

OPTIMIZED LOW HEAT HIGH PERFORMANCE CONCRETE MIXES FOR DGR SHAFT SEALING

C. M. Aldea¹, B. Shenton¹, B.J. Cornelius¹ and H. Leung²

¹ Amec Foster Wheeler, Hamilton, Ontario, Canada

² Nuclear Waste Management Organization, Toronto, Ontario, Canada

corina.aldea@amecfw.com, barry.shenton@amecfw.com, bruce.cornelius@amecfw.com,
hleung@nwmco.ca

Abstract

Concrete is expected to be an important part of the shaft seals installed during the decommissioning and closure phase of a deep geological repository (DGR). Concrete structures are presently part of the design for the proposed Ontario Power Generation (OPG) DGR for Low and Intermediate Level Radioactive Waste (L&ILW) near the Bruce Nuclear site, and for the Nuclear Waste Management Organization's conceptual repository design for used nuclear fuel. A low heat high performance concrete (LHHP) reference mix design was previously developed and key properties evaluated. This paper presents interim results of a program aimed to optimize the LHHP reference mixture, to fabricate specimens of LHHP seal materials and to measure key performance parameters. A methodology was developed to design optimized LHHP mixtures using mix ingredients from local and sustainable sources, which included making changes to the type of cementitious material (CM), CM rate and source, type, source and size of aggregate, type and dosage of superplasticizer, and water to CM ratio.

1. Introduction

In the DGR concept, low-pH concrete is more appropriate to be used instead of conventional concrete. In particular, due to long-term material compatibility requirements, the concrete leachate pH must be lower than normal, and therefore the concrete mixtures have been made with very low amounts of cement while utilizing 40% or more of alternative binders, such as silica fume and fly ash. According to the current understanding, low-pH concrete should not disturb the function of the bentonite clay materials which are also part of the engineered barrier system. This is accomplished by avoiding the development of a high-pH leachate by replacing leachable calcium compounds with silica in the low-pH concrete. Innovative research has been done to develop and validate the performance of low-pH concrete for use in high level radioactive nuclear waste containment structures [1, 2]. For example, this type of concrete is planned for deposition tunnel end plugs acting as hydraulic and mechanical barriers in Finland's deep underground repository [2]. Low-pH concrete is also planned for use in the shaft seals in Canadian DGRs, including OPG's proposed DGR for low & intermediate level waste at the Bruce Nuclear Site, as well as NWMO's conceptual design of a used fuel DGR. The following are among the practical requirements for the concrete in plastic and hardened state in order to fulfil its purpose for this application:

- All components of the mix design must be commercially available and it must be possible to produce the concrete in a conventional concrete plant.
- The components should be selected based on reasonable prospects that they would be commercially available over an extensive timeframe, recognizing that sealing of repositories is decades in the future.
- The geometry of the plug requires the plastic concrete to be self-compacting. The method of placement requires that the plastic concrete keeps its self-compacting properties for at least two hours.
- The concrete must release low exothermal heat during curing and the volume changes of the young and mature concrete must be minimized to limit or avoid cracking.

In addition, the concrete must meet other performance specifications noted below. Based on the requirements mentioned, key properties of the plastic and hardened concrete must be quantified in order to design a concrete mix that fulfils the intended purpose.

A low heat high performance concrete (LHHP) reference mix design was previously developed by AECL in the 1990's. This design was adopted by OPG as reference concrete for its proposed DGR shaft seal, and key properties evaluated. Table 1 presents details of the reference LHHP mix design compared with other low pH concrete mix designs developed for use in nuclear waste containment in the literature.

Table 1 Low pH concrete mix designs used in nuclear waste containment

Mix ingredient (kg/m ³)	OPG (Reference)	SKB B200 [1]	SKB B300 [1]	Posiva ternary mix [2]	Posiva binary mix [2]
Cement (sulphate resistant)	95.6	120	180	105	120
Silica fume	95.6	80 (densified)	120 (densified)	91	80
Fly ash	-	-	-	84	-
Fine filler	190.9 (silica)	369 (limestone)	269 (limestone)	114 (silica)	256 (silica)
Silica sand	889.4	1037 (0 - 8 mm)	1035 (0 - 8 mm)	NA	NA
Granitic aggregate	1035.7 (5 - 20 mm)	558 (8 - 16 mm)	557 (8 - 16 mm)	NA	NA
Total aggregate	1925.1	1595	1592	1840	1805
Superplasticizer (dry mass)	10.16 (naphtalene-based)	6.38 (polycarboxylate-based)	7.08 (polycarboxylate-based)	NA (naphtalene-based)	NA (naphtalene-based)
Water	95.6	165	165	126	125
Water-to-cementitious materials ratio	0.500	0.825	0.550	0.450	0.625

This paper presents interim results of a program aimed to optimize the LHHP reference Canadian mixture, to fabricate specimens of LHHP seal materials and to measure key performance parameters.

