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EVALUATION OF THE CHARACTERISTIC PROPERTIES OF GROUTS MADE WITH HIGH VOLUME OF SUPPLEMENTARY CEMENTITIOUS MATERIALS

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ABSTRACT

Building on international experience in decommissioning experimental reactors through *in-situ* decommissioning (ISD) techniques, two Canadian experimental reactors that have been in storage with surveillance mode for the past three decades, Nuclear Power Demonstration (NPD) and the Whiteshell Reactor No. 1 (WR-1) are proposed to be decommissioned *in situ* resulting in two disposal facilities. The approach proposed by the applicant is to encase the below-grade structures in two specially-formulated grouts, with the above-grade structures dismantled and either removed or grouted below grade. Finally, a concrete cap and a low permeability engineered cover would be installed to achieve closure.

One area of interest for both ISD projects is that the grouted structures would be below the water table. The long-term behaviour of the specially-formulated grouts and existing structures with regards to groundwater flow and solute transport therefore needs to be adequately assessed and understood from long-term human health and ecological risk assessment perspectives.

The Canadian Nuclear Safety Commission (CNSC) has initiated a research project aimed to characterize some properties of the grouts that Canadian Nuclear Laboratories (CNL) has indicated that it intends to use for the NPD and WR-1 ISD projects. This research aims to support CNSC staff in their regulatory assessment of the validity of the assumptions made in CNL's safety analysis reports and, more generally, of the adequacy of the proposed grouts to fulfil their functions in the ISD projects.

The paper presents the details of the ongoing experimental research project conducted by the CNSC. In particular, in addition to characterizing some of the usual properties of the grouts (such as workability, air content, temperature, unconfined compressive strength, etc.), the experimental program will characterize the grouts' bleeding, static segregation, adiabatic behaviour, pH, Young's modulus, tensile strength as well as density, absorption and leaching properties. The shrinkage will also be assessed, with a particular focus on the early-age strain behaviour of both mixes. Finally, the (relatively) long-term behaviour of the grouts will be assessed through a characterization of their hydraulic conductivity at different ages and under different crack opening conditions.

INTRODUCTION

The Canadian Nuclear Safety Commission (CNSC) is 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 environment and to respect Canada's international commitments on the peaceful use of nuclear energy. The Canadian Nuclear Laboratories (CNL) has been contracted by Atomic Energy of Canada

Limited (AECL) to manage and operate its sites and facilities across the country. It is also contracted to carry out AECL's mandate to enable nuclear science and technology and to protect the environment by fulfilling the government of Canada's radioactive waste and decommissioning responsibilities.

CNL has proposed an *in-situ* decommissioning (ISD) approach for the Nuclear Power Demonstration (NPD) site. The NPD site is located in Rolphton Township, in the Town of Laurentian Hills in Renfrew County, Ontario, Canada. It is on the south bank of the Ottawa River, about 3 km downstream of the Des Joachim's Dam, approximately 25 km upstream of the Chalk River Laboratories (CRL) site, and approximately 200 km northwest of Ottawa. The NPD Nuclear Generating Station was shut down in 1987 and placed into a safe interim storage condition. The proposed ISD approach aims to isolate the contaminated systems and components inside the below-grade structure thus creating a waste disposal facility on the NPD site. CNL proposed to fill all below-grade areas with grout. To do so, a grout batch mixing plant would need to be assembled on site, to produce the required grout. CNL plans to demolish the above-grade structures. They would be size reduced and placed into the below-grade structure as infill prior to final grouting. The ventilation stack, a current roosting structure for chimney swifts, is required to be retained. The grouted reactor system and components would then be capped with a concrete cap and covered with an engineered barrier.

CNL is also proposing an ISD approach to decommission the Whiteshell Reactor N°1 (WR-1), a former nuclear research reactor that was safely shutdown in 1985 and maintained in a "storage with surveillance" state since then. The WR-1 reactor is located at the Whiteshell Laboratories (WL) site in Pinawa, Manitoba, approximately 100 km northeast of Winnipeg, near the towns of Lac du Bonnet and Seven Sisters. The below-grade reactor structures, systems and components (SSCs) would be permanently disposed of *in-situ*. Most of the above-grade structures would be demolished and the wastes recycled or disposed of in other waste disposal facilities. Some above-grade structures would also be demolished and placed below-grade for encapsulation within the WR-1 Building. A concrete cap and engineered cover would then be constructed over the below-grade structure to protect the structure from water.

