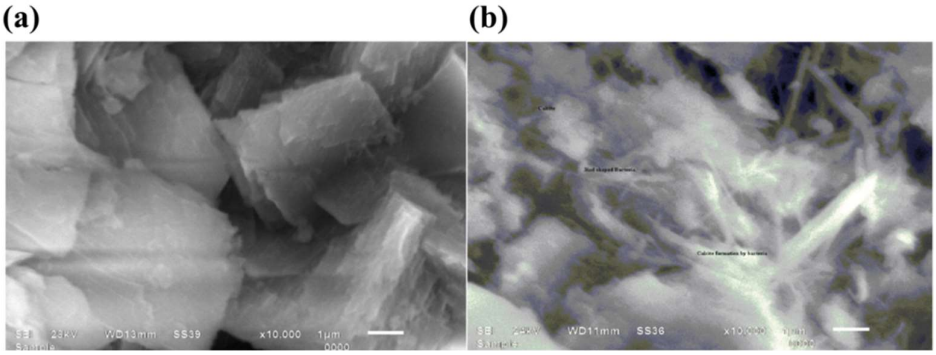


Figure 4. SEM images of (**a**) control and (**b**) concrete with the addition of *S. pasteurii*: bacterial calcite precipitation can be seen. Reprinted with permission from Ref. [114]. Copyright © 2012 Elsevier Ltd.

4. Degradation of Mild Steel Reinforcement

The degradation of the mild steel reinforcements within NPP concrete structures is caused mainly by corrosion along with other causes, such as elevated temperature, fatigue and irradiation. The main reasons for the corrosion in mild steel reinforcements are the thermal and mechanical stresses, corrosive external and internal environments, moisture content, presence of microorganisms and stray electrical currents. Electrochemical corrosion can occur either by the formation of a galvanic cell with two different metals in the concrete or by the formation of concentration cells due to the presence of different concentrations of dissolved ions. Generally, the high alkalinity of concrete (pH > 12) provides protection to steel from anodic activity. However, the ingress of chloride ions and sulfate ions can reduce the pH to less than 11, resulting in rust formation on the reinforcing steel.

Concrete corrosion mechanism becomes complex when chloride and sulfate ions interact with hydrated cement phases. It becomes more complex when the cations associated with chloride and sulfates are present [115]. Zuquan et al. found that the presence of sulfate in the sulfate–chloride composite can prevent the entry of chloride into the concrete at an initial exposure period, though, it increases the entry of chloride at a later stage of the exposure period [116]. It is found that reinforcement corrosion doesn't initiate when exposed to only sulfate ions while considerable corrosion can occur in a mixed chloride–sulfate solution [117]. The presence of sulfate ions in a chloride environment is independent of the initiation time of reinforcement corrosion: the concentration of magnesium sulfate and sodium sulfate can enhance the corrosion current density [118]. Thus, it may be established that for parts of NPPs located in areas prone to chloride exposure, the unavoidable presence of sulfate ions creates favorable conditions for accelerated corrosion and hence, appropriate mitigation strategies are imperative in such situations.

A typical mechanism of corrosion in NPPs is the microbially influenced concrete corrosion (MICC). It is known that concrete is typically highly alkaline and normal microbes cannot survive at this pH. However, the adhesion of several microbes are possible when the pH of the concrete is reduced to 9.5 by any of the attacks discussed in the above sections [6]. Sulfur compounds can be oxidized to sulfuric acid as a result of microbial reaction, which leads to the corrosion and degradation of concrete structures. Sulfuric acid may react with free lime and form calcium sulfate which results in the formation of a corroding layer on the concrete's surface and it may penetrate into the concrete [119]. Similarly, nitrifying bacteria can cause deterioration of concrete structures as they produce nitric acid. Therefore, any microbial metabolites, such as organic acids, sulfuric acid, nitric acid, etc. can cause biodeterioration of concrete [120,121].