2. Criteria for optimization of LHHPC

A methodology was developed to design optimized LHHPC mixtures using mix ingredients from local and sustainable sources, which included making changes to the OPG reference mix in terms of the type of cementitious material (CM), CM addition rate and source, type, source and size of aggregate, type and dosage of superplasticizer, and water to CM ratio (w/cm).

Optimized LHHPC mixtures used mix ingredients from existing local and sustainable sources, and were obtained by making the following changes to the original reference LHHPC mix design:

- Type of CM, including replacing sulphate resistance cement with general use (Type GU) cement and a reduced dosage of silica fume (SF) by partial or complete replacement with other supplementary cementing materials (SCM), such as ground granulated blast furnace slag (slag);
- CM addition rate;
- CM source (supplier), including binders from various manufacturers which are locally available;
- Type, source (supplier), shape and size of nonreactive aggregate, including crushed quarried carbonate coarse aggregate, open pit natural coarse aggregate and open pit sand from local sources in Ontario;
- Type of superplasticizer (SP), including replacing naphthalene-based SP with polycarboxylate-based SP;
- Water-to-cementitious material ratio (w/cm) varied depending on the mix ingredients, including the type of CM, SP, and aggregate sources. LHHPC mixes developed in this program used the lowest practical w/cm to meet the specified performance targets.

3. Optimization test program

Multiple steps were taken for the preparation of the optimized LHHPC mix formulations. Mix designs were prepared and trial batches made, which were then evaluated and screened based on selected plastic and early age hardened performance targets for the project. For the LHHPC mixes which met the performance targets, production batches were prepared to measure all of the project performance parameters.

3.1 Optimization of LHHPC test program

The methodology used for LHHPC optimization is summarized in Table 2. Mix designs for trial batches were prepared in five series of mixes (Series 1 to Series 5), starting from the OPG original reference mix design. In Table 2 the grey cells represent the original reference LHHPC mix components, whereas the white cells represent ingredients for potential optimized LHHPC mix designs. The w/cm varied, as required, to meet the specified performance targets.

The purpose of the Series 1 mixes was to determine the effect of replacing all of the SF with slag and all of the high sulphate-resistant hydraulic cement (Type HS) with cement Type GU,

while keeping all other constituents constant. It was anticipated that the removal of silica fume would significantly alter the water demand of the concrete, which would allow reduction of SP addition levels, water content, or both, which could improve the plastic and hardened properties of the LHHPC. This was done with both the original SP (sodium sulphonated naphthalene) and the polycarboxylate-based SPs (new SP).

Table 2 LHHPC optimization matrix

Mix design variables	OPG (reference, amount by mass kg/m ³)	Series 1	Series 2	Series 3	Series 4	Series 5
Cement Type HS	95.6					
Cement Type GU, source 1		√	√	√		√
Cement Type GU, source 2					√	√
Silica fume	95.6			√	√	√
Slag		√	√	√	√	√
Silica flour	190.9	√	√	√	√	√
Silica sand	889.4	√				
Natural concrete sand			√	√	√	√
Coarse granitic aggregate	1035.7	√				
Carbonate quarry aggregate			√	√	√	√
Natural carbonate and crystalline pit aggregate			√	√	√	√
Superplasticizer (naphtalene-based, dry mass, kg)	10.16	√				
Superplasticizer (polycarboxylate-based)			√	√	√	√
w/cm	0.50	√	√	√	√	√

The Series 2 mixes replaced the granitic aggregate from the Series 1 mix with both quarried and natural pit aggregate, as well as replaced the silica sand with commercial concrete sand. The binder was a binary 50:50 blend of Type GU cement and slag. These mixes were used to confirm that the required properties of the LHHPC are met with the alternative carbonate and natural pit aggregates.

