Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

EFFECTS OF SLIGHTLY ELEVATED TEMPERATURES ON CONCRETE MATERIALS AND STRUCTURES PROPERTIES

Cédric Androuët[1]

[1] Technical Specialist, Canadian Nuclear Safety Commission, Ottawa, Canada (cedric.androuet@cnsc-ccsn.gc.ca)

ABSTRACT

Climate change is a global phenomenon and Canada's national climate change assessments project the changes to continue. The rise in global temperatures due to climate change over the past several years has caused many utilities to see the operating temperatures of their nuclear power plants increasing, with some instances where the temperature limitations may have been reached or exceeded.

Temperature limitations for nuclear power reactors in North America are established in United States (US) and Canadian codes and standards (American Concrete Institute, 2013; ASME, 2023; CSA Group, 2019, 2025). Overall, temperature limitations are set to 65°C (150°F) over long-term periods, except for local areas (around penetrations for hot piping) where the temperature limit is 95°C (200°F) for the US codes, and 100°C (210°F) for the Canadian standards. Higher temperature limitations are set for short-term periods for the interior surface of the structures: 175°C (350°F) over large areas and 345°C (650°F) over local areas affected by impingements from steam or water jets.

Several studies have performed literature reviews focusing on the impact of elevated temperatures on a wide range of concrete properties (Acosta Urrea, 2018; Kassir et al., 1996; Mohammed, 2019; Naus, 2010). In addition, significant research has been conducted in the past several years to better characterize and understand the behaviour of concrete materials and structures when subjected to elevated temperatures. The objective of this paper is to synthetize the major findings of the various studies, with a focus on the properties relevant for nuclear power plant concrete structures when subjected to slightly elevated temperatures. To align with CNSC's philosophy to ensure clarity on the regulatory requirements, the paper will also provide a regulatory perspective on how the CNSC expects that utilities would approach the impact of slightly elevated temperatures on nuclear concrete structures in the Canadian context. In particular, the paper will describe the type of technical information and analyses that would be required for CNSC staff to perform their regulatory oversight assessments of existing and new nuclear power plants.

INTRODUCTION

Climate change is a global phenomenon and Canada's national climate change assessments project the changes to continue. Understanding the impact these changes have on the reinforced concrete containment structures is necessary to help inform mitigation decision-making. Amongst the main climate variables that interfere with the concrete degradation mechanisms is the temperature to which the concrete is exposed. The rise in global temperatures due to climate change over the past several years has caused many utilities to see the operating temperatures of their nuclear power plants (NPPs) increasing, with some instances where the temperature limitations may have been reached or exceeded.

Temperature limitations for nuclear power reactors in North America are established in United States (US) and Canadian codes and standards (American Concrete Institute, 2013; ASME, 2023; CSA Group, 2019, 2025). Overall, temperature limitations have been established based on available thermal test data on concrete performance (CSA Group, 2023), and are set to 65°C (150°F) over long-term periods, except for local areas (around penetrations for hot piping) where the temperature limit is 95°C (200°F) for the US codes, and 100°C (210°F) for the Canadian standards. Higher temperature limitations are set for short-term periods for the interior surface of the structures: 175°C (350°F) over large areas and 345°C (650°F) over local areas affected by impingements from steam or water jets. Nevertheless, what is intended by short-term and long-term periods, as well as local and large areas, is not clearly defined.

Several studies have performed literature reviews focusing on the impact of elevated temperatures on a wide range of concrete properties (Acosta Urrea, 2018; Kassir et al., 1996; Mohammed, 2019; Naus, 2010). In addition, significant research has been conducted in the past several years to better characterize and understand the behaviour of concrete materials and structures when subjected to elevated temperatures. The objective of this paper is to synthesize the major findings of the various studies, with a focus on the properties relevant for NPP concrete structures when subjected to temperatures below 400°C (750°F).

Being the nuclear energy and materials regulatory body in Canada, the CNSC's mission is to regulate the use of nuclear energy and materials, to protect health, safety, security, and the environment, and to respect Canada's international commitments on the peaceful use of nuclear energy. To align with CNSC's philosophy to ensure clarity on the regulatory requirements, the paper will also provide a regulatory perspective on how the CNSC expects that utilities would approach the impact of slightly elevated temperatures on nuclear concrete structures in the Canadian context. In particular, the paper will describe the type of technical information and analyses that would be required for CNSC staff to perform their regulatory oversight assessments of existing and new NPPs.

