Benefits of Ultra High Performance Concrete (UHPC) in the nuclear industry

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Cédric Androuët
Canadian Nuclear Safety Commission

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BENEFITS OF ULTRA HIGH PERFORMANCE CONCRETE (UHPC) IN THE NUCLEAR INDUSTRY

Cédric Androuët[1]

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

ABSTRACT

Ultra-High Performance Concretes (UHPC), or Ultra High Performance Fiber Reinforced Concretes (UHPFRC), are cementitious composite materials with a very high compressive strength (typically higher than 150 MPa) incorporating fibers, providing the material with a high tensile strength, a very high ductility as well as an extremely low permeability. These properties, along with their exceptional resistance to blast and impact, make UHPC excellent candidates for various possible applications and use in the nuclear industry, for which safety requirements are paramount. A wide range of potential applications and concepts of UHPC for new structures and retrofitting solutions in the nuclear industry is conceivable. Some of these applications have been proven to be feasible through experimental work, mock-ups and industrial projects. This paper focuses first on a description of the key characteristics of UHPC that are relevant for its use in the nuclear industry, amongst which are blast and impact resistance, shielding and confinement properties, durability properties as well as fire resistance capabilities. Next, the paper presents several existing applications of UHPC in the nuclear industry, along with potential future applications and concepts of UHPC for new structures and retrofitting solutions in the nuclear industry, and for nuclear waste management concepts.

INTRODUCTION

Ultra High Performance Fiber Reinforced Concretes (UHPFRC) are cementitious composite materials with a very high compressive strength (typically higher than 150 MPa) incorporating fibers, which provide the material with a high tensile strength, a very high ductility and an extremely low permeability. These properties, along with their exceptional resistance to blast and impact, make UHPFRC excellent candidates for various possible applications and use in the nuclear industry, for which safety requirements are paramount. Ultra High Performance Concrete (UHPC) and UHPFRC differ in that UHPC may or may not contain fibers. In this paper, UHPC will refer to UHPFRC as per common industry practice.

The main advantage of fiber-reinforced concretes (FRC), and of UHPC in particular, over traditional concretes is their tensile strength and ductility. When using a sufficient amount of fibers, UHPC present a high tensile strength (typically between 8 and 15 MPa) as well as a strain-hardening behavior followed by a strain softening behavior after macrocrack localization. UHPC strength and ductility allow them to develop very high-energy absorption and dissipation capacities, and post-cracking tensile stress transferring capability. Thus, UHPC exhibit an outstanding resistance to blast, impact and ballistic loads (Das and Nanthagopalan, 2022; Sherif et al., 2020). This makes them excellent candidates for use in the protection of strategic structures for which blast, impact and ballistic resistance is paramount, such as nuclear power plants (NPPs). Furthermore, because the amount and size of their pores are significantly reduced in comparison to traditional concretes, UHPC have exceptional durability properties (very low porosity and permeability, outstanding resistance to freeze-thaw cycles, enhanced corrosion resistance of steel rebars, etc.). Some other key characteristics of UHPC relevant for their use in the nuclear industry encompass their shielding and confinement properties as well as their capability to reduce rebar congestion.

A wide range of potential applications and concepts of UHPC for new structures and retrofitting solutions in the nuclear industry is conceivable. Some of these applications have been proven to be feasible through experimental work, mock-ups, and industrial projects. Amongst these are the precast prestressed UHPC beams and girders at Cattenom NPP (France), several design of spent fuel casks incorporating UHPC, retrofitting solutions for nuclear reactor containment walls, and steel plate UHPC composite modules for Small Modular Reactor (SMR) construction.

This paper will first describe the key characteristics of UHPC that are relevant for its use in the nuclear industry. Next, it will present several existing applications of UHPC in the nuclear industry, which will further pave the way to present potential future applications and concepts of UHPC for new structures and retrofitting solutions in the nuclear industry, and UHPC's potential contribution to nuclear waste management concepts.