For both the NPD and the WR-1 ISD projects, the grout, as a new feature of the facility, will interact with the waste. Furthermore, because the grouted structures would be below the water table, the long-term behaviour of the specially-formulated grouts and existing structures with regards to groundwater flow and solute transport needs to be adequately assessed and understood from long-term human health and ecological risk assessment perspectives. Specific safety functions of the grouts would be to inhibit groundwater movement, create an alkaline environment (limiting the solubility of key contaminants and the corrosion of the system components), limit human intrusion and ensure isolation of radioactive waste. The grouts play a crucial role in preventing the migration of radioactive or hazardous contaminants from the closed facility to the groundwater so that concentrations in the groundwater do not exceed regulatory standards. Characterizing the behaviour of the grouts with time and possible degradation mechanisms is crucial in understanding the long-term performance of the grouts. Cracking behaviour influences the long-term performance of the grouts. For example, low tensile strength at early age could increase the risk of crack formation. Furthermore, unbonded joints (cold joints), shrinkage crack evolution and cracking due to other degradation mechanisms and thermo-chemo-mechanical phenomena will impact the hydraulic conductivity of the grout.

The two different grout mix-designs that CNL intends to use are uncommon, with a binder consisting of a mix of 10% of Ordinary Portland Cement (OPC) + 90% of Ground Granulated Blast Furnace Slag (GGBFS) for NPD, and 23% OPC + 77% of Fly Ash (FA) for WR-1. Properties and behavior of such special grouts are overall unknown. In addition to having requested CNL to perform some characterization of the proposed mix-designs, the CNSC has initiated a research project aimed to characterize some properties of the grouts which CNL has indicated that it intends to use for the NPD and WR-1 ISD projects. This research is performed to support CNSC staff in their regulatory assessment of the validity of the assumptions made in CNL's safety analysis reports and, more generally, of the adequacy of the proposed grouts to fulfil their functions in the ISD projects. The purpose of the experiments is to assess the behaviour of both grouts with time and possible degradation mechanisms. In particular, the early-age behaviour of the grout is paramount, with expected very low tensile strengths. The relatively long-term behaviour of the grouts will be assessed as well through a characterization of its shrinkage and of its hydraulic conductivity at different ages and under different crack opening conditions. In addition, to account for potential variations in the mixes when produced on-site, CNL has used a modified version of the NPD grout and the thus modified grout mix-design will be cast and submitted to a series of tests as well.

The paper presents the details of the ongoing experimental research project conducted by the CNSC. In particular, in addition to characterizing the usual properties of the grouts (such as workability, air content, temperature, unconfined compressive strength, etc.), the experimental program will characterize the grouts' bleeding, static segregation, adiabatic behaviour, pH, Young's modulus, tensile strength as well as density, absorption and leaching properties. The shrinkage will also be assessed, with a particular focus on the early-age strain behaviour of both mixes. Finally, the relatively long-term behaviour of the grouts will be assessed through a characterization of the grouts' hydraulic conductivity at different ages and under different crack opening conditions.

MIX DESIGNS

The mix-designs in Table 1 have been calculated from the publicly available mix-designs (Canadian Nuclear Laboratories, 2022, 2024), by proportionally adjusting the quantities to a total grout volume of 1 m^3, assuming twenty litres of entrapped air, using documented specific gravity values and for a sand in Saturated Surface Dry (SSD) condition. The mixes produced will quantitatively account for the actual water content of the sand (either subtract water from the total water to be added should the water content of the sand be greater than in its SSD condition, or increase the total water to be added should the water content of the sand be smaller than in its SSD condition). To account for potential issues such as heterogeneity, segregation, or bleeding, a preliminary testing phase will be conducted to validate the fresh state properties and performance of the grouts, focusing on key fresh state properties, such as those obtained via the slump flow test (including the Visual Stability Index (VSI) and the T_{50}), the J-ring test and the Self-Healing S test (CSA Group, 2024; National Concrete Masonry Association, 2007). The abovementioned adjustments will be performed by correcting, as needed, the dosage of High Range Water Reducer (HRWR) and Viscosity-Modifying Admixture (VMA).