GENERAL BEHAVIOUR

When concrete made of Portland cement is subjected to elevated temperatures, a series of significant changes in the physicochemical composition and microstructure of the hardened Portland cement paste occur as temperature rises, resulting in a progressive breakdown in the structure of the concrete, even if the increase in temperature is moderate (Naus, 2010). Two main reasons have been proposed to explain the causes of thermal damage to Portland cement-based materials when exposed to elevated temperatures (DeJong and Ulm, 2007; Naus, 2010):

- microcracking induced by thermal mismatch of some mesoscopic properties and interfaces (Willam et al., 2005)
- dehydration of the primary hydration products in the hardened cement paste matrix (Bažant and Kaplan, 1996).

As the temperature increases, the surface, capillary, and bound water are lost, a process that is further accelerated by the reduced cohesive forces between water molecules due to water expansion (Tufail et al., 2017). From 20°C to 80°C, the hydration products are not altered and the changes in properties are mainly due to physical effects (e.g. changes in van der Waals cohesive forces) where loss of capillary water begins along with water expansion (Naus, 2010). From 80°C to 100°C, ettringite dehydrates and decomposes, and water physically bonded to the cement matrix and aggregates evaporates, thus increasing capillary porosity and microcracking (Pimienta et al., 2018). Between 100°C and 200°C, water expulsion continues at a faster rate (Naus, 2005). The calcium silicate hydrates (C-S-H) start to dehydrate and decompose (Pimienta et al., 2018) with the maximum rate of dehydration occurring at about 180°C (Naus, 2005), and gypsum decomposes between 150°C and 170°C (Tufail et al., 2017).

For the range of temperatures of interest in this paper and for the vast majority of aggregates used in the production of concrete (except for serpentine and Thames gravel, for example), thermal instabilities and crystalline transformations occurring in the aggregates should not be a concern and are not addressed in this article, as these effects are typically observed for temperatures greater than 400°C (Naus, 2010).

MECHANICAL PROPERTIES

Mechanical properties of concrete materials and structures are affected when exposed to elevated temperatures. Their deterioration are generally attributed to three main factors (Naus, 2010), which are: physicochemical changes in the cementitious paste; physicochemical changes in the aggregates; and thermal incompatibility between the aggregates and the cementitious paste. Based on the information available in the literature, the impacts of slightly elevated temperatures on some of the main mechanical properties of concrete materials and structures are summarized below.

Compressive Strength

Several studies were performed over the past 60 years analysing the impact of elevated temperatures on the compressive strength of various concrete mix-designs (Freskakis, 1984; Freskakis et al., 1979; Kasami et al., 1975; Kassir et al., 1996; Mohammed, 2019; Nanstad, 1976; Naus, 2005, 2010; Pimienta et al., 2018). Variations in the residual compressive strength of concrete after exposure to a temperature up to 315°C (or 600°F) have been compiled by (Kassir et al., 1996). These results are representative of the results obtained by the other researchers mentioned above and are presented in Figure 1a.

The experimental data were obtained for specimens tested under both cold and hot conditions, with the upper and lower bound strength curves representing the full spread of the database. While the upper bound of the test data indicates almost no reduction in the compressive strength, the mean, 84% percentile, and lower bound data indicate a significant reduction of the compressive strength as soon as the temperature rises above the reference temperature of 21°C. For example, at a temperature of 93°C, the mean, 84% percentile, and lower bound data indicate a reduction in the compressive strength to 84%, 77% and 68% of its original value, respectively.

Several factors may impact the extent of decrease in the compressive strength of concrete when exposed to elevated temperatures. Amongst them is the temperature at which the specimens are tested, namely whether the specimens are tested cold (i.e. residual compressive strength following exposition to elevated temperatures), or hot (at the elevated temperature). This has been demonstrated to have a significant impact, as the residual concrete compressive strength, i.e. tested cold, is generally much lower than the relative concrete compressive strength when tested hot (Freskakis et al., 1979; Kassir et al., 1996; Naus, 2010). The moisture content of the specimens at time of testing also has an impact on the strength of concrete exposed to elevated temperatures, with the compressive strength of unsealed specimens being in general significantly higher than the compressive strength of sealed specimens, when exposed to elevated temperatures (Kassir et al., 1996; Naus, 2010). Finally, results published in literature indicate that the original concrete compressive strength, type of cement, aggregate size, heating rate, and water-binder (W/B) ratio, have little effect on the relative compressive strength of concrete when exposed to elevated temperatures (Naus, 2010; Naus and Graves, 2006).

