

Specific factors influencing the strength and durability characteristics of concrete structures of nuclear power plants.

Factori specifici care influenteaza rezistenta si durabilitatea structurilor din beton ale centralelor nucleare

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Abstract. *The purpose of this article is to provide an overview of the environmental effects that may influence the durability of concrete structures in nuclear power plants. Over time, the properties of concrete change as a result of the evolution of microstructural processes as well as under the action of environmental factors. These transformations are not necessarily severe enough to compromise the ability of concrete to meet its performance requirements. However, under certain conditions, concrete may experience undesirable deterioration due to inadequate specifications, noncompliance with those specifications, or unfavorable behavior of the cement paste or aggregate constituents as a result of physical or chemical actions.*

Key words: Nuclear structures, concrete, high temperatures, radiation, corrosion, durability, concrete shrinkage

Rezumat. *Scopul acestui articol este de a oferi o prezentare generală a efectelor de mediu care pot influența durabilitatea structurilor din beton ale centralelor nucleare. Odată cu trecerea timpului, proprietățile betonului se modifică ca urmare a evoluției proceselor microstructurale, dar și sub acțiunea factorilor de mediu. Aceste transformări nu sunt, în mod necesar, suficient de severe pentru a compromite capacitatea betonului de a îndeplini cerințele de performanță. Totuși, în anumite condiții, betonul poate suferi degradări nedorite din cauza unor specificații neadecvate, a nerespectării acestora sau a comportării nefavorabile a pastei de ciment hidratate ori a agregatelor, ca urmare a solicitărilor fizice sau chimice.*

Cuvinte cheie: structuri nucleare, beton, temperaturi ridicate, radiații, coroziune, durabilitate, contracția betonului

1. Introduction

Classic factors influencing concrete durability include mechanical actions, aggressive environmental conditions, and reinforcement corrosion.

In addition, nuclear structures may be exposed to high temperatures and ionizing radiation, which can accelerate concrete degradation and prestress loss.

These effects should be explicitly considered in long-term durability assessments.

2. The influence of high temperatures

Elevated temperature can significantly impact all heat treated and drawn wires. Such wires may not regain their initial strength when cooled because subsequent heating destroys crystal transformations achieved by the initial heat-treating process. Short term heating (e.g. 3–5 min) even to temperatures as high as 400°C, however, may not harm mechanical properties of prestressing wire [1]. A Belgian study [2] involving 30 types of prestressing steel indicated that thermal exposures up to ~200°C do not significantly reduce (<10%) tensile strength of prestressing wires or strands. References [3] and [4] support these results. The effect of elevated temperatures (from 21–649°C) on the stress-strain behavior of one type of prestressing steel (ASTM A 421) is provided in Ref. [5]. As temperature levels experienced by prestressing tendons in Nuclear Power Plant (NPP) containment are typically below 200°C, the risk of thermal damage under normal operating conditions is low.

The loss of prestressing force increases at elevated temperatures due to increases in the relaxation of steel and volumetric changes of concrete (i.e. creep and shrinkage). As shown in **Fig. 1**, the change in slope of prestress force versus time is associated with a reactor startup, when temperatures increase from about 20°C to 30–45°C [6].

Elevated temperature exposures impact the relaxation of prestressing tendons. As exposure temperature and initial stress levels increase, prestressing wire relaxation losses can increase significantly [7–8].

Results obtained from prestressing wires obtained from four British manufacturers indicate that as exposure temperature was increased from 18–120°C, stress relaxation was approximately proportional to the temperature increase [8].

Fig. 2 shows a 15.2 mm 7 wire strand stress loss from initial stress of 75% of specified minimum breaking strength [9]. Relaxation at 40°C is about twice as much as at 20°C. Based on testing performed by Briton Wires [7], the average relaxation after 40 years was estimated to be 2% at 20°C and 5% at 40°C.

Relaxation tests were performed at Forsmark NPP (Sweden) for 1000 hours, and to 70% of their ultimate strength at temperatures of 20°C and 50°C. Results were 1.4% at 20°C and 2.7 % at 50°C.

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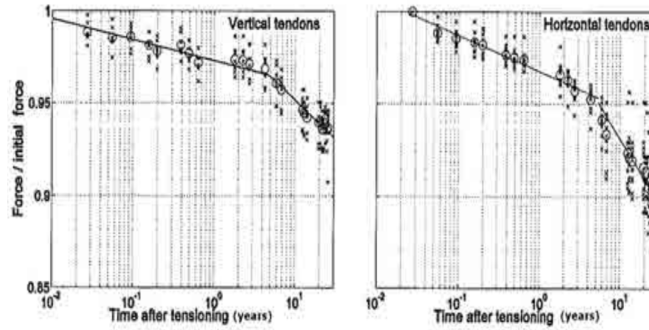


Fig. 1. Prestressing (initial) and residual force as a function of time as measured by fixed gauges at Forsmark 1(adapted from Ref. [6]).