Table 1: Grouts mix-designs (Canadian Nuclear Laboratories, 2022, 2024)

Component (kg/m^3)	NPD grout	NPD modified grout	WR-1 grout
Ordinary Portland Cement (OPC) Type GU – CSA A3000:23	38.0	41.7	89.4
Ground Granulated Blast Furnace Slag (GGBFS) – CSA A3000:23	342.2	374.9	-
Fly Ash (FA) Class F – CSA A3000:23	-	-	298.5
Water – CSA A23.1:24	345.3	287.9	233.1
Sand (quartz) – CSA A23.1:24	1343.7	1471.2	1577.8
Polycarboxylate HRWR Sika® ViscoCrete 2100 CSA A23.1:24 / ASTM C494	4.611	2.005	3.061
Diutan gum based VMA Kelco-Crete® DG CSA A23.1:24 / ASTM C494	0.297	0.325	0.302

EXPERIMENTAL PROGRAM

The ongoing research project initiated by the CNSC aims to assess the behavior of the grouts described above considering their age and the possible degradation mechanisms, through the characterization of some of their properties. The results obtained with this project will support CNSC staff in their regulatory assessment of the validity of the assumptions made in CNL's safety analysis reports and, more generally, of the adequacy of the proposed grouts to fulfil their function in the ISD projects.

Standardized test procedures will be used to characterize the properties listed below.

- Slump-flow of self-consolidating grout (including T_{50} measurement and VSI), as per CSA A23.2-19C (CSA Group, 2024).
- Passing ability of self-consolidating grout, as per CSA A23.2-20C (CSA Group, 2024).
- Air content of plastic grout by pressure method, as per CSA A23.2-4C (CSA Group, 2024).
- Density and yield of plastic grout, as per CSA A23.2-6C (CSA Group, 2024).
- Temperature of freshly mixed hydraulic cement grout, as per CSA A23.2-17C (CSA Group, 2024).
- Bleeding of flowable grout, as per CSA A23.2-1B (CSA Group, 2024).
- Static segregation of self-consolidating grout using column technique, as per ASTM C1610/C1610M-21 (ASTM International, 2025). To account for the maximum size of aggregates being smaller than for traditional self-consolidating concretes for which this test has been designed, one test will be conducted using the sieve size prescribed by the standard, and another test will be performed with a sieve size of 500 μm.
- Compressive strength of cylindrical grout specimens, as per CSA A23.2-9C (CSA Group, 2024). In addition to the curing conditions specified by the standard, additional sets of curing conditions representative of the conditions at site will be evaluated, for temperatures ranging from 10°C to 23°C and relative humidities ranging from 50% to 100%.
- Splitting tensile strength of cylindrical grout specimens, as per CSA A23.2-13C (CSA Group, 2024). In addition to the curing conditions specified by the standard, additional sets of curing conditions representative of the conditions at site will be evaluated, for temperatures ranging from 10°C to 23°C and relative humidities ranging from 50% to 100%.
- Static modulus of elasticity and Poisson's ratio of grout in compression, as per ASTM C469/C469M-22 (ASTM International, 2025).
- Density, absorption and voids in hardened grout, as per CSA A23.2-11C (CSA Group, 2024).

The strategy followed to evaluate several of the grouts' properties which may not be determined through the use of standardized tests alone are detailed below.

Setting Time

The setting time of the grout mixes will be evaluated by a combination of the ASTM C191-21 Vicat tests (ASTM International, 2025) and of ultrasonic tests. A high-precision ultrasonic measuring system specifically designed to measure the setting times of building materials such as mortars and grouts will be used. As the binder hydrates and hardens, the ultrasonic wave velocity increases. By computing the first derivative of the evolution of the ultrasonic wave velocity vs time, the initial and final setting times can be identified.

Free Shrinkage

The evaluation of the free shrinkage of the grouts will be conducted in accordance with the testing procedure specified by CSA A23.2-21C (CSA Group, 2024). A drawback of the CSA A23.2-21C testing methodology relies in the fact that it does not permit to capture the deformational behavior of the mix at early-age. Consequently, an embedded PMFL-50T strain gauge (50 mm length, uncertainty of ±7 μm/m) will be fixed longitudinally in the center of the specimen, and measurements will be started as soon as the specimens are cast, as was previously successfully done by (Androuët and Charron, 2021; Rossi et al., 2013).