Tensile Strength

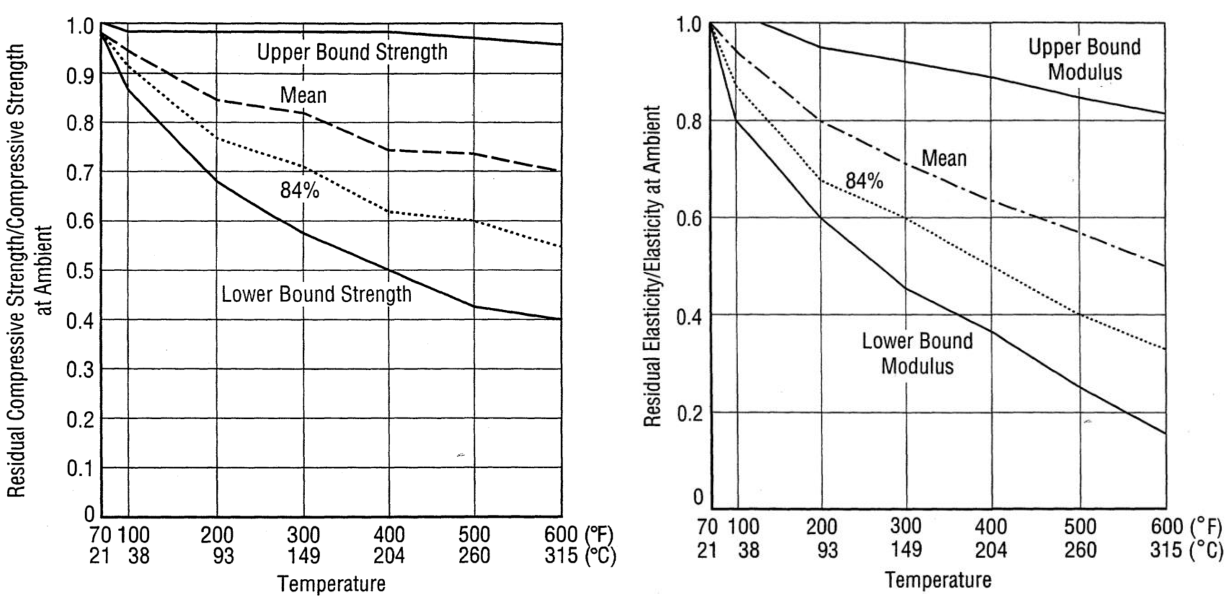
Because of the direct link existing between the tensile strength of concrete and the concrete's resistance to cracking, evaluation of the impact of elevated temperatures on the tensile strength of concrete is important. The impact of elevated temperatures on the tensile strength of concrete has been investigated by a number of researchers through the realization of several series of splitting tensile tests, direct tensile tests, and flexural tests as summarized in (Kassir et al., 1996; Nanstad, 1976; Naus, 2010).

The literature reviews performed by (Kassir et al., 1996; Nanstad, 1976; Naus, 2010) constitute state of the art reports as they contain most of the test results and knowledge developed by the community over the past 60 years. The overarching conclusion is that, generally, the loss in tensile strength is, in proportions, comparable to the corresponding loss in compressive strength, though tensile testing of concrete tends to be more sensitive to deterioration at elevated temperatures (Kassir et al., 1996; Nanstad, 1976; Naus, 2010).

Elastic Modulus

The elastic modulus (ratio of stress to strain in the elastic region) is of paramount importance in depicting the structural behavior of concrete elements. A substantial amount of studies have evaluated how the elastic modulus of concrete is impacted when exposed to elevated temperatures (Davis, 1965; Freskakis et al., 1979; Harada et al., 1972; Kasami et al., 1975; Kasami et al., 2017; Kassir et al., 1996; Kottas et al., 1979; Lankard et al., 1971; Mohammed, 2019; Naus, 2010; Schneider et al., 1982; Xiao and König, 2004). Variations in the elastic modulus of concrete after exposure to a temperature up to 315°C (or 600°F) have been compiled by (Kassir et al., 1996). Similarly to the results presented in Figure 1a for the compressive strength, the results compiled by (Kassir et al., 1996) for the elastic modulus are representative of the results obtained by the other researchers mentioned above and are presented in Figure 1b.

The experimental data presented in Figure 1b were obtained for specimens tested under both cold and hot conditions and at various moisture loss conditions, with the upper and lower bound strength curves representing the full spread of the database. The elastic modulus exhibits a significant decrease when exposed to elevated temperatures as soon as the temperature rises above the reference temperature of 21°C, the decrease being much more significant than for the compressive strength, as displayed in Figure 1. For example, at a temperature of 93°C, the upper bound, mean, 84% percentile, and lower bound data indicate a reduction in the elastic modulus to 95%, 80%, 67% and 60% of its original value, respectively. The decrease in the elastic modulus for the temperature range of concern outlined in the US and Canadian codes and standards (American Concrete Institute, 2013; ASME, 2023; CSA Group, 2019, 2025) is therefore very significant and cannot be overlooked.



a. Compressive strength b. Elastic Modulus

Figure 1: Reduction of some properties of Concrete at Elevated Temperatures (Kassir et al., 1996).