Corrosion failures due to microbial activity in NPPs can occur normally in stagnant systems or in a system which experiences a continuous flow at low fluid velocities. Contradictorily, some of microorganisms can be used to protect the concrete structures such as in bacteria-based self-healing systems as the bacterial metabolic products can fill the micro-cracks in concrete such that the durability increases [122,123]. In addition, some

microbial biofilms can act as a protective layer against biological damage on the surface of concrete materials [124]. The major corrosion-resistant metallic materials used in NPPs are Zr alloys, Ni-based alloys and stainless steel. However, these materials can also become damaged under certain operating conditions of NPPs. However, this can be minimized by using a new material with enhanced corrosion-resistant properties (e.g., addition of 30% chromium to a Ni alloy) or by selecting suitable physicochemical properties of the reactor water. The radiation-assisted corrosion cracking in NPPs can be reduced by lowering the electrochemical corrosion potential by hydrogen water chemistry with or without noble metal technologies [125].

The effective means of mitigating the concrete corrosion is to prevent the ingress of moisture and chlorides [126]. By increasing the concrete covering of steel bars, and by enhancing the quality of concrete, the corrosion-related degradation of concrete can be minimized [127]. Similarly, the use of corrosion inhibitors is recommended for mitigating the corrosion provide that it should provide corrosion protection during all stages of plant operation [125]. The use of alternative reinforcement with high quality material, using corrosion-resistant mineral admixtures, and coatings providing a physical barrier against corrosion can be considered as other strategies of corrosion mitigation.

Cathodic protection is an efficient method to inhibit corrosion of reinforcement steel in concrete structures by using it as either sacrificial anode cathodic protection (SACP), or impressed current cathodic protection (ICCP), or both. Electrochemical realkalization can provide long-term corrosion protection to steel in carbonated concrete structures [128]. Electrochemical chloride extraction methods can be used to treat deeply chloride contaminated and corroded concrete structures [129]. The key method for the mitigation of MICC is to inhibit favorable growth conditions for microbes, by using expensive corrosion-resistant steel alloys, or introducing chemical biocides and mechanical removal of formed biofilms in addition to the use of regenerative biofilms [130].

The properties of steel are affected when temperatures rise above 200 °C. Since the temperature on the steel reinforcement is far below this limit during normal operation, the effect of temperature is insignificant on the steel reinforcement. Neutron radiation can produce changes in the yield strength and ductility of carbon steel [89]. The steel located in the shield wall of primary containment units are the most susceptible to radiation damage. The concrete covering of mild steel reinforcement is able to protect the steel from radiation damage. However, detailed research needs to be carried out to evaluate the effect of radiation on reinforcing steel. The effects of fatigue on reinforcing steel may result in the loss in bonding strength of the steel and concrete as a result of vibration. However, failures of steel reinforcement due to fatigue as unlikely.

5. Degradation of Prestressing Steel

Prestressing steel in NPP concrete structures can be damaged by corrosion, irradiation, fatigue, elevated temperature, and losses of prestressing forces [4]. The majority of corrosion-related damage to prestressed parts occurs in localized areas; however, this can also happen uniformly throughout the steel. Localized corrosion attack can be caused by pitting, stress–corrosion cracking (SCC) and hydrogen embrittlement. Pitting is an electrochemical process and leads to the loss of materials at the tendon surface of the prestressed steel which reduces its capacity to support loads. SCC can normally cause fractures of a ductile material under stress, while hydrogen embrittlement is the entry of hydrogen atoms into the metal lattice which reduces its ductility. To protect the corrosion of prestressed steel, organic corrosion inhibitors, such as petrolatum or Portland cement grout can be used to fill the ducts containing the post-tensioned tendons [4].

