



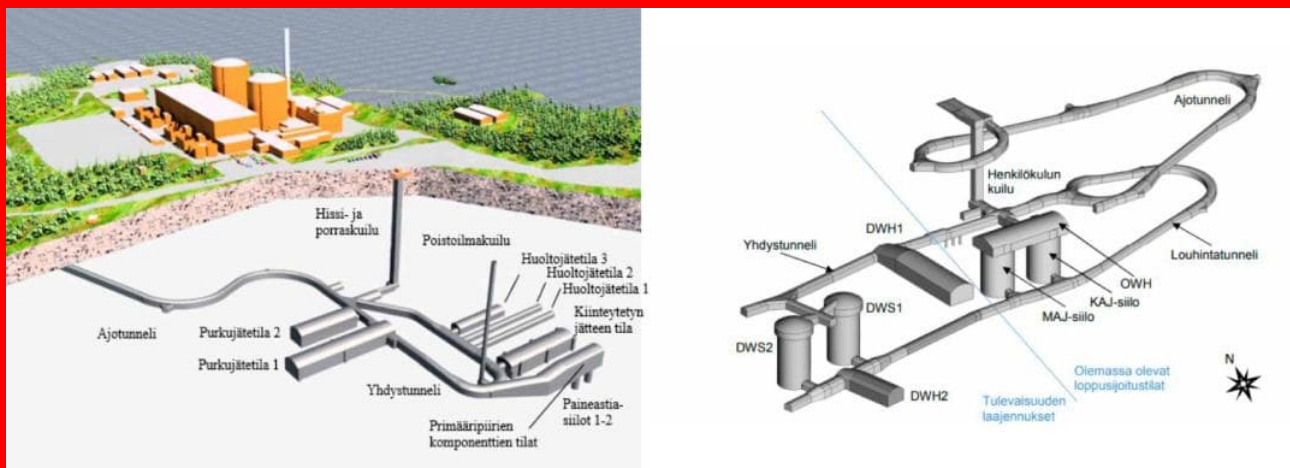
Aalto University
School of Engineering

Aalto University
School of Engineering
Civil Engineering Department

Concrete mixtures, specimen preparations, storage solutions and testing plan

WP2 – Design new durable concretes for the LILW repositories

Fahim Al-Neshawy and Abobaker Ba Ragaa



Aalto University School of Engineering, Department of Civil Engineering
PL 12100, FI-00076 AALTO
<http://civileng.aalto.fi>

Table of Contents

1	Introduction	4
1.1	LILW Radioactive waste classification.....	4
1.2	LILW facilities in Finland	5
1.3	Concrete structures in the LILW radioactive waste disposal	7
1.3.1	Reinforced concrete silo concept	7
1.3.2	Reinforced concrete rock vault concept	8
1.4	Repository site groundwater conditions in Finland.....	9
1.5	Estimated LILW repositories exposure classes.....	10
2	Concrete mixtures – Planning.....	11
2.1	Cement types and admixtures.....	11
2.2	Water to cement ratio and minimum strength class	13
2.3	Aggregate to binder ratio	13
3	Preparation of specimens.....	14
3.1	Concrete mixes	14
3.2	Preparation of hardened concrete specimens.....	14
4	Testing of concrete.....	18
4.1	Testing of fresh concrete.....	18
4.1.1	Slump test (EN 12350-2)	18
4.1.2	Air content test – pressure method (EN 12350-7)	18
4.1.3	Testing fresh concrete density (EN 12350-6).....	19
4.1.4	Temperature monitoring during concrete curing	20
4.2	Testing of hardened concrete	21
4.2.1	Compressive strength test (EN 12390-3)	21
4.2.2	Tensile splitting strength test (EN 12390-6).....	22
4.2.3	Density of hardened concrete (EN 12390-7).....	23
4.2.4	Carbonation resistance of concrete.....	23
4.2.5	Modulus of elasticity in compression (EN 12390-13).....	24
4.2.6	Shrinkage of concrete (EN 12390-16)	25
4.2.7	Chloride migration coefficient (NT Build 492).....	26
4.2.8	Micro X-ray Fluorescence (μ XRF).....	27
4.2.9	Petrographic analysis of hardened concrete – Thin Section Analysis (TSA)	29
4.2.10	Electrochemical measurement of steel rebar corrosion (NDT)	31
4.2.11	Measurement of chloride profiles – Potentiometric titration.....	32