Several factors may impact the extent of decrease in the elastic modulus of concrete when exposed to elevated temperatures. As for the compressive strength, the temperature at which the specimens are tested and the moisture content of the specimens at time of testing (Kassir et al., 1996) are the most impactful parameters. The elastic modulus is generally much lower when tested cold (i.e. residual elastic modulus) than when tested hot (i.e. during the elevated temperature event), and the impact of the moisture content of the specimens at time of testing on the elastic modulus is similar to its impact on the compressive strength, with a more significant decrease of the elastic modulus in sealed conditions (Naus, 2010). The drying kinetics may also play a substantial role as the decrease in elastic modulus has been seen to be somewhat proportional to the quickness of drying following the elevated temperature event. Finally, the type of cement, W/B ratio and original concrete strength appear to have little effect on the impact of slightly elevated temperatures on the loss of elastic modulus.

Bond Between Reinforcement And Concrete

To ensure a collaborative composite behaviour, reinforced concrete structures rely on the bond between reinforcement and concrete, which arises mainly from friction and adhesion between concrete and steel. Since concrete and steel have different coefficients of thermal expansion, the bond strength, and consequently the overall structural behaviour and structural capacity, could be influenced by a rise in temperature. Experimental data reporting on the effect of exposure to elevated temperatures on the steel-concrete bond are somewhat limited (Naus, 2010). Nevertheless, a general trend consisting in a progressive decrease of the bond strength as the temperature increases has been observed.

One of the main parameters influencing the bond strength is related to the type of reinforcement being used, since the bond strength of plain round bars decreases more significantly with an increase in temperature than that of deformed steel reinforcement bars (Diederichs and Schneider, 1981). The condition of the reinforcement also plays a role, as rusted bars have been observed to be slightly less sensitive to the increase in temperatures in terms of bond strength loss, when compared non-rusted bars (Diederichs and Schneider, 1981).

Creep And Long-Term Exposure

Creep can be defined as an increase in strain in a structural element with time due to sustained stress. Creep is an important parameter to be considered in structural design and analysis as it may have undesirable and detrimental effects by affecting strains, deflections, crack openings and stress redistribution (Kassir et al., 1996; Naus, 2010). Temperature may affect creep of hardened cement paste through both thermal and structural effects (Dias et al., 1990). Overall, the thermal effect is due to the temperature at loading being seated in the molecular agitation caused by temperature, while the structural effects widely depends on the maximum exposure temperature, assuming slow rate of heating and cooling (Naus, 2010).

Literature reviews (Geymayer, 1972; Kassir et al., 1996; Naus, 2010) were performed to compile data on the impact of elevated temperatures on the specific creep, or specific creep rate (the average slope of the creep curve during a specified period in semi-log plot). The results of the experimental program described in (Hannant, 1968) are presented in Figure 2. This program aimed at determining the strain behaviour and creep characteristics of concrete specimens subjected to temperatures varying between 27°C and 95°C (203°F) for periods of loading up to two years, using the same concrete mix-design as was utilized for the construction of the pressure vessel of the Oldbury NPP (England). It was observed that the magnitude of the creep strain significantly increased with temperature, the creep strain at 95°C being about 5 times that at 27°C. It was also observed that the relationship between creep and temperature is approximately linear up to a temperature of around 70°C, after which the creep strain increases more rapidly for a similar increase in temperature (Hannant, 1968). This is similar to results obtained by other researchers as outlined in (Acosta Urrea, 2018; Kassir et al., 1996; Naus, 2010), where increasing temperatures result in substantially higher creep strain, most investigators reporting creep strain at 100° in the order of four to six times higher than at room temperatures, after a 60 to 100-day loading period (Naus, 2010). For temperatures above 95°C, creep strain continues to significantly increase as temperatures rise (Kassir et al., 1996).