For the Series 3 mixes, SF was introduced at a level 10% of the total binder content in order to establish the effect of silica fume on both plastic and hardened properties. It was anticipated that the increased water demand of the silica fume would require additional SP, compared to the Series 2 mix designs, in order to maintain workability. The silica fume limit of 15% of the total binder was selected to meet the limits established in CSA A3001-13, Table 9 [3].

The Series 4 mixes used the proportions of the optimum mixes from Series 3 with the replacement of the Type GU cement from the first source with Type GU cement from a second source. The purpose of this series was to establish whether the LHHPC properties are sensitive to variations of Portland cement source. While all Type GU cements must meet the CSA A3001-13 requirements [3], differences in cement fineness and chemistry (particularly alkali content) can affect the properties of the concrete.

The final Series 5 mixes were designed based on the information gathered in the preceding Series to produce a set of optimum LHHPC formulations, using both sources of Type GU

cement, all types of carbonate and granitic aggregate, silica fume, slag, and the polycarboxylate-based SP.

3.2 Mix ingredients and characterization

Manufacturers and sources for mix ingredients suitable for LHHPC were identified and selected. The LHHPC mix ingredients include CM (binders), coarse and fine aggregate, fine filler and SP. All of the mix ingredients used for LHHPC optimization were characterized prior to being used for the project. Based on the characterization test results, the mix ingredients were all within typical property ranges and met the CSA requirements [3-4] for use in Portland cement based concrete. They are all suitable to be used for concrete mixes and consequently for LHHPC mixes.

General use Portland cement (Type GU) from two sources (Source 1 and Source 2) was used for the project. The Supplementary Cementitious Materials (SCMs) for the project were slag and silica fume. Binary blends using cement Type GU and slag, as well as ternary blends with cement Type GU, slag and silica fume were evaluated as potential binders. The ternary blends using cement Type GU, SF and slag incorporated a reduced dosage of SF compared to the reference mix Table 1. The dosage rates of SF and slag met the proportion limits established in CSA A3001-13, Table 9 [3]. The reference mix design did not meet these limits.

The replacement of silica fume with slag was desirable as currently available silica fume materials at the addition levels of the reference mix entrained too much air for the LHHPC to meet the performance targets. Furthermore, silica fume may result in the generation of hydrogen gas, depending on the (variable) amount of silicon metal, which may be an issue in a mass concrete structure underground (i.e., enclosed spaces). Blast furnace slag was selected as alternative replacement for SF in this study; however, it may be a source of sulphide, which could be a factor in a repository for used fuel with copper containers.

The original reference LHHPC mix used Type HS cement. However, there is currently limited availability of Type HS cement as a result of the cement industry moving away from manufacturing special-use cements. Type HS cements have been replaced by blending varying amounts of SCM with Type GU cements to provide blended cements meeting the performance targets of a high sulphate resistance, and categorized as HSb cements in CSA A3000-13 [3]. A blend of Type GU cement and slag at the levels used for this program (approximately 50:50) easily meet the performance targets for a Type HSb cement. Also, addition of silica fume in the ternary blends (Series 3, 4 and 5) further enhanced the sulphate resistance of the cementing materials. These factors eliminate the need for HS cement, which is unlikely to be available in the future (e.g., envisaged timing for the installation of shaft seals at the closure of a Canadian DGR).

The original reference mix used granitic aggregate to meet the geochemical properties of the granitic host rock for which it was designed. Only aggregate classified as non-reactive were considered for this project. Gradation of aggregates was selected to conform to current CSA concrete standards (CSA A23.1-09) Section 4.2.3 Aggregates, and in particular CSA A23.1-09

(Tables 10 and 11) for fine and coarse aggregate, respectively, with particular attention to their potential for alkali silica and alkali carbonate reactivity [4].

The L&ILW DGR would be constructed about 680 m below ground surface in the low permeability Cobourg limestone formation. The optimized LHHPC was formulated specifically for shaft sealing in this formation. The carbonate aggregate will have an inherent chemistry closer to that of the limestone host rock, as well as being compatible with the saline groundwater. The carbonate aggregate used in the testing program conformed to requirements of CSA A23.1 for aggregate used in concrete. High quality carbonate aggregate is widely available in southern Ontario and is the most common aggregate used in construction.