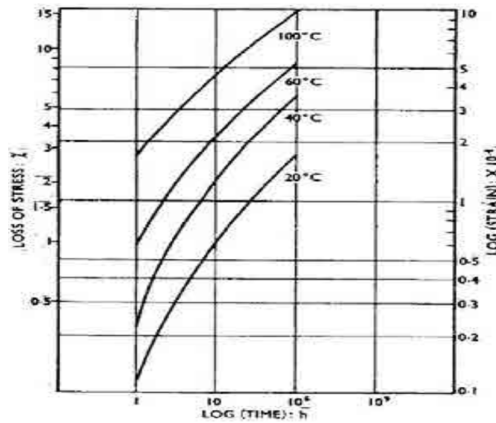


Fig 2 Relaxation of stabilized (low relaxation) 7 wire strands at 75% of f_{pk} at various temperatures [9].

Temperature has significant effect on creep [3, 5, 8, 9]. This is not typically addressed in generic creep prediction models, and temperature is only of concern for prestressed nuclear Containment Concrete Structures (CCS). Creep rate increases with temperatures up to about 70°C. The creep rate at 70°C was shown to be about 3.5 times higher than the rate at 20°C, at least for the first 15 months under load [10].

Based on results from a number of studies [3], creep at temperatures of between 40 and 50°C is about twice the creep at a temperature of 20°C. This is consistent with the results in **Fig. 3**, showing short term creep. Investigations in Ref. [11] show that the creep strain is 2–3 times greater at 52°C than at 27°C.

Elevated temperature effects on drying shrinkage are less pronounced than the effect of reduced relative humidity. A 15% increase in shrinkage can be expected when temperature is increased from 23°C to 60°C at a constant relative humidity [11].

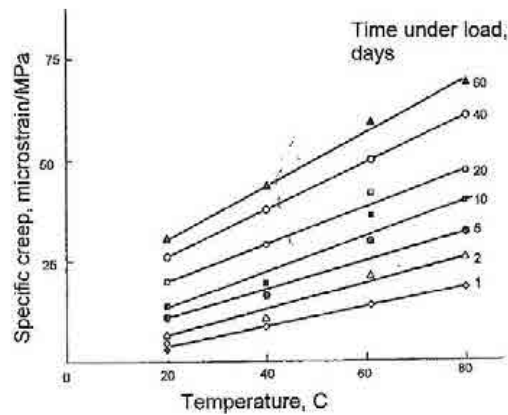


Fig. 3. Effects of temperature on creep [11]

2.1. Mechanical and structural changes

High temperatures affect the properties of concrete as follows:

Accelerated creep

Creep is the increased strain or deformation of a structural element under a constant load.

There are multiple levels of creep that a concrete structure can undergo:

- Primary creep is the immediate elastic strain or initial creep when the load is first applied to the concrete.
- Secondary creep is the slow progress of this creep over time resulting from a sustained load.
- Tertiary creep is the accelerated creep that eventually leads to a break or rupture of the structure.
- Drying creep is when basic creep and shrinkage are exceeded at drying.

Over time, hardened concrete can gradually change shape under constant pressure, causing a deformation.

Concrete creep has been accepted as an inevitable fact for decades. In fact, creep is still calculated in concrete projects to determine whether the structure will sustain the anticipated load.

- **Thermal shrinkage**

Thermal shrinkage in concrete is the reduction in volume and contraction of hardened concrete as it cools down from the high temperatures generated by the

Specific factors influencing the strength and durability characteristics of concrete structures of nuclear power plants chemical heat of hydration. It occurs when concrete, often in large pours, expands while setting and subsequently contracts upon cooling, leading to cracking if restrained.

2.2. Precompression losses.

Creep and thermal contraction lead to a decrease in stress in the prestressing cables, affecting the load-bearing capacity and tightness of the envelope.

2.3. Reinforcement corrosion amplification

High temperatures accelerate the diffusion of aggressive ions (**Carbonation, Corrosion, Chloride penetration**), favoring reinforcement corrosion and decreasing durability.