5	Storage of concrete specimens.....	34
6	References	36
7	Appendices.....	39
7.1	Exposure classes related to environmental actions on reinforced concrete structures – EN 206-1.....	39
7.2	Permitted cements and additions in different exposure classes.....	40
7.3	Recommended limiting values for concrete composition and properties with design working life of 100 years.....	40
7.4	Details of the hardened concrete test specimens for each concrete mix.....	41
7.5	Example of the chemical analysis of the ground water at Olkiluoto.....	47
7.6	Example of the chemical analysis of the ground water at Loviisa.....	48
7.7	Details of the storage salt solutions.....	49

1 Introduction

1.1 LILW Radioactive waste classification

Radioactive waste includes any material that is either intrinsically radioactive, or has been contaminated by radioactivity, and that is deemed to have no further use. Every radionuclide has a half-life – the time taken for half of its atoms to decay, and thus for it to lose half of its radioactivity. Radionuclides with long half-lives tend to be alpha and beta emitters – making their handling easier – while those with short half-lives tend to emit the more penetrating gamma rays. Eventually all radioactive waste decays into non-radioactive elements. The more radioactive an isotope is, the faster it decays. LILW radioactive waste is typically classified as either low-level (LLW), or intermediate level (ILW), depending on its level of radioactivity.

Low-level waste (LLW)

Low-level waste (LLW) has a radioactive content not exceeding four giga-becquerels per tonne (4 GBq/t) of alpha activity or 12 GBq/t beta-gamma activity. LLW does not require shielding during handling and transport, and is suitable for disposal in near surface facilities.

LLW is generated from hospitals and industry, as well as the nuclear fuel cycle. It comprises paper, rags, tools, clothing, filters, etc., which contain small amounts of mostly short-lived radioactivity. To reduce its volume, LLW is often compacted or incinerated before disposal. LLW comprises some 90% of the volume but only 1% of the radioactivity of all radioactive waste [1].

Intermediate-level waste

Intermediate-level waste (ILW) is more radioactive than LLW, but the heat it generates (<2 kW/m³) is not sufficient to be taken into account in the design or selection of storage and disposal facilities. Due to its higher levels of radioactivity, ILW requires some shielding.

ILW typically comprises resins, chemical sludges, and metal fuel cladding, as well as contaminated materials from reactor decommissioning. Smaller items and any non-solids may be solidified in concrete or bitumen for disposal. It makes up some 7% of the volume and has 4% of the radioactivity of all radioactive waste [1]. ILW generally contains long-lived radionuclides in concentrations that require isolation and containment for periods beyond several hundred years (for example, beyond 300 to 500 years) [2].

In Finland, radioactive waste generated as a result of the use of nuclear energy is classified as very low, low or intermediate-level waste in accordance with the Nuclear Energy Act. Radioactive waste resulting from the use of nuclear energy is to be classified in accordance with the following principles[3]:

- 1) Very low-level waste (VLLW) refers to radioactive waste whose average activity concentration of significant radionuclides does not exceed 100 kBq/kg and whose total activity per licensed disposal facility does not exceed 1 TBq and α activity does not exceed 10 GBq.

- 2) Low-level waste (LLW) refers to radioactive waste whose activity is so low that it can be treated without any special radiation protection arrangements. The activity concentration of the waste is normally not more than 1 MBq/kg.
- 3) Intermediate-level (ILW) waste refers to radioactive waste whose activity is so high that effective radiation protection arrangements are needed when handling it. The activity concentration of the waste is usually between 1 MBq/kg and 10 GBq/kg.