In addition to the curing conditions specified by the standard, additional curing conditions representative of the conditions at site will be evaluated, for temperatures ranging from 10°C to 23°C and relative humidities ranging from 50% to 100%.

Restrained Shrinkage

One of the objectives of the grouts within the facilities is to encapsulate the contaminated structures, systems and components (SSCs) inside the below-grade structure. The existing SSCs are likely to restrain the deformations of the grouts, amongst which are the deformations due to shrinkage, thus potentially generating cracks which would become preferential pathways for groundwater movement (Androuët, 2024).

Ring tests are very effective in simulating real life conditions, allowing for the evaluation of the grouts' response to stress and its cracking potential. A review of the restrained testing procedures has been provided in (Kanavaris et al., 2019), where the efficiency of the restrained shrinkage ring tests has also been outlined. Rings are characterized by the internal radius of steel (RIS), the outer radius of steel (ROS), the outer radius of concrete (ROC) and the height of the specimen, as presented in Figure 1.

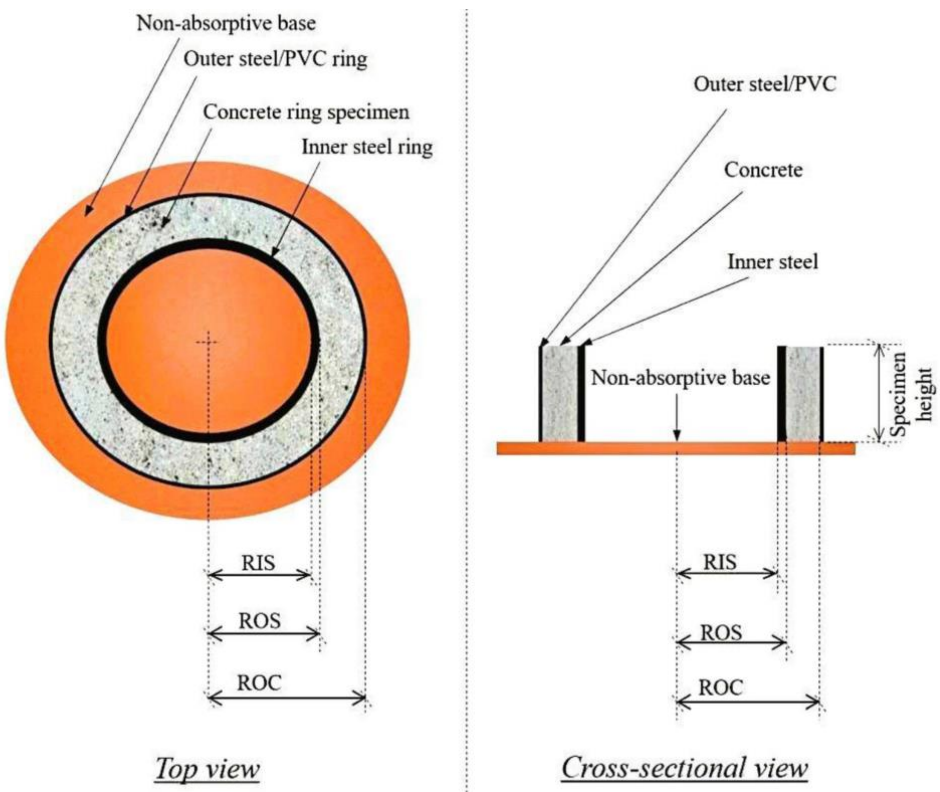

Figure 1: Main geometric characteristics of restrained shrinkage rings (Kanavaris et al., 2019).

These geometric characteristics will result in a degree of restraint (DR) calculated according to Equation 1 (Kanavaris et al., 2019).

$$DR = \frac{A_{rc} \cdot E_{rc}}{A_{rc} \cdot E_{rc} + A_{cm} \cdot E_{cm}} \cdot 100\% \tag{1}$$

where: DR is the degree of restraint (in %); A_{rc} and A_{cm} are the cross-section area of the steel and grout ring, respectively (in mm^2); E_{rc} and E_{cm} are the modulus of elasticity of steel and grout, respectively (in GPa).