Elevated temperatures can possibly affect the steel wires. However, it was found that short-term heating of 3–5 min at around 400 °C was not harmful to the prestressed wire [131]. Generally, the damage of prestressed steel occurs only at particular localized areas after long-term exposure at around 200 °C. Radiation affects the prestressed steel in a similar manner as reinforcing steel. Fatigue in prestress steel results in concrete failure,

mainly due to flexural compression, shear forces, and flexural and tensile stress variations. Most of the fatigue failures normally occur at the tendons by stress concentrations at crack locations.

6. Degradation of Liner Plate and Structural Steel

Corrosion is the major degradation process of the liner plate and structural steel of NPPs similar to the corrosion process of reinforcing steel. Corrosion of the liner plate and structural steel include galvanic corrosion, pitting and crevicing. Structural steel is protected from the corrosive environment since it is embedded in the concrete; however, the presence of pores and high concrete permeability may allow fluids to reach the steel and increase the corrosion rate.

Fatigue is the other cause of degradation of liner plate and structural steel due to load cycles and vibration. Fatigue problems occur only when abnormal circumstances occur, such as material flaws and stress concentration factors. The fatigue sites in the liner plates are commonly at base metal delaminations, weld defects and arc strike areas, structural attachments and concrete-to-floor boundaries. Table 6 summarizes different damages in the concrete structures caused by different damage mechanisms. It includes damages to concrete, steel reinforcements, prestressed steel, liner plate and structural steel. Additionally, the potential areas of NPPs where damage occurs are also included.

Table 6. Summary of damage mechanisms and potential affected areas in concrete structures.

Material	Damage Cause	Potential Areas	Preventive Measures
Concrete	Chemical attack	Surface exposed to cooling water sources, containment shield, floor and slabs, areas exposed to water	Use of mineral admixtures at suitable replacement levels in binder, use of cements with low water/cement ratios, low alkali, and low C_3A
	Freeze–thaw cycles	Structures for water collection, water intake and discharge structures, cooling water sources	Use of concrete with improved ductility, use of mineral admixtures
	Thermal attack	Containment shield structures, areas close to hot piping system or reactor pressure vessel.	Use of concrete made with high density aggregates (such as magnetite, barite, hematite, ilminite, etc.)
	Radiation	Containment areas near reactor pressure vessel, some localized areas	Use of concrete made with high density aggregates (such as magnetite, barite, hematite, ilminite, etc.)
	Abrasion	cooling water intake and discharge structures, floor and slab elements	Use of concrete with improved ductility
	Fatigue and vibration	Areas under equipment support, containment areas near line anchors	Use of concrete with improved ductility
Steel reinforcement	Corrosion	Outer layer steel in all structures	Use of corrosion inhibitors, coatings and cathodic protection
	Radiation	Containment structures near reactor pressure vessel boundaries	The concrete covering of steel gives protection from radiation
	Fatigue	Local areas subjected to repeated loads	Unlikely to have failures of steel reinforcement due to fatigue

Table 6. *Cont.*

Material	Damage Cause	Potential Areas	Preventive Measures
Prestressed steel	Corrosion	Containment building	Use of organic corrosion inhibitors
	Stress relaxation	Fuel pool structures in containment building	-
Liner plate and structural steel	Corrosion	Localized areas or uniformly throughout the steel	Use of coatings and cathodic protection
	Fatigue	Weld defects and arc strike areas, structural attachments and concrete-to-floor boundaries	Improving weld details and other geometric considerations

7. Conclusions and Future Perspectives: Observations and Recommendations for Concrete Use in NPPs

The evaluation of the long-term durability of concrete structures is of the highest importance for increasing the lifetime of NPPs. Under the service environment of NPPs, the concrete structures suffer slow degradation processes and can change the chemical conditions and physical integrity of the concrete structures as time goes on. Most of issues on the concrete structures such as alkali–silica reaction, leaching, delayed ettringite formation, carbonation, etc., might be enhanced under severe or accelerated conditions. These degradations result in the growth of the microstructures, cracking and variations in the transport properties of concrete structures.