2.3.1 Carbonation

Carbonation is a deleterious mechanism in concrete that can occur when atmospheric carbon dioxide (CO_2) reacts with hydration products, such as calcium hydroxide ($\text{Ca}(\text{OH})_2$), to form calcium carbonates (CaCO_3).

Carbonation lowers the concrete pH, which may promote reinforcement corrosion and, eventually, lead to the formation of cracks, delamination, and spalling. The presence of sufficient moisture is essential for the carbonation process [12]. Also, the rate of carbonation depends on the quantity of $\text{Ca}(\text{OH})_2$ in the matrix and concentration of CO_2 [13].

To perform accelerated carbonation tests, special chambers are utilized with a high content of CO_2 .

After performing the tests, by applying a phenolphthalein solution to a concrete surface, which appears pink, if the pH level is high, the carbonation depth can be determined. If a specimen shows no color change, it can be considered carbonated (see Figure 4).

Roux et al. [14] measured the resistance of RPC200 to carbonation. Using accelerated treatment at 100% CO_2 , no carbonation was detected after 90 days of exposure. Sohail et al. [11] compared the carbonation rate of NSC and UHPC.

Both types of cylinders were placed in an environmental chamber with 50% CO_2 for six months. After six months, there were no signs of carbonation on UHPC, and a 12 mm carbonation depth was observed on Normal Strength Concrete (NSC). The studies of Pierard et al. [15] have also confirmed the superiority of Ultra-High Performance Concrete (UHPC) over NSC in terms of carbonation resistance: the researchers estimated the minimum concrete cover for a 100-year carbonation resistance of 65 mm for conventional concrete and 5 mm for UHPC (the specimens were exposed to a 1% CO_2 atmosphere for one year). Valcuende et al. [16] reported no statistically significant differences in carbonation of UHPC prepared using different curing temperatures (20 °C, 60 °C, or 90 °C) and fiber contents (0%, 1%, or 2%).

Excellent carbonation resistance was observed for UHPC prepared using different waste materials as a cement substitution. Sun and Lai [17] have performed the tests using UHPC prepared with silica fume, fly ash, and slag.

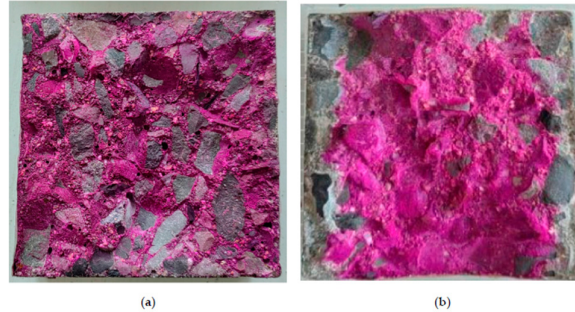


Fig 4. Examples of (a) pre-carbonized and (b) carbonized concrete specimens (reprinted from Ref. [18]).

2.3.2 Corrosion

Corrosion of steel in concrete is an electrochemical process. General corrosion refers to a relatively uniform reduction of thickness over the surface of a corroding material. It is relatively easy to measure and monitor. Pitting corrosion is a localized form of corrosion where the bulk of the surface remains unattached. Pitting is often found at locations where resistance against general corrosion provided by passive surface films or coatings has broken down.

Both water and oxygen must be present for corrosion to occur. There is no corrosion in dry concrete or in fully immersed concrete that does not contain entrained air. The electrochemical potentials that form corrosion cells may be generated in two ways:

- (1) Composition cells formed when two dissimilar metals are embedded in concrete, such as rebar and aluminum conduit, or when significant variations exist in steel surface characteristics;
- (2) Concentration cells formed due to differences in concentration of dissolved ions near steel, such as alkalis, chlorides and oxygen [19].

One of two metals (or different parts of the same metal) becomes anodic and the other cathodic to form a corrosion cell. Corrosion may also be induced by stray electrical currents or galvanic action with embedded steel of different composition. Figure 5 illustrates the electrochemical process of steel corrosion in moist and permeable concrete.

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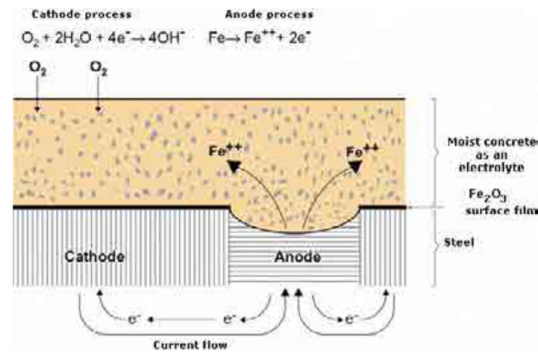


Fig 5. Electrochemical reaction illustrating corrosion of steel in concrete (adapted from Ref. [20]).