The locally available fine aggregate was composed of natural sand. The coarse aggregates included natural gravel comprising a granitic crystalline (e.g., igneous, metamorphic) source, manufactured (crushed) dolomitic limestone and an open pit aggregate (predominantly natural, not crushed). The use of natural aggregates is known to enhance the workability of the concrete over concrete produced with manufactured (crushed) aggregates.

The silica flour product used as fine filler for LHHPC optimization mixes is from the same source as that used for the original reference mix.

Two types of superplasticizers were evaluated: sodium sulphonated naphthalene and polycarboxylate-based SP. Sodium sulphonated naphthalene based SP is one of the first generation of SP, and is scarcely used now due to the development of more modern technologies. However, sodium sulphonated naphthalene based SP is still available. The original reference mix used sodium sulphonated naphthalene-based SP. A polycarboxylate-based SP was selected based on its more effective performance (as per literature) in concretes containing Portland cement with SF and slag. The new polycarboxylate-based SPs are currently preferred in the concrete industry, and are both more effective at lower dosages and universally available. It is likely that the older generation of sodium sulphonated naphthalene based SPs will become increasingly difficult to source in the future (e.g., envisaged timing for the installation of the shaft seals at the closure of a Canadian DGR).

3.3 Requirements for LHHPC

Table 3 Requirements for LHHPC

No.	Performance parameters	Performance targets
1	Bulk density	>2400 kg/m ³
2	Porosity at 180 days	≤5%
3	Saturated hydraulic conductivity	<1 x 10 ⁻¹² m/s
4	Unconfined compressive strength (UCS)	>25 MPa at 7 days, >60 MPa at 90 days
5	Maximum temperature rise	≤15°C
6	Shrinkage rate over 200 days	<1% (volume)
7	pH in water	≤11
8	Slump	200 +/- 50 mm provided no bleeding and/or segregation
9	Slump flow	300 - 500 mm provided no bleeding and/or segregation

For the DGR seal application the following nine performance parameters were identified for LHHPC: bulk density, porosity, saturated hydraulic conductivity, unconfined compressive strength (UCS), maximum temperature rise, shrinkage rate, pH in water, slump and slump flow. Table 3 presents the performance parameters and performance target values for LHHPC. The optimized LHHPC mixes should meet the performance targets in Table 3.

3.4 Methodology for trial batches

Trial batches, which included multiple trial mixes, for LHHPC from Series 1 to Series 5 in Table 2 were prepared and evaluated using the following methodology:

- Trial mixtures developed for the LHHPC optimization program were first evaluated for slump value, air content and a general assessment of workability. Excessive air being entrained in the concrete would result in decreased strength and decreased density. Personal field experience was used to determine if the test mix is sufficiently workable to be placeable in the field. The placeability of the concrete is not a quantifiable property and relies on field experience with similar high performance and conventional concrete mix formulations. There is no correlation between slump and the compressive strength, permeability or porosity of the concrete – these factors are controlled by the combination of cementing materials and SP used and the overall water content of the concrete. The optimization test program was stopped for those LHHPC trial mixtures that did not meet the targeted early age parameters.
- A critical aspect of plastic concrete is its tendency to segregate during mixing and placing if the slump is too high. Two concrete mixes with the same slump value can be radically different in terms of their practical workability and tendency to segregate, and this aspect of the LHHPC mix optimization was closely monitored.
- For the purposes of mix screening, slump and air content are the first parameters that indicate if a mix is suitable or rejected. If the mix was deemed suitable, samples were cast and plastic density was measured. If plastic density is acceptable, the next test point was the seven day compressive strength measurements. For those mixes meeting or within 3-5 MPa of the 7 day compressive strength target, a second batch of concrete was produced for determination of temperature rise, shrinkage and 90 day UCS measurements. It is known that high dosages of SP can affect early strength development, so non-conformance to the minimum 7 days compressive strength target was generally not used to eliminate a mix formulation for further testing. Provided these parameters were met, the mix formulation was deemed suitable for the full suite of testing.

Upon completion of the trial batches the following objectives were achieved:

- New mix designs were developed based on the reference mix. The new mix designs have a higher dosage of cement, lower SF content and a lower dosage of SP than the reference mix.
- A new type of cement (Type GU), which is a general use cement, was used.
- New cement sources were used in addition to the cement source used for the original reference mix.