We can summarize that concrete damage occurs mainly by physical and chemical methods. All these processes lead to the formation of cracks, splits, deformations and a loss of strength. These damages result in an increase in the porosity as well as the permeability and variation in gap structures of the concrete followed by an acceleration in the deterioration process. From the detailed review presented in this study the following observations have been made regarding the degradation mechanisms and associated mitigation methods:

Chemical attack of concrete in NPPs:

- Sulfate and acid attack are the most commonly occurring causes of concrete degradation in NPPs
- Of the various chemical degradation mechanisms of concrete, the least critical or rarely occurring event in NPPs is the carbonation of concrete.
- Of the various methods for reducing or preventing chemical attack the most effective is the use of mineral admixtures at suitable replacement levels in the binder. The use of these supplementary cementitious materials invariably prevents all kinds of chemical degradation mechanism by means of either alkali or lime sequestration, pore refinement, changes in ionic transport properties, etc.
- Another common recommendation for improving resistance of concrete against chemical attack is the use of low water/cement ratios.
- The use of specific types of cement such as low alkali cement for ASR prevention and low C_3A cement for sulfate attack resistance is also suggested.

Physical degradation of concrete in NPPs:

- Physical degradation issues specific to NPPs include elevated temperature and radiation exposure which needs to be addressed while designing concrete. General issues such as freeze–thaw effect and salt-crystallization are location specific and may be of a concern only if the NPP is located in regions of very cold climate or where sea water is used as coolant.
- Issues specific to components such as abrasion and erosion in parts related to movement of cooling water have to be addressed separately.

- In general, concrete with improved ductility (such as by using rubber crumps) is considered suitable to overcome many of these issues such as freeze–thaw degradation, abrasion and erosion resistance, etc.
- As in the case of chemical attack, the use of mineral admixtures is beneficial for almost all causes of physical degradation.
- Concrete made with specific aggregates, such as magnetite, barite, hematite, ilminite, etc., (in general high-density aggregates) exhibit a higher resistance to degradation damages caused by elevated temperatures and radiation exposure.

Observation regarding degradation of steel elements used in NPPs:

- Though there are different mechanisms of degradation of steel elements in NPPs, such as elevated temperature, fatigue and irradiation, the major issue is electrochemical corrosion.
- Corrosion mitigation strategies include modifying the concrete matrix characteristics as well as adding external corrosion protection techniques, such as cathodic protection.

A summary of the conclusions from the study as well as recommendation for the concrete design for NPPs is given below:

- Since mineral additions can enhance chemical and physical characteristics of concrete, mixture proportions may be suitably designed to include required binder replacement with these mineral admixtures.
- A low water-to-cement ratio as well as low water-to-binder ratio, extended curing time, and reduced alkali content in the concrete can protect the concrete from chemical attack.
- Special aggregates based on availability and requirement should be chosen for each component of the NPPs while designing the concrete.
- The use of fibers in concrete is also recommended to increase crack resistance and mitigate further degradation.

As a future perspective, it is proposed that the concrete structures for NPPs should be made with the addition of minerals and other constituents together in the concrete mix to minimize damages in concrete structures. However, there is a need to optimize each addition to obtain the optimum replacement level for each admixture so that one component does not affect the properties of other components. To obtain the optimum level of protection, a detailed investigation is required to find the individual replacement level of different constituents. In addition, the performance of NPPs should be monitored over a long period of time at different conditions so that the changes can be measured, monitored, and analyzed to provide technical support for long-term operation and maintenance decisions.

Author Contributions: Conceptualization, P.A.R. and A.A.; resources, A.A.; writing—original draft preparation, P.A.R., S.K.N. and A.A., writing—review and editing, S.K.N., I.B. and A.A.; supervision, P.A.R. and A.A.; project administration, A.A.; funding acquisition, I.B. and A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors gratefully acknowledge the support of the Indian Institute of Technology Palakkad and the Emirates Nuclear Technology Center at Khalifa University, Abu Dhabi (UAE).

Conflicts of Interest: The authors declare no conflict of interest.

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