The dimensions of the rings used as part of this experimental program are of 40 mm (height), 87 mm (RIS), 105 mm (ROS), 135 mm (ROC), 18 mm and 30 mm (thickness of the steel and the grout rings, respectively). With an assumed E_{rc} of 200 GPa, and an estimated E_{cm} evolving at early age between 4 and 8 GPa, the DR obtained is above 90%. The rings are instrumented with four temperature-compensated strain gauges each (in full bridge configuration). The restrained shrinkage will be studied at a temperature of 23°C and a relative humidity of 50%.

pH

The pH measurement test of hardened grout will be performed as an ex-situ leaching method. The method has been described by (Räsänen and Penttala, 2004) and implemented to low pH cementitious materials used in underground repository for the geological disposal of high-level radioactive waste by Alonso et al. (2012). The samples will be prepared according to the method proposed by (Räsänen and Penttala, 2004): 30 g of hardened grout is powdered using a Retch PM400 ball mill with a grinding time of 20 s. 15 g of the powder is mixed with 15 g of distilled water in a rotating mixer at a speed of 35 rpm for 15 min. After the mixing, 10 ml of the solution is poured into a vial and the pH is measured with a Thermo Scientific OrionStar benchtop pH meter using Merck Certipur buffer solutions (traceable to NIST). The standard deviation of the method is 0.27 pH units. Three samples per mix will be measured at the age of 56 days.

Adiabatic Thermal Behaviour

Because of the potential effects of the heat of hydration on the early-age and long-term characteristics of the grouts, evaluating the adiabatic thermal behaviour of the mixes is paramount.

The adiabatic temperature rise will be measured using an adiabatic concrete calorimeter. The measurements will be conducted according to the European standard EN 12390-15:2019 (European Committee for Standardization, 2019b) with a test duration of 7 days, or until equilibrium state is reached. The dimensions of the test sample are that of a 15 cm cube. The test is conducted in a controlled ambient temperature (at 20°C ± 1°C), where the adiabatism error is less than 0.05°C/h. A fresh sample is positioned in a calorimeter cell ensuring adiabatic conditions by avoiding heat exchange with the environment. Since this condition cannot be obtained in practice in a passive system (no insulating material is infinitely non-conductive), the temperature of the room surrounding the specimen is forced to be equal (or slightly lower by max 0.5°C) to the temperature of the sample during all the tests. Two PT 100 temperature sensors are used, one positioned in the sample and one in the calorimeter cell. The temperature measurements are used by a PID closed-loop control system to ensure stable sample conditioning according to the standard requirements. The temperature sensors are platinum PT 100 having 0.01°C resolution and 0.1°C accuracy. In addition, an embedded PMFL-50T strain gauge is fixed longitudinally in the centre of one of the specimens to enable the determination of the Coefficient of Thermal Expansion.

Hydraulic Conductivity

Because the grouted structures of both projects would be below the water table, the long-term behaviour of the specially formulated grouts with regards to groundwater flow and solute transport needs to be adequately assessed and understood, in a long-term assessment of human health and ecological risk assessment perspective. To that end, the hydraulic conductivity of the mixes in various conditions will be evaluated.

The hydraulic conductivity test proposed is based on a test arrangement of the EN 12390-8 standard (European Committee for Standardization, 2019a), which determines the depth of penetration of water under a pressure of 500 ± 50 kPa applied for 72 ± 2 hours on one surface of the specimen. The surfaces of the test specimen not exposed to the water pressure are periodically monitored to note the presence of water. The result is the maximum depth of penetration of the waterfront in the concrete (measured after splitting the sample in half). The test is performed on half-cylinders (100×200 mm cylinders cut in half) in a non-steady state, meaning no flow through the samples is measured.

Based on the penetration depth of water, in the non- stationary flow state of the test setup, the hydraulic conductivity for water (K_w) is quantified according to Equation 2 (Valenta, 1969).

$$K_w = \frac{\alpha \cdot d^2}{2 \cdot H \cdot t} \tag{2}$$

where K_w is the hydraulic conductivity (in m/s), d is the water penetration depth (in m), α is a unitless number representing the permeable porosity, i.e. the interconnected pore spaces through which fluids can move, t is the test time (in s), and H is the hydrostatic head causing the water percolation (in m).

To convert the hydraulic conductivity K_w (in m/s) into intrinsic permeability k_w (in m^2), independent of the properties of the liquid used during the test, Darcy's law is used according to Equation 3.

$$k_w = 1.02 \times 10^{-7} K_w \tag{3}$$

Because of the very significant impact that cracks may have on the hydraulic conductivity of cementitious-based materials (Androuët, 2024), in addition to the characterization of the hydraulic conductivity of the grouts in sound conditions, the hydraulic conductivity of the grouts in various cracked conditions, along with the impact of cold joints on the hydraulic conductivity, will also be evaluated.