Most of the radioactive waste generated in Finland comes from the use of nuclear energy. The amount of radioactive waste stored at the power plant sites and the amount of radioactive waste to be disposed of in the repositories for low and intermediate-level waste at the power plant sites at the end of 2019 and the estimated values for 2030 and 2050 are presented in Table 1.

Table 1. The amount of VLILW radioactive waste stored and disposed of in Finland [3] [4].

Waste type	Quantity stored by the end of 2019 [m ³]	Quantity disposed by 2019 [m ³]	Final disposal by 2030 [m ³]	Final disposal by 2050 [m ³]
Very low-level	204	n.a. ^(a)	2300	6900
Low-level	1691	6541	8761	10661
Intermediate level	1970	2117	8278	9078

^(a) Included in the figure of low level waste

The values in Table 1 also include radioactive waste from radiation practices that has been disposed of at the LILW disposal facility in Olkiluoto. Radiation practices generate radioactive waste requiring disposal at a rate of approximately 1 m³ per year [3].

1.2 LILW facilities in Finland

Nuclear waste in Finland arises from the two nuclear power plants at Olkiluoto and Loviisa, together comprising four units. Other radioactive wastes, so called small user waste, arise from a number of facilities using radioisotopes in medical, research and industrial applications.

Teollisuuden Voima Oyj (TVO) takes care of its operational waste and power plant decommissioning waste. Their final disposal takes place in the operational waste repository (VLJ repository) at Olkiluoto. In Olkiluoto, the decommissioning waste generated during the dismantling of the plant units will also be deposited in facilities to be built in the same underground repository. The repository also accommodates small radioactive waste generated in Finnish healthcare, industries, and research institutions. Waste is packed into concrete containers and transported to the repository using a radiation-protected vehicle. In the LILW repository, the concrete containers are placed into silos for low and intermediate level waste that have been excavated into the bedrock down to the level of 60–100 meters below the ground surface. Low level waste consists of mixed waste polluted by radioactive substances. Low level waste includes:

- Fire-protected fabrics

- Plastic wrappings and protective clothing used during maintenance work
- Replaced machinery parts and pipes from the nuclear power plant

The low level waste is packed into 200-liter drums and compressed to half of its volume using a hydraulic press. The radioactivity of the containers is measured before storage. Intermediate level waste includes [5]:

- Ion-exchange resin from the circulating water cleaning system
- Liquids from various washing processes
- Sludge that forms when solid matter collects as sediment at the bottom of pumps and tanks

The processes generate nuclear waste and one possible disposal location of the waste is Loviisa LILW repository owned by Fortum Power and Heat Oy. Waste created in nuclear power plant operations is governed by either regular (non-radioactive) or radioactive waste management rules. Examples of the regular waste include the waste created in a typical work environment, in goods transport, office tasks etc. Radioactive waste is classified as either low-level, intermediate-level (LILW) or high-level waste, based on how it was created, its original purpose and radioactivity level [6].



Figure 1. Locations of the final disposal sites for LILW waste in Finland and the existing nuclear sites [4].

At the end of 2019, the filling rate of LILW disposal facility's low-level waste disposal silo (MAJ – Low-level nuclear waste silo) in Olkiluoto[5] was 65% and that of the intermediate-level waste silo (KAJ – Intermediate-level nuclear waste silo) was 57%. In Loviisa[6], LILW disposal facility's the low-level maintenance waste facility 1 (HJT 1 – maintenance waste facilities, Loviisa) is full. At the end of 2019, filling rates for maintenance waste facilities 2 (HJT 2) and 3 (HJT 3) were 61% and 16%, respectively. The operation of the repository for intermediate-level waste in Loviisa (KJT – Intermediate-level waste facilities) was starting, with a filling rate of 0.1% at the end of 2019. Both LILW disposal facilities will have sufficient capacity for a long time to come. The need for the extension of LILW disposal facilities will become topical before the power plant units are decommissioned and dismantled.