OVERVIEW OF SOME UHPC PROPERTIES RELEVANT FOR THE NUCLEAR INDUSTRY

The Danish researcher Hans Hendrik Bache was the first to recognize and apply the core basic principles for developing UHPC (Buitelaar, 2018), amongst which the fundamentals are reducing the water-binder ratio, optimizing the particle packing density, minimizing the size of flaws, and improving the ductility by including a sufficient amount of fibers (Bache, 1981; Richard and Cheyrezy, 1995; Rossi, 2013; Shah and Weiss, 1998; Wille et al., 2011). The UHPC developed by applying these basic principles are characterized by their exceptional mechanical properties and durability. In addition to their fresh state properties being optimizable depending on the application (e.g. from a self-leveling to a highly thixotropic behavior), one of the most known characteristics of UHPC is their ultra high compressive strength, typically higher than 120 or 150 MPa (American Concrete Institute, 2018; CSA Group, 2019; SIA, 2016). However, the main advantage of UHPC is their tensile strength and ductility. When using a sufficient amount of fibers, UHPC present a high tensile strength (typically between 8 and 15 MPa) as well as a strain-hardening behavior, followed by a strain softening behavior after macrocrack localization. This behavior is illustrated in Figure 1.

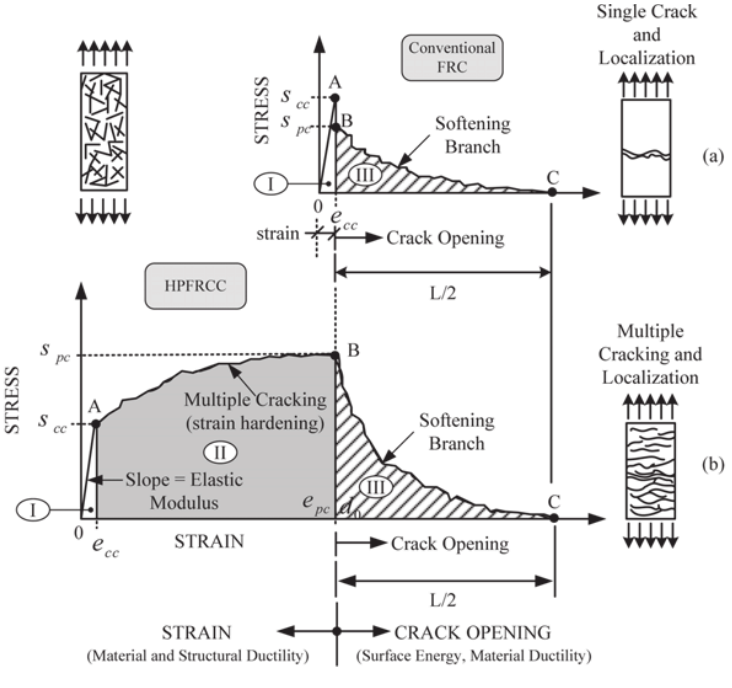

Figure 1: Typical tensile stress-strain behavior of FRC and UHPC (Naaman, 2003)

The tensile stress-strain behavior of UHPC can be divided into three main phases (SIA, 2016). Phase I is the elastic phase, when the cementitious-based matrix withstands the loads. In phase II, following the exceedance of the matrix tensile strength, multiple microcracks start to develop, and fibers dispersed throughout the UHPC allow it to develop a strain-hardening phase, due to the fibers' bonding effect within the matrix. In phase III, a macrocrack typically localises and fibers are getting pulled out from the matrix until it fails in a ductile manner (Gu et al., 2015; Naaman, 2003). The tensile capabilities of UHPC in terms of strength and ductility depend significantly on a number of different factors such as fiber shape, fiber dispersion, fiber aspect ratio, fiber orientation and fiber surface condition (Abbas et al., 2016; Delsol and Charron, 2013). Curing conditions also showed to have a significant importance in the development of mechanical and long-term properties of UHPC (Abbas et al., 2016; Androuët and Charron, 2021; Androuët et al., 2022).

Another essential advantage of UHPC is their exceptional durability. Because of their very high particle packing and low water content, the amount and size of their pores are significantly reduced in comparison to traditional concretes, which provide UHPC with a very dense microstructure, a very low water absorption and a very low chloride diffusion coefficient, thus drastically reducing the corrosion risk (Abbas et al., 2016). The low permeability and porosity of UHPC also enhances UHPC's resistance to freezing-thawing cycles (Abbas et al., 2016). The durability performance of UHPC when exposed to a marine environment was demonstrated by (Moffatt et al., 2020) for up to 21 years of exposition: UHPC exhibited significantly enhanced durability performance compared to typical high-performance concrete (HPC) and normal-strength concretes. Only minimal surface damage was observed, chloride profiles revealed penetration to a depth of approximately 10 mm only, regardless of the exposure duration, and electrochemical corrosion monitoring showed passivity for reinforcement at a cover depth of 25 mm after 20 years of exposition.