- A new binary CM incorporating Type GU cement and slag, as well as a ternary CM incorporating Type GU cement, slag and SF were used.
- A new type of SP was used (polycarboxylate-based), which is currently available and routinely used for production of concrete. A much lower SP dosage was possible while maintaining suitable workability and slump.
- New types and sources of coarse and fine aggregate were used (Ontario concrete sand and carbonate coarse aggregate).
- New shapes of coarse aggregate were used: crushed quarried carbonate coarse aggregate and open pit natural coarse aggregate.

The test program proceeded to the next step of preparing production batches of the best candidates for optimized LHHPC mixes and initiation of the full suite of testing.

3.5 LHHPC production batches

Based on workability and early age strength performance, eleven mixes were selected for production batches to produce specimens required for the test program. Table 4 presents details of the mix designs used for the LHHPC production mixes.

Based on the plastic and early compressive strength data collected for the selected Mixes 1 to 6 in Table 4, it was possible to make further adjustments to the LHHPC formulation to enhance workability without adversely affecting the long-term performance of the concrete. Additional work was conducted to further reduce the SP dosage rate to reduce the “sticky” and thixotropic properties inherent with heavily superplasticized concrete. This required an increase in w/cm which can affect the early strength characteristics of the concrete. However, based on experience with the mixes it was anticipated that the modified production mixes would meet project UCS targets.

Table 4 LHHPC mix designs for production batches

Mix ingredients (kg/m ³)	Production LHHPC mixes										
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11
Cement Type GU, Source 1	112.00	112.00	108.00	108.00	-	-	-	108.00	108.00	-	-
Cement Type GU, Source 2	-	-	-	-	108.00	108.00	108.00	-	-	108.00	108.00
Silica fume	-	-	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Slag	112.00	112.00	88.00	88.00	88.00	88.00	88.00	88.00	88.00	88.00	88.00
Silica flour	190.90	190.90	190.90	190.90	190.90	190.90	190.90	190.90	190.90	190.90	190.90
Natural silica sand	-	-	-	-	-	-	875.95	-	-	-	-
Natural concrete sand	903.21	901.36	910.60	911.53	910.60	908.75	-	891.20	889.35	896.74	894.89
Granitic coarse aggregate	-	-	-	-	-	-	1020.95	-	-	-	-
Crushed carbonate quarry coarse aggregate	1051.79	-	1060.40	-	1060.40	-	-	1037.80	-	1044.26	-
Natural carbonate and crystalline pit coarse aggregate	-	1049.64	-	1061.47	-	1058.25	-	-	1035.65	-	1042.11
Polycarboxylate-based SP	3.00	3.00	3.00	3.00	3.00	3.00	5.29	2.36	1.71	1.70	1.30
Water	109.76	110.88	108	108	108	108	108	125.28	125.28	120.96	120.96
w/cm	0.490	0.495	0.500	0.500	0.500	0.500	0.500	0.580	0.580	0.560	0.560

3.6 Curing conditions

Material properties have been measured for LHHPC exposed to one curing regime, at room temperature (20 to 25°C) and under reference saline SR-270 water, which simulates the host rock pore water condition at the Bruce site. The LHHPC cast specimens were cured in sealed plastic cylinder molds for the first 7 days to allow adequate setting, with the molds stored in a temperature controlled 100% humidity curing chamber. LHHPC specimens were then demolded and immersed in reference saline SR-270 water and cured until they reach the required testing age.

Table 5 presents the reference SR-270 water chemical composition. Test water with SR-270 reference composition was prepared using laboratory grade salts. The chemical composition of the reference SR-270 water prepared in the laboratory for the project was confirmed by testing. The iron was removed from SR-270 water composition, as in the aerobic laboratory environment, it oxidizes and coagulates and therefore it cannot stay in solution under these conditions.