1.3 Concrete structures in the LILW radioactive waste disposal

Finland currently has two rock cavern repositories for short-lived LILW, one located at each nuclear power plant site. They are owned and operated by the nuclear utilities for their own waste, with a small amount of space reserved for non-utility wastes. Both repositories are excavated in the crystalline bedrock at the nuclear power plant site and are accessed via ramps (approximately 1 km long) for waste transport. A shaft with elevator access is provided for personnel only.

1.3.1 Reinforced concrete silo concept

The concept of silo type repositories has been implemented by TVO in the operational waste repository (VLJ repository) at Olkiluoto [7]. The scheme is illustrated in Figure 2. The silo concept consists of a case in which disposal containers and waste packages are placed on top of each other in several levels and the remaining space is filled with a backfill. The experimental works has been aimed at development of suitable concrete mixture composition, investigation of its properties in both fresh and hardened state, durability and resistance to groundwater, corrosion of reinforcement and degradation processes of concrete.

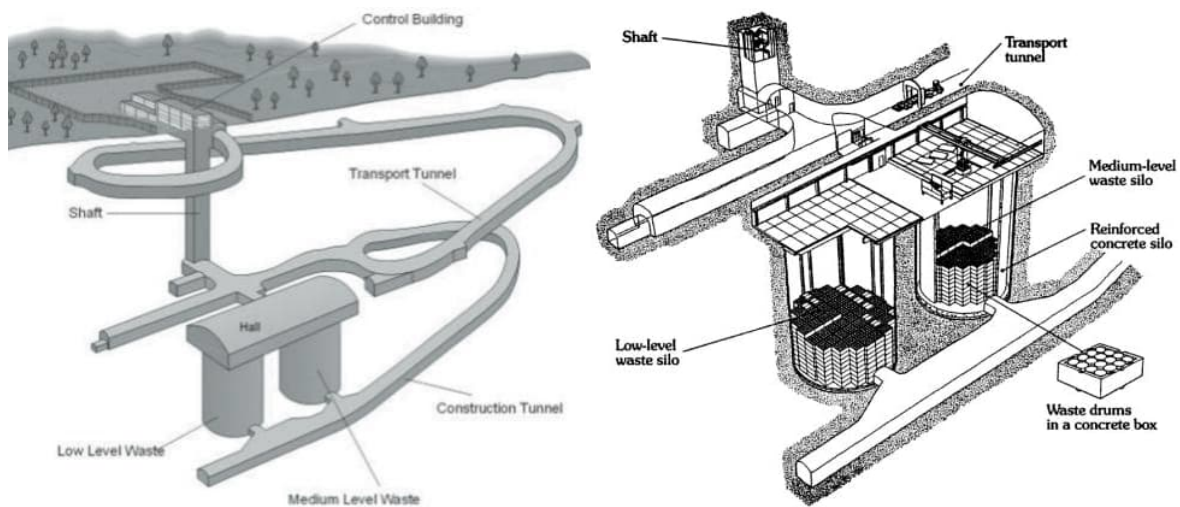


Figure 2. Schematic of the Olkiluoto VLJ Repository for LILW [8].

The construction of the LILW repository at the Olkiluoto site began in 1988 and operation began in 1992. The repository consists of two large silos (approximately 24 m ID x 34 m H) at a depth of 60 to 95 m in tonalite bedrock, one for solid LLW and the other for bituminized LLW. The silo for solid LLW is a shotcreted rock silo, while the silo for bituminized waste consists of a thick-walled concrete silo inside a rock silo where concrete boxes containing drums of bituminized waste are stacked. The repository is shown schematically in Figure 2.

At closure, the void space above the silos will be backfilled with local origin crushed rock. The reported inventory at VLJ was 5,681 m³ of LILW at the end of 2016 [9]. The LILW from the new Olkiluoto 3 reactor will be disposed of in the same repository. The repository will be extended in the future with additional silos of similar design, to be able to receive all the

waste from Olkiluoto 1, 2 and 3 reactors during the planned 60 years of operation of the units as well as for decommissioning waste.