Blast Resistance

Nuclear structures must be designed against blast and explosions which may occur for a variety of reasons, both from the inside (accidental pressure, pipe rupture reaction, etc.) and outside (terrorist or military attack) of nuclear structures. Several researchers assessed UHPC performance against blast loads in the past two decades (Cavill et al., 2006; Das and Nanthagopalan, 2022; De Carufel et al., 2016; Sherif et al., 2020). Concrete structures submitted to blast loading may experience several failure modes (shear damage, flexural damage, spalling damage, etc.) (Das and Nanthagopalan, 2022) against which UHPC exhibit outstanding performance (Cavill et al., 2006; Sherif et al., 2020).

Amongst the number of experiments conducted to demonstrate the superior performance of UHPC against blast loadings, Cavill et al. (2006) illustrated the very significant difference between the behavior of UHPC panels vs standard reinforced 50-MPa concrete (SRC) against blast loads, the former showing almost no damage after being submitted to blast, while the latter exhibited heavy scabbing, reinforcing bars exposed and cavities of approximately 480 mm x 300 mm with a depth of about 50 mm. De Carufel et al. (2016) also showed that, while specimens made of standard reinforced 50-MPa concrete showed extensive concrete damage and buckling of compression steel reinforcement after being submitted to a reflected pressure of 80 kPa, specimens made of UHPC showed minor damage and prevented rebar buckling at the same reflected pressure. A reflected pressure of 97 kPa was required to cause failure of the UHPC specimen, which was due to rupture of tension steel. Also, while the SRC specimen showed significant fragmentation, the UHPC specimen showed an ability to eliminate secondary blast fragments. (Astarlioglu and Krauthammer, 2014) showed that UHPC specimens can resist four times higher impulsive loadings before failure compared to that of SRC specimens, in addition to exhibiting 30% smaller displacements. Similar observations were made by (Ngo et al., 2007). When subjected to blast loadings, because of their increased energy absorption capacity and improved ductility, UHPC structures allow for the development of multiple micro-cracks without fragmentation or spalling, preventing global structural damages (Abbas et al., 2016).

Impact Resistance

A very significant amount of research was performed to evaluate the impact and ballistic resistance of UHPC (Abbas et al., 2016; Cavill et al., 2006; Das and Nanthagopalan, 2022; Kodera et al., 2022; Othman and Marzouk, 2016; Tremblay et al., 2021).

Because of the complex nature of the material and distinct characteristics under compression and tension, the mechanisms of penetration and perforation in concrete are relatively more complicated than in metals (Das and Nanthagopalan, 2022). It is however admitted that the effect of a projectile on the front side of a target plate causes compressive shock waves, which spread and transmit over the thickness as tensile waves on the rear free surface. When the combined pressure of the compression waves and the reflected tension waves surpass the concrete's tensile capacity at the rear free surface, then concrete scabbing is expected (Das and Nanthagopalan, 2022). Such effect of the projectile impact on concrete is illustrated in (Lu, 2018).

UHPC's high strength and ductility properties provide structures made of UHPC with the ability to dissipate high energy under impact loads (Abbas et al., 2016). Also, the synergistic effects of high matrix strength, homogenous mixture, high volume fibre content and fibres bonding with matrix also contribute to UHPC's higher impact resistance than SRC (Gu et al., 2015). Because of these properties and their superior resistance to deterioration due to impact such as spalling, scabbing and cracking, UHPC have a demonstrated significant ability to resist impact loadings (Das and Nanthagopalan, 2022; Liu et al., 2022).

Fire And High Temperatures

UHPC may be more susceptible to fire and potentially explosive spalling during heating than conventional concretes (Abbas et al., 2016; Banerji et al., 2019; Gu et al., 2015). In addition to stresses due to significant thermal gradients potentially generating spalling, it is generally accepted that spalling of concrete submitted to high temperatures is due to the vaporisation of porewater, itself increasing the vapour pore pressure (Abbas et al., 2016; Bensalem et al., 2021). Releasing the increased vapour pore pressure is difficult due to the very small porosity and dense microstructure of UHPC, which makes UHPC more prone to explosive spalling under high temperatures and fire conditions (Banerji et al., 2019; Bensalem et al., 2021).