Figure 6 presents examples of rebar corrosion in general civil engineering structures.

In good quality, well compacted concrete, reinforcing steel with adequate cover should not be susceptible to corrosion, because the highly alkaline conditions ($\text{pH} > 12$) cause a passive iron oxide film ($\gamma\text{-Fe}_2\text{O}_3$) to form on the concrete surface (i.e. metallic iron will not be available for anodic activity). The passive film may be relatively thick to inhibit corrosion by providing a diffusion barrier to reaction products of the reacting species (Fe and O_2) or, as is more common, the layer can be very thin.

The film does not actually stop corrosion, but reduces corrosion rates to insignificant levels [21].

Corrosion can occur if this passivating environment is altered by a reduction of concrete pH or by the introduction of chlorides that destabilize the passive layer.



Fig 6. Corrosion of reinforced concrete. (a) Seawater structure; (b) bridge structure on highway 401 in Ontario, Canada (adapted from Refs [22] and [23], respectively).

3.The influence of ionizing radiation

Irradiation in the form of either fast and thermal neutrons emitted by the reactor core or gamma rays produced as a result of capture of neutrons by members (particularly

steel) in contact with concrete can affect the concrete. Changes in the properties of concrete appear to depend primarily on the behavior of the concrete aggregate that can undergo a volume change when exposed to radiation. [24]

Behavior of the concrete aggregate that can undergo a volume change when exposed to radiation. [24] The fast neutrons are mainly responsible for the considerable growth, caused by atomic displacements, that has been measured in certain aggregate (e.g., flint). Quartz aggregates that contain crystals with covalent bonding should be more affected by radiation than calcareous aggregates that contain crystals with ionic bonding. [25] Furthermore, when nuclear radiation is attenuated or absorbed in the concrete almost all the absorbed radiation is converted into heat.

Nuclear heating occurs as a result of energy introduced into the concrete as the neutrons or gamma radiation interact with the molecules within the concrete material. The heat generated may have detrimental effects on the physical, mechanical, and nuclear properties of the concrete. Reference [26] indicates that nuclear heating is negligible for incident energy fluxes less than 10^{10} MeV/cm² per s. Determination of whether any deterioration that may occur in concrete properties is due to radiation damage or thermal effects can be difficult.

Prolonged exposure of concrete to irradiation can result in decreases in tensile and compressive strengths and modulus of elasticity. Figure 7 presents a summary of the effects of neutron radiation on the compressive strength and modulus of elasticity of several concretes.

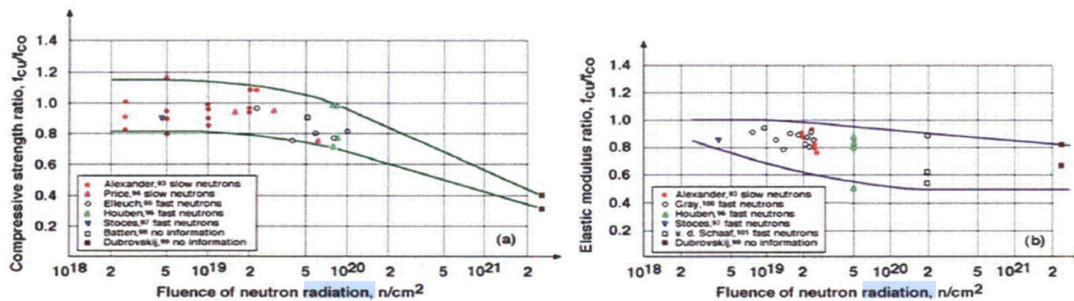


Fig.7 Effect of neutron radiation on concrete compressive strength and modulus of elasticity relative to unirradiated and unheated control specimen results

Results in the literature indicate that:

- (1) for some concretes, neutron radiation above 1×10^{19} neutrons/cm² or doses of 10^{10} rad can cause significant reductions in compressive strength and modulus of elasticity, relative to unirradiated and unheated control specimens. Gamma radiation may cause a reduction in compressive strength;

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(2) tensile strength of concrete is significantly reduced at neutron fluences exceeding 10^{19} n/cm² with the decrease of tensile strength caused by neutron radiation more pronounced than the decrease of compressive strength;

(3) resistance of concrete to neutron radiation apparently depends on the type of neutrons (slow or fast) involved, but the effect is not clarified;