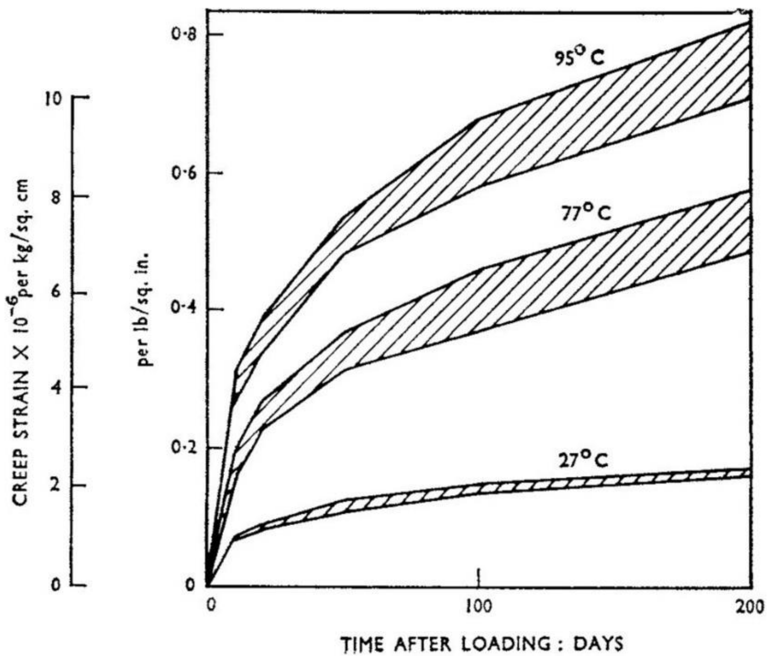


Figure 2: Variation with time of creep per unit stress (Hannant, 1968).

Several parameters have a substantial impact on the increase in creep strain due to slightly elevated temperatures. Amongst those, the main one relates to the moisture conditions of the samples. For tests performed under two moisture conditions (sealed specimens and air-dried specimens at 46% relative humidity), it was noticed that, after 200 days of loading, the creep of the wet (sealed) specimens tested at 73°C was about 10 times greater than that of the dried (unsealed) specimen tested at the same temperature (Hannant, 1968). For temperatures above 71°C, an order of magnitude between 0.7 to 5 times greater than the corresponding values for unsealed concrete is generally adopted (Naus, 2010). Similar results were also reported by (Acosta Urrea, 2018). A minority of researchers have observed a phenomenon called "creep maximum" occurring between 50°C and 80°C, but most have not. In any case, this term is a misnomer, as these few observations are related to a potential maximum of the specific creep rate, not to the corresponding creep strain which continues to increase (Naus, 2010). Finally, creep recovery has been observed to be less than the associated creep strain, the degree of creep recovery being more dependent on the stress levels than on the exposition to slightly elevated temperatures (Naus, 2010).

Although results for exposure of concrete to elevated temperatures for relatively long periods of time are limited and are, at times, contradictory (Naus, 2010), the general trend indicates that strength and modulus of elasticity decrease with the increasing exposure time. The elastic modulus is generally more affected than the compressive strength, in particular for temperatures above 110°C (Naus, 2010). It was also observed that the rate of reduction of the strengths (compressive and tensile) and modulus of elasticity increases with increasing temperatures (Kassir et al., 1996).

THERMAL CYCLING

Concrete exposed to thermal cycling generally exhibits poorer mechanical properties than concrete exposed to single heating (Bertero and Polivka, 1972; Kassir et al., 1996; Lankard et al., 1971; Naus, 2010).

Several studies have been conducted to identify the influence of thermal cycling on the mechanical properties of concrete (Bertero and Polivka, 1972; Campbell-Allen and Desai, 1967; DeFigh-Price, 1984; Komendant et al., 1978). The results indicate that the compressive, tensile, and bond strengths, as well as the modulus of elasticity, are significantly reduced. As an example, (Bertero and Polivka, 1972) examined the impact of exposing concrete specimens to thermal cycles between 21°C and 150°C. The results obtained, some of these being presented in Figure 3, are representative of the literature. The concrete exhibited a 50% loss of compressive strength and a 30% loss in modulus of elasticity after 14 cycles at 150˚C. After 18 thermal cycles to 177°C, a decrease in the elastic modulus of up to 50% was even observed by (DeFigh-Price, 1984). Generally, a further decrease in the elastic modulus would occur with an increase in the number of thermal cycles (Naus, 2010).

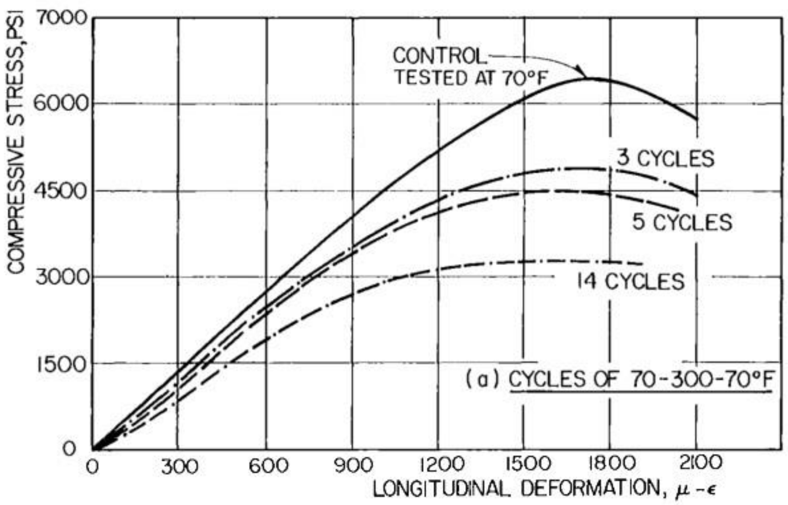


Figure 3: Effect of thermal cycles on the compressive stress-strain behaviour of concrete (Bertero and Polivka, 1972).