1.3.2 Reinforced concrete rock vault concept

Concrete vaults are one of the most common methods used in the world today for disposal of LLW [10]. They are modular in nature, so can be scaled to a range of small to very large capacities and offer the flexibility to accept a wide variety of waste package sizes, including very large and heavy objects such as steam generators and reactor pressure vessels. They can also be constructed in a variety of geological settings at surface or near-surface at various depths up to several tens of meters. The basic vault consists of a thick-walled concrete structure of various dimensions, often with a built-in drainage and/or water monitoring system. The concept of Vault type repositories has been implemented by Fortum in the maintenance waste halls at Loviisa.

Vaults are typically filled with waste packages from either the top (using a fixed or mobile crane) or side (using a forklift or similar vehicle), then covered with a concrete cap and engineered multi-layered cover system when full. Temporary weather covers can be used during the loading phase to protect the wastes and the structure and to minimize water ingress from precipitation. Spaces between waste packages are typically backfilled with sand, gravel or concrete to form a monolithic structure prior to capping [8].

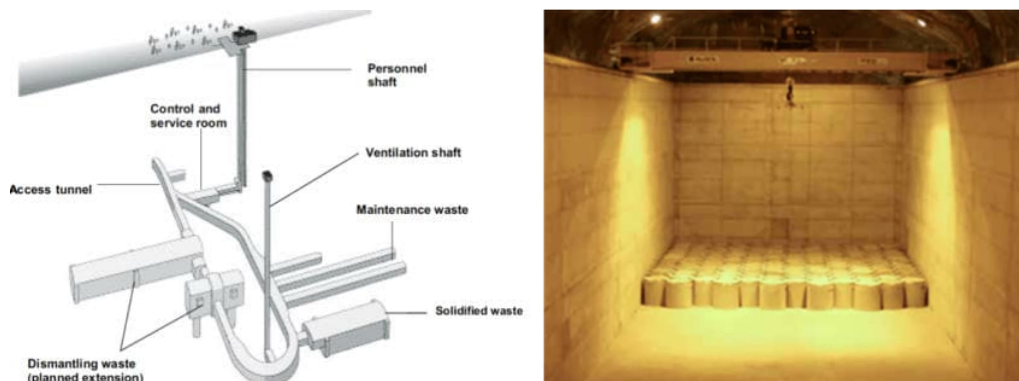


Figure 3. Schematic of Loviisa Repository for LILW [8].

At Loviisa, the construction of the repository was started in 1993 and the operation of the first phase of the disposal facility was started in 1998. As shown in Figure 3, the Loviisa repository is located at a depth of approximately 110 m in granite bedrock. The repository consists of tunnels for solid LLW (“maintenance waste”) and a cavern for solidified ILW.

The maintenance waste tunnels have dimensions of 6 m W x 5 m H x 110 m long and have a waste capacity of 1200 m³ (or 6,000 drums). The tunnel has a concrete floor and shotcrete walls with provisions for wall drainage. The waste drums are stacked five layers high within the tunnel. The LLW tunnels are not backfilled.

The reported inventory at Loviisa to end of 2016 was 1,886 m³ of LLW [9]. Inside the ILW cavern, the waste packages are emplaced in a trench-type structure made of reinforced concrete (approximately 70 m L x 14 m W x 11 m H). The vault will accommodate about 5,000 cylindrical concrete ILW containers (1 m³ each internal volume, 1.7 m³ external

volume), stacked in 5 layers. The space between containers will be backfilled with concrete as each layer is filled and will be capped with concrete once filled. The space above the capped trench will be filled with crushed rock.