A very well-known solution to enhance the resistance of UHPC to fire and high temperatures, and mitigate the issue described above, is to incorporate polypropylene fibers in the UHPC mix (Abbas et al., 2016; Bensalem et al., 2021; Gu et al., 2015). Melting of polypropylene fibers occur at a temperature of about 160-170°C, which allows interconnection of the pore system, providing it with the ability to distribute and release the build-up of vapour pore pressure (Abbas et al., 2016; Gu et al., 2015). (Zhang et al., 2018) also suggest that the creation of microcracks (due to the difference between the thermal expansion coefficients of the fibers and the UHPC matrix) may provide additional interconnectivity to the pore system, hence improving UHPC's resistance to fire and high temperatures. Furthermore, the Canadian standard includes a requirement for a minimum amount of polypropylene fibers in UHPC mixes exposed to fire (CSA Group, 2019). Finally, while this is less systematic than for polypropylene fibers, some researchers have seen an improvement of the behavior at high temperatures thanks to the addition of steel fibers which may reduce and delay spalling (Abbas et al., 2016), most likely due to the degraded bond strength between the steel fibers and the UHPC matrix (Abdallah et al., 2017). A combined use of both polypropylene and steel fibers also showed a synergistic effect in improving the resistance of UHPC to fire and high temperatures (Li et al., 2019). Combining both polypropylene fibers and steel fibers may typically be the most interesting solution to prevent damages due to fire and high temperatures, considering the combined overall benefits provided by both types of fibers.

Shielding

A growing interest in assessing the radiation shielding capabilities of UHPC and in developing high radiation shielding UHPC mix-designs was observed over the past five years. While typical UHPC has good radiation shielding capability (Khan et al., 2020), the use of alternative minerals, partially or totally replacing the aggregates in the mix-designs, has been investigated to increase the UHPC density and enhance its radiation shielding capability.

Amongst the various minerals considered as a partial or total replacement of the aggregates in the UHPC mix-designs, hematite, barite, magnetite and ilmenite have been studied the most (Azreen et al., 2020; Han et al., 2022; Heniegal et al., 2022; Khan et al., 2020; Zeyad et al., 2022). The radiation shielding capabilities of the UHPC was shown to be typically increasing through a linear relationship with the increasing density of the UHPC mixes (Han et al., 2022; Heniegal et al., 2022; Khan et al., 2020; Zeyad et al., 2022).. Heavy iron (amang) and lead glass were investigated as replacements to aggregates but were found unsuitable mainly due to issues related to radiological safety and to decrease of the compression strength, respectively (Azreen et al., 2018). Finally, the radiation shielding of a UHPC and of a typical concrete with similar densities were compared, and it was shown that, at a same dry density, the thickness required to obtain a similar degree of radiation shielding was about 40% lower for UHPC than for traditional concrete, mainly due to their very high particle packing and very dense microstructure (Khan et al., 2020), which would provide very substantial benefits in terms of dead loads and foundation design of NPP structures.

APPLICATIONS OF UHPC IN THE NUCLEAR INDUSTRY

A variety of existing applications using UHPC in the nuclear industry have demonstrated its capabilities. An even wider diversity of potential applications is conceivable.

One of the first applications of UHPC in NPPs is the development and installation of precast, prestressed UHPC girders at the Cattenom NPP (France). Built during the 1980s, the Cattenom NPP crossflow cooling towers have since been exposed to an aggressive environment (water with significant sulphates and chlorides content, freeze-thaw cycles, etc.) which caused the structures supporting the splash fill to be damaged in their early age. As part of their restoration, the durability properties of UHPC and its capabilities to reduce the section dimensions were instrumental in the design of the additional required superstructure (Lion et al., 2020; Toutlemonde et al., 2010). The two different girder designs (lengths of 14.3 m and 6 m) were optimized with prestressing reinforcement only, and it was shown that no transverse reinforcement was required, as illustrated in Figure 2 (Birelli, 2009). Samples were extracted from the structures 10 and 20 years after their installation. Tests showed that the mechanical properties of the UHPC are stable (and even slightly increase) after 23 years, indicating good stability of the hydrates. The characterization performed also showed that the ingress of chlorides is so small that it can’t even be measured, and that the fibers are homogeneously distributed within the elements and are not corroded (even close to the surface), reflecting an absence of carbonation and chlorides in the UHPC (Lion et al., 2020; Toutlemonde et al., 2010).