SHIELDING

For many decades, concrete has been used in NPPs for its several benefits, including several logistic (availability, cost-effectiveness, ease of construction) and technical benefits (limited porosity, compressive strength), amongst which are its shielding properties (Barbhuiya et al., 2024; Kanagaraj et al., 2023; Naus, 2010). Being a polyphase composite material made of aggregates contained in a cementitious-based paste, concrete possesses many physical qualities providing it with interesting radiation shielding characteristics: gamma rays are absorbed by the high-density aggregate materials and neutrons are attenuated by hydrogen atoms (Naus, 2010). Two sources of heat co-exist in a concrete shield: heat coming from the exterior of the material (e.g. hot parts of the reactor system), and heat internally generated by slowing down neutrons and gamma rays entering the concrete shield (Naus, 2010).

An experimental test program was performed by (Peterson, 1960) to determine the effect of high temperatures on neutron attenuation in an ordinary concrete with a 0.43 W/B ratio. The thermal neutron distribution measured through the thickness of a concrete element, as a function of temperature, is presented in Figure 4, where the y axis (thermal neutron flux) is in a logarithmic scale. The results have shown that significant changes in attenuation effectiveness were observed after the concrete had been exposed to elevated temperatures of 100°C, 200°C, and 300°C. The results of additional tests performed on concrete containing iron-limonite, magnetite-limonite, and ferro-phosphorous aggregates showed that, though these concretes exhibit better radiation shielding capabilities, the relative impact of elevated temperatures on them is similar to that observed for the ordinary concrete. Similar results were obtained in the determination of the radiation attenuation properties of two types of high-density concretes by (Bunch, 1958), where neutron and gamma attenuation properties were considerably impaired by being exposed to elevated temperatures of 100°C, 175°C and up to 320°C. It was also observed that the density of the concrete was affected in a similar fashion as the radiation attenuation. Overall, its was concluded that the loss of free and bound water, the dehydration of C-S-H, and the pre-existing cracking condition of the concrete elements appear to be the main contributors to the loss of radiation attenuation capability within the range of temperatures from ambient to 300°C (Bunch, 1958; Naus, 2010; Peterson, 1960).

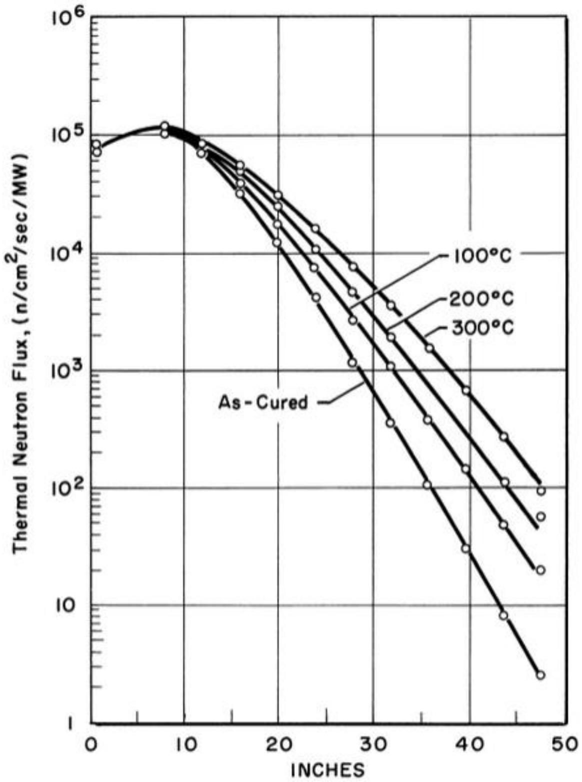


Figure 4: Thermal neutron distribution vs concrete thickness and temperature (Peterson, 1960).

CONCLUSION

This paper has described how slightly elevated temperatures may negatively impact several concrete materials and structures properties. In particular, their significant impact on the concrete tensile strength, elastic modulus, creep effects, bond between reinforcement and concrete, and shielding capabilities, has been highlighted. The paper has also stressed how long-term exposure and thermal cycling may negatively impact concrete materials and structures.

The CNSC is committed to continuously fulfilling its mandate to protect health, safety, security, and the environment. To align with CNSC's priority to be a modern and trusted nuclear regulator, and CNSC's philosophy to ensure clarity on the regulatory requirements, a regulatory perspective on how the CNSC expects that utilities would approach the impact of slightly elevated temperatures on nuclear concrete structures in the Canadian context is provided below.