(4) resistance of concrete to neutron radiation depends on mix proportions, type of cement, and type of aggregate;

(5) the effect of gamma radiation on concrete's mechanical properties requires clarification;

(6) the deterioration of concrete properties associated with a temperature rise resulting from irradiation is relatively minor;

(7) coefficients of thermal expansion and conductivity of irradiated concrete differ little from those of temperature-exposed concrete;

(8) when exposed to neutron irradiation, the modulus of elasticity of concrete decreases with increasing neutron fluence;

(9) creep of concrete is not affected by low-level radiation exposure, but for high levels of exposure creep probably would increase with exposure because of the effects of irradiation on the concrete's tensile and compressive strengths;

(10) for some concretes, neutron radiation with a fluence of more than 1×10^{19} neutrons/cm² can cause a marked increase in volume;

(11) generally, concrete's irradiation resistance increases as the irradiation resistance of the aggregate increases;

(12) irradiation has little effect on shielding properties of concrete beyond moisture loss caused by a temperature increase. Furthermore, there is an indication that nuclear radiation can significantly increase the reactivity of silica-rich aggregates to alkali (i.e., alkali-silica reaction). [27]

Results from an investigation of the effect of irradiation on the strength of a nuclear power plant concrete indicate that for a dose up to 6×10^5 Gy the compressive, splitting-tensile, and flexural strength of concrete decreased with dose, reaching a reduction of about 10%, 5%, and 5%, respectively, at the maximum dose. [28]

It was noted in the reference that interaction of concrete with irradiation generated a succession of chemical reactions starting with radiolysis of water and terminating in formation of calcite crystals that decrease both the size of pore space and the strength of the concrete.

Section III, Division 2 of the American Society of Mechanical Engineers (ASME) Pressure Vessel and Piping Code specifies an allowable radiation exposure level of 1×10^{21} n.vt [29].

The British Specification for Prestressed Concrete Pressure Vessels for Nuclear Reactors [30] states that the maximum permissible neutron dose is controlled by the effects of irradiation on concrete properties. These effects are considered insignificant for doses up to 5×10^{17} neutrons/cm².

Table 2.7 in Ref. [31] provides estimated radiation environments at the outside surface of light-water reactor pressure vessels for a 1000 MW(e) plant operating at an 80% capacity factor. The results indicate that radiation levels in a concrete primary shield wall may approach the above limits after 40 years of operation (equivalent to 32 full-power years). However, these values represent upper bounds and are likely higher than actual exposure levels, due to attenuation effects caused by air gaps, insulation, and other materials that may be positioned between the pressure vessel and surrounding concrete structures.

3.1. Microstructural changes

Gamma and neutron radiation causes:

- Radiolysis of interstitial water, generating free radicals that induce microcracks.
- Modification of cement hydration, reducing matrix cohesion with effects on decreasing compressive and tensile strengths.
- Increased porosity, favoring the penetration of aggressive agents, accelerating aggregate alkali reaction

3.2 Radiation–temperature interaction

High temperatures amplify the effects of radiation, accelerating chemical reactions and increasing prestressing losses. This interaction is critical for the durability of prestressed concrete.

4. Comparative analysis with common sustainability factors

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Common factor	Normal effect	Temperature amplification	Radiation amplification	Notes for prestressed concrete
Material quality	Porosity, strength	Increased creep and shrinkage	Microcracking and matrix degradation	Strength and durability may be affected
Mechanical actions	Static and dynamic loads	Accelerated loss of prestress	Reduction of the cohesion of the concrete microstructure	Prestressing stresses decrease more rapidly
Aggressive environment	Diffusion of water and ions	Acceleration of diffusion	Increase in permeability	Corrosion of reinforcement is more likely
Reinforcement corrosion	CO ₂ , chlorides	Faster diffusion	Microcracking favors the penetration of aggressive agents	Combination of factors can affect homogeneity and tightness

5. Conclusion

High temperatures and ionizing radiation:

- Accelerate **Creep** and **Shrinkage**, increasing stress losses and reducing precompression.
- Promote microcracking and increased porosity, accelerating the diffusion of aggressive agents, reducing durability.
- Amplify the effects of classical degradation factors (**Carbonation, Corrosion, Chloride penetration, Aggressive Environment**).
- Create synergistic effects, where combined degradation is much faster than under normal conditions.

The evaluation of the durability of prestressed concrete in nuclear power plants must integrate, in addition to classical influencing factors, combined temperature-radiation modeling.

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