Several designs of containment structures for advanced nuclear reactors technologies and SMRs (e.g. Westinghouse AP1000® Pressurized Water Reactor, GEH BWR-X300® Boiling Water Reactor, etc.) include the use of Steel Plate Concrete (SC) Composite Structures, where concrete is sandwiched between two cross tied steel plates to which it is connected by shear studs. A number of authors have proposed to use UHPC for the concrete infill of SC structures, to take advantage of UHPC’s enhanced performance. (Li et al., 2015; Sawab et al., 2016) developed a UHPC mix-design and demonstrated the superior structural performance of large-scale SC beams designed to be representative of typical nuclear containment structures of NPPs, using the newly developed UHPC for the concrete infill. In particular, it was highlighted that UHPC provided a very significantly higher contribution to the overall shear strength of the tested elements (both in plane and out of plane) in comparison to traditional concrete. (Wang et al., 2023) assessed the dynamic behavior of SC structures with a UHPC core when subjected to impact loads. The use of UHPC with 2% of steel fibers (length of 13 mm and diameter of 0.18 mm) proved to be effective in the improvement of material utilization and energy dissipation.

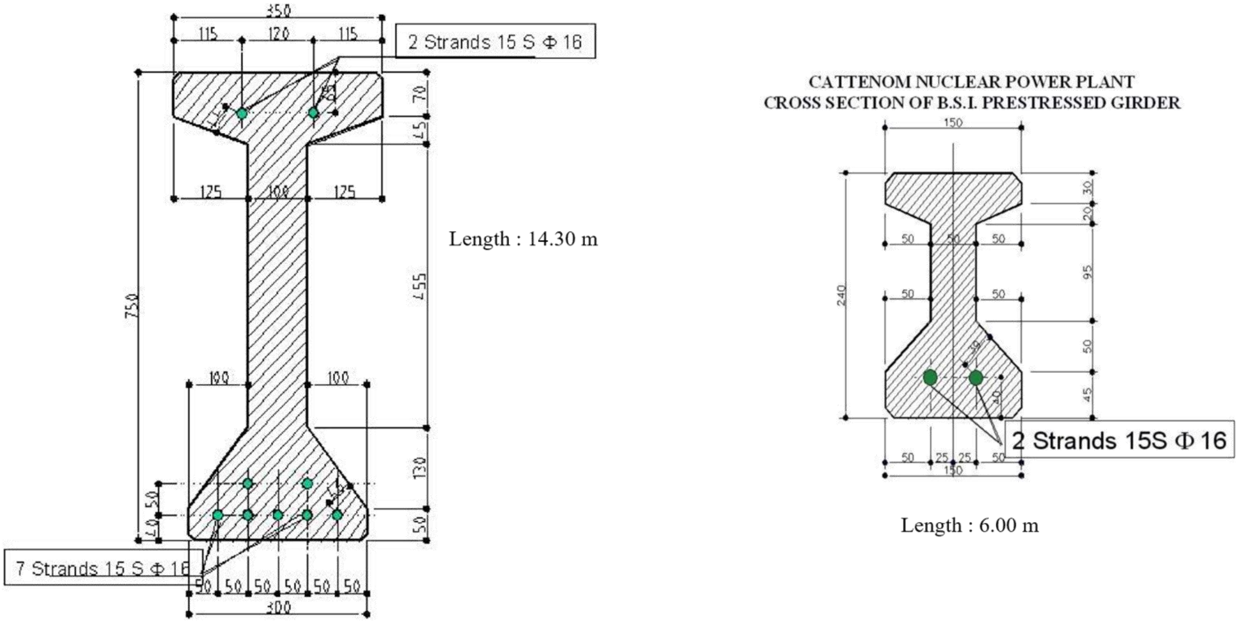

Figure 2: Cross-sections of the UHPC prestressed girders at Cattenom NPP (Birelli, 2009)

(Kang et al., 2022) proposed a novel containment design methodology based on the utilization of UHPC. Thanks to the UHPC very high compressive strength, it was possible to increase the levels of prestressing by a factor of 3 (in comparison with traditional prestressed containment structures). The UHPC's tensile ductility and strain hardening properties provided resistance against radial tensile forces as well as resistance against impact and impulsive loadings without requiring excessive transverse reinforcement. This allowed to significantly reduce rebar volume requirements, thus reducing rebar congestion, improving constructability and decreasing construction schedule. (Nagashima et al., 2022) assessed the feasibility of using UHPC for reactor buildings of NPPs and showed that the use of UHPC may result in buildings with an improved structural integrity and a reduced construction duration. (Qiao et al., 2022) also demonstrated through large-scale cast-in-place experimentations that UHPC may be used for nuclear reactor buildings. Moreover, (Masaki et al., 2022) performed in-plane loading tests for shear walls made with UHPC, for the purpose of applying UHPC to nuclear reactor buildings, and the series of experiments and modelling analyses they conducted confirmed its effectiveness. In particular, it was demonstrated that the seismic resistance performance of the shear walls made with UHPC was significantly improved thanks to the superior mechanical properties of the material.