Because of the detrimental effects outlined throughout this paper, should a licensee or an applicant envisions that concrete materials and structures would be subjected to temperatures above the temperature limitations set out in the codes and standards (CSA Group, 2019, 2025), the CNSC expects that a holistic and comprehensive evaluation of the expected temperatures' impacts on the concrete materials and structures be performed and supported by engineering analyses and calculations. Such evaluation should include assessments of both Ultimate and Serviceability Limit States, with due consideration given to the effects of elevated temperatures on the materials' properties, as well as a fulsome assessment of the expected temperatures' impacts on all functions of the specific concrete structures (e.g. leak-tightness, shielding capabilities, etc.). The impacts of the expected temperatures on the long-term durability of the concrete materials and structures should also be assessed in a systematic manner. Furthermore, operational constraints and logistics should also be considered in the evaluation to ensure that effects of potential thermal cycles as well as long-term exposure be duly taken into account and addressed.

REFERENCES

Acosta Urrea, F. (2018). *Influence of elevated temperatures up to 100 °C on the mechanical properties of concrete*.HEFT 84, Karlsruher Institut für Technologie (KIT) Scientific Publishing.

American Concrete Institute (2013). *Code Requirements for Nuclear Safety-Related Concrete Structures (ACI 349-13) and Commentary*. 349-13, 349-13, American Concrete Institute.

ASME (2023). *Boiler and Pressure Vessel Code*. ASME BPVC.III.2-2023 - ACI 359-23, New York, NY, USA.

Barbhuiya, S., Das, B.B., Norman, P., Qureshi, T. (2024). "A comprehensive review of radiation shielding concrete: Properties, design, evaluation, and applications," *Structural Concrete*, 1-47.

Bažant, Z.P., Kaplan, M.F. (1996). *Concrete at High Temperatures: Material Properties and Mathematical Models*, Longman Group Limited.

Bertero, V.V., Polivka, M. (1972). "Influence of Thermal Exposures on Mechanical Characteristics of Concrete," *Concrete for nuclear reactors*, ACI Special Publication SP-34,

Bunch, W.L. (1958). *Attenuation properties of high density Portland cement concretes as a function of temperature*, *13 ed*., UC-34, Physics and Mathematics, TID-4500, HW-54656, Hanford Atomic Products Operation, Richland, Washington, D.C.

Campbell-Allen, D., Desai, P.M. (1967). "The influence of aggregate on the behaviour of concrete at elevated temperatures," *Nuclear Engineering and Design*, 6 (1), 65-77.

CSA Group (2019). *Requirements for nuclear safety-related structures*. N291:19, Toronto, Ontario, Canada.

CSA Group (2023). *Commentary on the CSA N287 series of Standards*. N287COM:23, Toronto, Ontario, Canada.

CSA Group (2025). *Design requirements for concrete containment structures for nuclear power plants*. N287.3:25, Toronto, Ontario, Canada.

Davis, H.S. (1965). "Effects of High Temperature Exposure on Concrete," *Presented at the ANS 11th annual meeting*, Gatlinburg, Tennessee.

DeFigh-Price, C. (1984). "Effects of Long-Term Exposure to Elevated Temperature on Mechanical Properties of Concrete," *Symposium on Concrete and Cementitious Materials for Radioactive Waste Management*, ACI, New York, NY.

DeJong, M.J., Ulm, F.-J. (2007). "The nanogranular behavior of C-S-H at elevated temperatures (up to 700 °C)," *Cement and Concrete Research*, 37, 1-12.

Dias, W.P.S., Khoury, G.A., Sullivan, P.J.E. (1990). "The thermal and structural effects of elevated temperatures on the basic creep of hardened cement paste," *Materials and Structures*, 23, 418-425.

Diederichs, U., Schneider, U. (1981). "Bond strength at high temperatures," *Magazine of Concrete Research*, 33 (115), 75-84.

Freskakis, G.N. (1984). "Behavior of Reinforced Concrete at Elevated Temperatures," *Proceedings of the 1984 ASCE Conference on Structural Engineering in Nuclear Facilities*, Raleigh, North Carolina.

Freskakis, G.N., Burrow, R.C., Debbas, E.B. (1979). "Strength Properties of Concrete at Elevated Temperatures," *Proceedings of the 1979 ASCE specialty conference on the structural design of nuclear plant facilities*, Boston, Massachusetts.

Geymayer, H.G. (1972). "Effect of Temperature on Creep of Concrete; A Literature Review," *Concrete for Nuclear Reactors*, ACI Special Publication SP-34,

Hannant, D.J. (1968). "Strain behaviour of concrete up to 95°C under compressive stresses " *Proceedings of the 1967 Prestressed concrete pressure vessels conference*, ICE Publishing, Church House, Westminster.