1.4 Repository site groundwater conditions in Finland

Groundwater consists of water that fills the voids in the reinforced concrete soils and sediments and in fractures of bedrock, forming a continuous entity and moving gravitationally. Considering a near surface repository, the location of the groundwater surface in the repository area needs to be continuously monitored. Considering the quality of the water at a repository site, the initial state (baseline characterisation) of the groundwater quality needs to be assessed in the environmental impact assessment prior to the start of the operations. This is important in order to be able to monitor the changes in the quality of the water during the operations and after closure of the repository. The quality of groundwater is also relevant information for the safety case [11].

Groundwater flow is an important factor, as it is used to estimate the evolution of the concrete barriers and the modelling of radionuclide transport in near-field and in the bedrock. After the closure the LILW repository will be filled by gradually inflowing groundwater. Examples of the time development of the groundwater flow rates of Loviisa's maintenance waste hall 2 (MWH2) and decommissioning waste hall 1 (DWH1) are presented in Figure 4. The uncertainty of the groundwater flow rate was estimated using sensitive analysis [12].

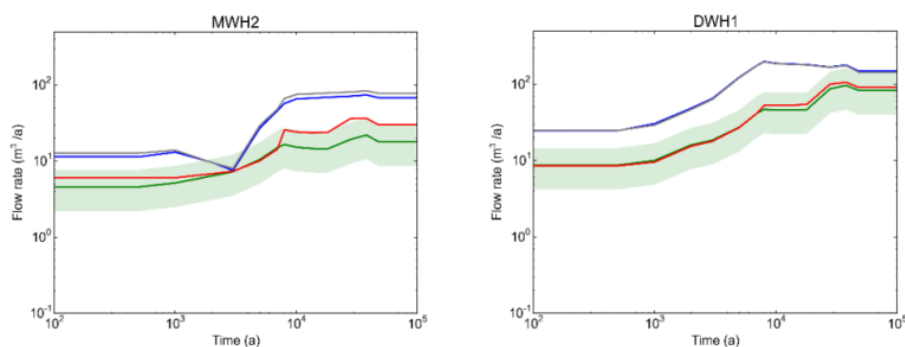


Figure 4. Groundwater flow through MWH2 and DWH1. The green shaded area indicates the range between 5th and 95th percentiles [12].

The chemical character of groundwater is influenced by the minerals and gases reacting with the water in its relatively slow passage through the rocks and sediments of the Earth's crust. Many variables cause extensive variation in the quality of groundwater, even in local areas. Generally, groundwater increases in mineral content as it moves along through the pores and fracture openings in rocks [13]. Ground water with a high concentration of magnesium chloride, and sulfate ion is known to cause deterioration to Portland cement concretes.

- Magnesium – Dissolved from practically all solids and rocks, but especially from limestone, dolomite, and gypsum, calcium (Ca) and magnesium (Mg) are found in

large quantities in some brines. Magnesium is present in large quantities in sea water.

- Sulfate – Sulfates (SO_4^{2-}) are dissolved from rocks containing gypsum, iron sulfides, and other sulfur compounds. Sulfate attacks have a major problem of concrete durability. They destroy the concrete by degrading its mechanical properties. These include sulfate reactions that cause swelling in concrete and crack networks. The sulfate attack is associated with the precipitation of secondary ettringite, a significant expansion and the chemo-mechanical deterioration (changes in properties, cracks, loss of strength and cohesion).
- Chloride – Chlorides (Cl) are dissolved from rocks and soils. The chlorides of calcium, magnesium, sodium, and potassium are readily soluble. Chloride attack on concrete deteriorates the durability of concrete by initiating the corrosion of the reinforcement, which may cause the failure of the structure. The chloride attack thus leads to concrete cracking, spalling, and eventually failure.

Table 2. Examples of the main chemical composition of groundwater samples from Olkiluoto and Loviisa (according to data provided by TVO and Fortum).