Cylindrical specimens resulting from 100×200 mm cylinders being cut in half will be used, which allows to accommodate the study of damaged samples and of cold joints in a similar way as by (Zhou et al., 2023). Pre-testing will be performed to evaluate the water pressure and duration of the test to ensure that the water penetration in the concrete is maintained in a non-steady state (i.e. not penetrating through the sample or leaking), both for sound and cracked specimens.

Leaching

The leaching test methodology is based on an adaptation of the method proposed by (European Committee for Standardization, 2011). The objective of the test is to estimate the long-term stability of the grouts and will be performed in distilled water. The leaching rates of various components, including Ca, Na, K, S, Cl, Si, Al, and heavy metals, will be determined. The methodology focuses on understanding the time-dependent leaching behaviour, identifying controlling mechanisms, calculating effective diffusion coefficients, and assessing cumulative release behaviour over a 3-month period.

Two repetitions will be performed for all grouts. The test specimens' dimensions are 40 × 40 × 160 mm for a volume of 0.256 litres, and the volume of leachant is about five times the sample volume (i.e. 1.28 litres). The specimens will be cured at a temperature of 23°C and a relative humidity of 65% for a period of 28 days. A total of 42 analyses will be performed, for seven different testing times (from one hour to three months).

Meso-Scale Test

To simulate and assess the ability of one of the grouts to fill a volume with various inserts (such as horizontal, oblique and vertical pipes, construction debris, utility pumps etc.), a meso-scale test will be performed by preparing and casting a 0.7 m x 0.7 m x 0.7 m block. Furthermore, an additional objective of pouring the block is to evaluate how the grouting of the ISD projects might be affected by logistics and operational needs (e.g. delamination due to cold joints), which will be assessed by filling the block in three separate casts.

The assessment of the capacity of the grout to fill the volume adequately will be based on a comparison of the ability of water to fill the same volume. The filling ability of water is theoretically ideal, due to water's low viscosity and simpler chemical composition, making it best suited for establishing a filling reference for the specific volume with challenging inserts. The steps in assessing the ability of the grout to fill the volume are defined as:

① Complicated insert structures added to cubic mould. The mould is weighed (W_0).
② Water is poured slowly into the mould until it fills the volume.
③ The cubic mould filled with water is weighed (W_1). The difference between both weights provides the volume of water (V_w) needed to fill the whole volume ($V_g = V_w = W_1 - W_0$). This constitutes the theoretical maximum volume that a grout could fill.
④ Water is removed, and the mould is dried.
⑤ Grout is poured slowly in successive castings into the mould until it fills the volume. The cubic mould filled with grout is weighed (W_2). Simultaneously, the density of the grout is measured (ρ_g).
⑥ The volume of grout used to fill is determined ($V_g = (W_2 - W_0) / \rho_g$).
⑦ The ability of the grout to fill the predefined volume is determined as the ratio between the filling ability of the grout vs that of water, in volume (V_g / V_w, in %).

After the block has been filled in successive castings, the homogeneity of the grouts cast, along with the ability of the grout to fill the whole volume, including around and inside inserts, will be evaluated by conducting two cross-section cuts of the block (one longitudinal and one transversal). Homogeneity will be documented using visual assessment (based on photographic documentation).

CONCLUSION

As part of its mission to regulate the use of nuclear energy and materials to protect health, safety, security, and environment, the CNSC has initiated a research project aimed to characterize some properties of the uncommon grout mix-designs that CNL has indicated it intends to use for the NPD and WR-1 ISD projects. One area of interest for both ISD projects is that the grouted structures would be below the water table. The long-term behaviour of the specially-formulated grouts and existing structures with regards to groundwater flow and solute transport therefore needs to be adequately assessed and understood from long-term human health and ecological risk assessment perspectives. This research aims to support CNSC staff in their regulatory assessment of the validity of the assumptions made in CNL's safety analysis reports and, more generally, of the adequacy of the proposed grouts to fulfil their function in the ISD projects.