Harada, T., Takeda, J., Yamane, S., Furumura, F. (1972). "Strength, Elasticity and Thermal Properties of Concrete Subjected to Elevated Temperatures," *Concrete for nuclear reactors*, ACI Special Publication SP-34,

Kanagaraj, B., Anand, N., Diana Andrushia, A., Naser, M.Z. (2023). "Recent developments of radiation shielding concrete in nuclear and radioactive waste storage facilities – A state of the art review," *Construction and Building Materials*, 404 (133260).

Kasami, H., Okuno, T., Yamane, S. (1975). "Properties of Concrete Exposed to Sustained Elevated Temperature," *Proceedings of the 3rd International Conference on Structural Mechanics in Reactor Technology (SMiRT3)*, IASMiRT, London, UK.

Kasami, H., Tayama, T., Kaneko, T., Matsuzawa, K. (2017). "Effects of Cement on the Strength and Elasticity of Concrete Subject to Sustained Elevated Temperatures up to 300°C," *Proceedings of the 24th International Conference on Structural Mechanics in Reactor Technology (SMiRT24)*, IASMiRT, Busan, Republic of Korea.

Kassir, M.K., Bandyopadhyay, K.K., Reich, M. (1996). *Thermal degradation of concrete in the temperature range from ambient to 315°C (600°F)*. BNL 52384 - UC-406, United States Department of Energy, Washington D.C., USA.

Komendant, J., Nicolayeff, V., Polivka, M., Pirtz, D. (1978). "Effect of Temperature, Stress Level, and Age at Loading on Creep of Sealed Concrete," *Symposium Paper*,

Kottas, R., Seeberger, J., Hilsdorf, H.K. (1979). "Strength Characteristics of Concrete in the Temperature Range of 20° to 200°C," *Proceedings of the 5th International Conference on Structural Mechanics in Reactor Technology (SMiRT5)*, IASMiRT, Berlin, Germany.

Lankard, D.R., Birkimer, D.L., Fondriest, F.F., Snyder, M.J. (1971). "Effects of Moisture Content on the Structural Properties of Portland Cement Concrete Exposed to Temperatures up to 500F," *Symposium on Effect of Temperature on Concrete*, ACI Special Publication SP-25, Memphis, Tennessee.

Mohammed, H.H.H. (2019). *State of the Art Report (SOTAR) - Elevated Temperature Effects on Concrete*. Enclosure 4 to e-Doc 7280876 and Enclosure 4 to e-Doc 7289178.

Nanstad, R.K. (1976). *A Review of Concrete Properties for Prestressed Concrete Pressure Vessels*. ORNL/TM-5497, Energy Research and Development Administration.

Naus, D.J. (2005). *The Effect of Elevated Temperature on Concrete Materials and Structures—A Literature Review*. ORNL/TM-2005/553, U.S. Nuclear Regulatory Commission.

Naus, D.J. (2010). *A Compilation of Elevated Temperature Concrete Material Property Data and Information for Use in Assessments of Nuclear Power Plant Reinforced Concrete Structures*. ORNL/TM-2009/175, U.S. Nuclear Regulatory Commission.

Naus, D.J., Graves, H.L. (2006). "A review of the effects of elevated temperature on concrete materials and structures," *Proceedings of the 14th International Conference on Nuclear Engineering (ICONE14)*, ASME, Miami, Florida.

Peterson, E.G. (1960). *Shielding properties of ordinary concrete as a function of temperature, 15 ed.*, UC-34, Physics and Mathematics, TID-4500, HW-65572, Hanford Atomic Products Operation, Richland, Washington, D.C.

Pimienta, P., McNamee, R.J., Mindeguia, J.-C. (2018). *Physical properties and behaviour of High-Performance Concrete at high temperature*, Springer.

Schneider, U., Diederichs, U., Ehm, C. (1982). "Effect of temperature on steel and concrete for PCRV's," *Nuclear Engineering and Design*, 67 (2), 245-258.

Tufail, M., Shahzada, K., Gencturk, B., Wei, J. (2017). "Effect of Elevated Temperature on Mechanical Properties of Limestone, Quartzite and Granite Concrete," *International Journal of Concrete Structures and Materials*, 11, 17-28.

Willam, K.J., Rhee, I., Xi, Y. (2005). "Thermal Degradation of Heterogeneous Concrete Materials," *Journal of Materials in Civil Engineering*, 17 (3).

Xiao, J., König, G. (2004). "Study on concrete at high temperature in China—an overview," *Fire Safety Journal*, 39 (1), 89-103.