Table 5 SR-270 water composition (mg/L)

Parameter	SR-270	Parameter	SR-270	Parameter	SR-270	Parameter	SR-270
pH	5.8	HCO ₃	110	Li	5	Fe	30
Na	50,100	SO ₄	440	F	1	NO ₃	<5
K	12,500	Cl	168,500	I	2	PO ₄	-
Ca	32,000	Br	1,700	Br	80	TDS	275,000
Mg	8,200	Sr	1,200	Si	4		

3.7 LHHPC tests

The optimized LHHPC should meet the performance targets in Table 3 and therefore the test program includes measuring the properties listed in Table 3. The LHHPC test program is ongoing and the following properties have been measured for the production Mixes 1 to 11:

- Bulk density and porosity, e.g., total open porosity, following ASTM C642 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete [6]. Two (2) LHHPC samples are being tested per mix after 28 and 180 days curing. As part of the standard test procedure for UCS, the hardened density is also being determined by simple measurements based on volume and mass.
- Saturated hydraulic conductivity following a modified version of ASTM D5856 Standard Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall, Compaction-Mold Permeameter [6]. The test method and test setup is the same as used for the original reference LHHPC mix. The general configuration of the test cell was modified from the linear flow configuration in the ASTM procedure to a radial flow configuration to address issues with leakage along the interface between the specimen and cell wall. Hydraulic conductivity tests are being initiated at 90 days to allow for cement hydration of the LHHPC.

- Unconfined compressive strength (UCS) following ASTM C39/C39M Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [7]. The same two specimens per LHHPC mixture are being used for density and UCS per age and tested at the following ages: 7, 28, 56, 90, 180 and 270 days.
- Temperature rise and strain measurement are being conducted in proven semi-adiabatic curing boxes that closely replicate the curing regimes present in mass concrete structures. This non standard test method has proven to be superior to ASTM C1698 Standard Test Method for Autogenous Strain of Cement Paste and Mortar [8] during research conducted at AECL in 1996 - 1997 as the increased mass of the sample (68 kg vs. 14 kg for C1698) and additional thickness of insulation (300 mm as opposed to 50 mm for ASTM C1698) more closely replicates the heat energy profiles of mass concrete. The system encloses one cubic foot (0.03 cubic metres) of concrete surrounded by one foot (0.3 metres) of high density foam insulation on all sides. This arrangement retains the heat generated by the cement hydration to simulate the conditions of a mass structure. Strain and temperature are monitored by vibrating wire strain gauges fitted with integral thermistor temperature sensors.
- There are several types of shrinkage of concrete, but the types of shrinkage which are relevant for the LHHPC in a DGR are thermal and autogenous shrinkage. Autogenous shrinkage takes place for mass concrete over time as cement hydration progresses. Shrinkage of the LHHPC mixtures are being measured using embedded vibrating wire strain gauges to measure autogenous and thermal deformation throughout the initial setting and long term curing phases. Integral thermistors allow for correction of thermal effects on the strain measurements. The resulting readings are a composite of both thermal strain (initially expansive during setting and early curing) and autogenous shrinkage strain.
- pH in water following the Ex Situ Leaching (ESL) method recommended by Alonso et al. [9]. The ESL technique reduces the concrete to a fine powder, which is then mixed thoroughly at a 1:1 mass ratio with distilled, CO₂ free water followed by pH measurement. pH in water is being tested at the following ages: 7, 28, 56, 90, 180 and 270 days.
- Slump following ASTM C143/C143M Standard Test Method for Slump of Hydraulic-Cement Concrete [10].
- Slump flow following ASTM C1611/C1611M Standard Test Method for Slump Flow of Self-Consolidating Concrete [11].

4. Discussion of interim test results

The interim test results available to date for the LHHPC production Mixes 1 to 11 are summarized in Table 6.

Based on the interim results of the materials properties evaluated to date the preliminary conclusions are the following:

1. Bulk density: all of the production mixes meet the performance target for bulk density in Table 3.
2. 28-day porosity for Mixes 3, 5 and 7 meet the 180-day project target.

3. UCS: all the production mixes meet the 7-day UCS target except for Mix 2, which is marginally below the 7-day 25 MPa UCS target. The 56-day UCS for Mixes 1 – 11 meet and exceed the 90-day 60 MPa UCS target.
4. Maximum temperature rise: in general, mixes using cement from Source 1 exceed the maximum target temperature rise in Table 3 by 2-3 degrees. Temperature rise in mixes using cement from Source 2 all meet the specification. The cause of this finding is likely due to a higher alkali content in the cement from Source 1, which is known to accelerate cement hydration, thus completing the exothermic reaction sooner and generating heat at an earlier age. The exceedance of the temperature rise target for mixes with Source 1 cement can be addressed in practice by cooling the mix water and/or aggregates with ice prior to mixing.
5. Slump: all the production mixes meet the slump target.
6. Slump flow: all the production mixes meet the slump flow target.