The details of the ongoing experimental research project conducted by the CNSC have been presented. In particular, in addition to characterizing some of the usual properties of the grouts (such as workability, air content, temperature, unconfined compressive strength, etc.), the experimental program aims to characterize the grouts' bleeding, static segregation, adiabatic behaviour, Young's modulus, tensile strength as well as density, absorption and leaching properties. In addition to assessing the behavior of the grouts with time and evaluate the possible degradation mechanisms, the early-age behavior of the grout is paramount, with expected very low tensile strengths. In that perspective, the early-age strain behaviour of the grouts is evaluated. The (relatively) long-term behavior of the grouts is assessed as well through a characterization of their shrinkage and of their hydraulic conductivity at different ages and under different crack opening conditions.

REFERENCES

Alonso, M.C., García Calvo, J.L., Walter, C.S., Naito, M., Petterson, S., Puigdomenech, I., Cuñado Peralta, M.A., Vuorio, M., Weber, H., Ueda, H.F., Kiyoshi (2012). *Development of an accurate pH measurement methodology for the pore fluids of low pH cementitious materials*. ISSN 1402-3091, SKB R-12-02.

Androuët, C. (2024). "Impact of hydraulic conductivity, diffusion, and self-healing of cracked cementitious-based materials on the groundwater flow and solute transport modelling for in-situ decommissioning projects," *Proceedings of the International Conference on Decommissioning Challenges: Role and importance of innovations (DEM 2024)*, SFEN, Avignon, France.

Androuët, C., Charron, J.-P. (2021). "Shrinkage Mitigation of an Ultra-High Performance Concrete Submitted to Various Mixing and Curing Conditions," *Materials*, 14 (14).

ASTM International (2025). *Annual Book of ASTM Standards, Section 4: Construction*. West Conshohocken, PA, USA.

Canadian Nuclear Laboratories (2022). *Environmental Impact Statement for the In Situ Decommissioning of WR-1 at the Whiteshell Laboratories Site*. WLDP-26000-ENA-001 Rev4, Canadian Nuclear Laboratories.

Canadian Nuclear Laboratories (2024). *Environmental Impact Statement - NPD Closure Project*. 64-509200-ENA-004 Rev4, Canadian Nuclear Laboratories.

CSA Group (2024). *Concrete materials and methods of concrete construction/Test Methods and Standard Practices for concrete*. A23.1:24/A23.2:24, Toronto, Ontario, Canada.

European Committee for Standardization (2011). *Concrete - A study of the characteristic leaching behaviour of hardened concrete for use in the natural environment*. CEN/TR 16142, European Committee for Standardization,.

European Committee for Standardization (2019a). *Testing hardened concrete. Part 8: Depth of penetration of water under pressure*. EN 12390-8:2019, Brussels, Belgium.

European Committee for Standardization (2019b). *Testing hardened concrete. Part 15: Adiabatic method for the determination of heat released by concrete during its hardening process* EN 12390-15:2019, Brussels, Belgium.

Kanavaris, F., Azenha, M., Soutsos, M., Kovler, K. (2019). "Assessment of behaviour and cracking susceptibility of cementitious systems under restrained conditions through ring tests: A critical review," *Cement and Concrete Composites*, 95, 137-153.

National Concrete Masonry Association (2007). *Self-Consolidating Grout Investigation: Making and Testing Prototype SCG Mix Designs - Report of Phase II Research*. Project No. 05-330, Publication No. MR31, National Concrete Masonry Association.

Räsänen, V., Penttala, V. (2004). "The pH measurement of concrete and smoothing mortar using a concrete powder suspension," *Cement and Concrete Research*, 34 (5), 813-820.

Rossi, P., Charron, J.-P., Bastien-Masse, M., Tailhan, J.-L., Maou, F.L., Ramanich, S. (2013). "Tensile basic creep versus compressive basic creep at early ages: comparison between normal strength concrete and a very high strength fibre reinforced concrete," *Materials and Structures*, 47, 1773-1785.

Valenta, O. (1969). "Kinetics of water penetration into concrete as an important factor of its deterioration and of reinforcement corrosion," *RILEM International Symposium on the Durability of Concrete, Part I*, IASMiRT, Prague.

Zhou, Y., Zhang, R., Zhang, J., Li, Y., Li, Z., Xing, X., Zhang, Q., Feng, G. (2023). "Brazilian splitting testing of the restorative properties of eco-friendly epoxy resin on cracked granite samples with various widths," *Construction and Building Materials*, 401, 132907.