(Rossi, 2021) suggested to implement the utilization of UHPC in the design of the inner structure of the double-wall containment structures to replace the metallic liner, through what may be called a load-bearing contributing formwork technique. Such innovation would have the triple benefit of significantly increasing the durability of the wall thanks to the extreme durability of the UHPC panel (constituting a "lost formwork"), significantly contributing to the mechanical performance of the structure, and reducing the construction time by keeping the formwork in place. In the same vein, one could imagine a concept similar to the SC composite structures, where the steel plates would be replaced by UHPC panels, thus creating a hybrid structure composed of traditional concrete sandwiched between two UHPC panels. By being prefabricated, these panels would present not only superior mechanical and durability properties, but also superior quality. This concept would also allow the optimization of the construction process, therefore reducing construction schedules.

UHPC may be used in a variety of strengthening and retrofitting applications. (Corvez and Masson, 2013) proposed two approaches for retrofitting NPPs' containment walls with UHPC (cast-in place and prefabrication) and showed that UHPC may be a promising solution for retrofitting nuclear reactor containment walls in order to extend their operating lifetime. In a slightly different approach, (Massicotte et al., 2017) demonstrated that replacing ordinary concrete by UHPC in the deficient lap splice zones of elements subjected to shear forces have the potential to develop plastic hinges and eliminate brittle failures of such elements.

Nuclear waste management may also benefit from the use of UHPC. Several designs of radioactive waste containers and spent fuel storage concrete casks were developed in the past years (Jia et al., 2022; Othman and Sabrah, 2022; Othman et al., 2019). A waste unit made of Densit®, the first ever commercially available UHPC designed by Hans Hendrik Bache (Bache, 1981), was even developed for use in shallow land burial of low and medium level radioactive waste in 1986 (Brodersen, 1986). UHPC was demonstrated to present a high degree of corrosion protection for steel reinforcement, mainly thanks to their demonstrated high electrical resistivity, low diffusion coefficient and low permeability. (Othman et al., 2019) designed a waste container using UHPC as an alternative to traditional steel-concrete-steel containers, with the aim to overcome drawbacks of traditional containers such as heaviness, expensiveness and difficulty to fabricate. The waste container developed for low, intermediate and high level radioactive wastes has been optimized to have a structural stiffness at least equivalent to that of the existing steel-concrete-steel container under various loading scenarios that would arise during the container's normal activities (e.g. waste conditioning, transportation, handling) and accidental events (drops, collisions). While the shielding effectiveness of the proposed design has yet to be examined (Othman et al., 2019), the use of UHPC for the design of the waste container allowed to decrease the damage levels at lid to body interface and the thermal stresses and associated damage following an exposition to elevated temperatures (Othman and Sabrah, 2022). (Jia et al., 2022) performed a feasibility study exploring the potential for using UHPC in vertical concrete cask for storage of nuclear spent fuel. Experimental and numerical modelling were performed as part of the design process of the UHPC concrete cask, and it was shown that the UHPC concrete cask would reduce the shield damage observed on traditional concrete casks submitted to tip-over and end-drop impact loadings.

CONCLUSION

With their outstanding mechanical properties, extremely low permeability and exceptional resistance to blast and impact, UHPC have the potential to be used for a wide variety of nuclear applications. Some of these have been demonstrated to be feasible through a series of experimental work, mock-ups and industrial projects. Such projects include the precast prestressed UHPC beams and girders at Cattenom NPP, several designs of spent fuel casks incorporating UHPC, retrofitting solutions for nuclear reactor containment walls, and steel plate UHPC composite modules for Small Modular Reactor (SMR) construction, to name a few. Several potential future applications and concepts of UHPC for new structures and retrofitting solutions in the nuclear industry, as well as UHPC potential contribution to nuclear waste management concepts, may also be envisioned. Because of their exceptional properties, it is expected that an increasing number of projects involving UHPC in the nuclear industry will emerge in the near future.

DISCLAIMER

The views expressed in this paper are those of the Author and do not necessarily reflect official positions of the Canadian Nuclear Safety Commission (CNSC), the nuclear regulatory authority in Canada.

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