Table 6 LHHPC production batches interim test results

Performance parameter	Production LHHPC mixes										
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11
Bulk density, 28-day (kg/m ³)	2612	2620	2572	2598	2581	2610	2518	2618	2615	2615	2611
Porosity, 28-day (%)	6.24	5.84	4.80	5.88	4.80	6.06	4.46	6.22	6.84	6.09	6.58
UCS, 7-day (MPa)	28.60	24.90	35.80	33.90	28.60	27.00	32.90	40.70	41.10	37.90	35.50
UCS, 28-day (MPa)	55.30	53.90	65.00	59.90	63.60	57.70	57.30	58.90	56.60	55.30	55.50
UCS, 56-day (MPa)	65.50	60.40	74.20	69.40	73.00	65.80	66.70	64.60	63.70	64.10	64.10
UCS, 90-day (MPa)	65.80	62.10	74.50	69.90	74.50	64.80	67.10	65.80	64.70	67.00	65.70
Max. temp. rise (°C)	16.18	18.28	16.26	16.26	12.93	13.70	14.26	16.96	16.92	14.39	13.81
Slump (mm)	220	215	200	205	200	225	225	240	230	220	220
Slump flow (mm)	405	410	390	400	390	475	390	500	460	450	440

5. Summary and Conclusions

This paper presents interim results of a program aimed to optimize a LHHPC reference mixture, to fabricate specimens of LHHPC seal materials and to measure key performance parameters.

A methodology was developed to design optimized LHHPC mixtures using mix ingredients from local and sustainable sources, which included making changes to the type of CM, CM rate and source, type, source and size of aggregate, type and dosage of superplasticizer, and water to CM ratio.

LHHPC mix designs were prepared for trial batches, which were evaluated and screened based on workability and early age strength performance. Eleven optimized LHHPC mixes were selected for production batches and were prepared to measure all of the project performance parameters.

Based on the interim test results available to date the large majority of the eleven optimized LHHPC mixes meet the performance targets for bulk density, UCS, slump, and slump flow.

The LHHPC test program is on-going to measure the remaining key performance targets at different curing ages.

Upon completion of the test program, optimized LHHPC mixes will be recommended for the DGR shaft sealing material.

6. Acknowledgements

The project work has been conducted at Amec Foster Wheeler Earth & Environmental, Hamilton, Ontario, Canada office. Financial support provided by Ontario Power Generation for this project is greatly appreciated. Technical review, comments and suggestions provided by Nuclear Waste Management Organization are acknowledged.

7. References

- [1] C. Vogt, B.Lagerblad, K. Wallin, F. Baldy and J.-E. Jonasson, “Low pH self-compacting concrete for deposition tunnel plugs”, R-09-07 Svensk Kärnbränslehantering AB Swedish Nuclear Fuel and Waste Management Co., April 2009, 78 p.
- [2] E. Holt, M. Leivo and T. Vehmas, “Low-pH concrete developed for tunnel and plugs used in nuclear waste containment”, Proceedings of the Concrete Innovation Conference 2014 (CIC2014), Oslo, Norway, 2014 June 11-13.
- [3] CSA A3001 Cementitious Materials for Use in Concrete.
- [4] CSA A23.1/23.2 Concrete Materials and Methods of Concrete Construction, Test Methods and Standard Practices.
- [5] ASTM C642 Standard Test Method for Density, Absorption, and Voids in Hardened Concrete.
- [6] ASTM D5856 Standard Test Method for Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall, Compaction-Mold Permeameter.
- [7] ASTM C39/C39M Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.
- [8] ASTM C1698 Standard Test Method for Autogenous Strain of Cement Paste and Mortar.
- [9] M.C. Alonso, J.L.García Calvo, C. Walker, M. Naito, S. Pettersson, I. Puigdomenech, M.A. Cuñado, M. Vuorio, H. Weber, H. Ueda, K. Fujisaki, “Development of an accurate pH measurement methodology for the pore fluids of low pH cementitious materials”, SKB report R-12-02. August 2012.
- [10] ASTM C143/C143M Standard Test Method for Slump of Hydraulic-Cement Concrete.
- [11] ASTM C1611/C1611M Standard Test Method for Slump Flow of Self-Consolidating Concrete.