Chemical ions, [unit]	Olkiluoto, VLJ ground water [PVA2]	Olkiluoto, VLJ ground water [PVA3]	Loviisa, groundwater station [LPVA4]	Loviisa, groundwater station [LPVA5]
pH	7,5	7,9	7,7	7,6
Chloride Cl ⁻ , [mg/l]	320	2030	4000	5250
Magnesium Mg ²⁺ , [mg/l]	15	71	200	265
Sulfate SO ₄ ²⁺	130	320	470	590

1.5 Estimated LILW repositories exposure classes

During the operational period of the repository, moist air (relative humidity 70%, temperature 11.5 °C) with carbon dioxide content (500–600 ppm) surrounds the facilities. Estimated length of the period can be more than 100 years.

After sealing the repository, a cool (temperature 11.5 °C) and saline brackish groundwater will gradually fill the disposal zone. The time required for filling up the space with groundwater after its sealing is short compared to the designed service life. In the water-filled caverns, the velocity of the groundwater flow is not high enough to cause erosion of structures, but sufficient to transport away the leached material. Hydrostatic pressure will not cause pressure difference over concrete structures. Thus, the groundwater penetrates mainly by diffusion into concrete via system of pores, cracks, and defects of concrete.

Slightly alkaline (pH 7–9) groundwater contains moderate amounts of ions harmful for concrete and the steel reinforcement. These ions can be even more destructive, when the interaction between ions penetrating into concrete and cement hydrates is taken into account. As a single factor, chlorides are important due to their impact on steel reinforcement corrosion. The physical chemistry of the system is complex and the

competition between carbon, sulphate and chloride ions is expected to take place at least in ettringite AF_t (Al_2O_3 - Fe_2O_3 -tri) and monosulfate AF_m (Al_2O_3 - Fe_2O_3 -mono) phases [14].

Based on the environmental condition around the reinforced concrete structures at LILW repositories and the EN 206:2014 "Concrete. Specification, performance, production, and conformity" [15], the exposure classes (presented in appendix 1.) are estimated as:

- XC2 – Corrosion induced by carbonation for wet rarely dry reinforced concrete structures. Concrete subjected to long-term water contact.
- XD2 – Corrosion induced by chlorides other than from sea water for wet rarely dry reinforced concrete structures. Concrete exposed to water containing chlorides.
- XA1 to XA3 – Chemical attack

2 Concrete mixtures – Planning

2.1 Cement types and admixtures

For alkaline cementitious systems, a man-made Portland cements have been in use for only ~150 years. However chemically similar lime – based cements have a longer history of use, perhaps 6 000 years.

The Egyptians also made use of gypsum (calcium sulfate) – based cements beginning ~6 000 years ago. So, we can access historic structures although, with few exceptions, access with sampling has been confined to those portions which are exposed to the atmosphere. These will almost certainly have had a different history than buried materials, so the performance of historic materials, while of interest, is not always relevant specially to underground environments.

Also, the composition of the cementitious materials available today differs from those of historic materials and we have no certain benchmarks with which to establish the properties of historic materials when they were fresh. For example, the Roman harbour works at Ostia (near the former mouth of the river Tiber) used mass concrete based on lime- activated volcanic ash, the latter often somewhat altered by hydrothermal processes prior to its use in construction. When Ostia was built, the works were clearly intended to provide accommodation for sea – going vessels, i.e., the concrete was exposed to salt water. But at present, these concrete facilities are inland and no longer exposed to salt water. Nevertheless, with care in sampling and inferring the exposure history, examination of historic concretes gives comfort that engineering properties may persist over long time spans, certainly equal to ten half-lives of short-lived radioisotopes, which imply service lives of 300-500 years, or more are attainable [16].

The Swedish Nuclear Fuel and Waste Management (SKB) plans to dispose of long-lived low and intermediate level waste (LILW) in a deep geological repository, named SFL. The total capacity of SFL is estimated to 16 000 m³ [17]. The constructions in SFL rely to a large extent on the use of cement as binder material, and consists of CEM I Portland cement with the following characteristics:

- It complies with the requirements of EN 197-1:2011 focused on composition, specifications and conformity criteria for common cements.

- It has a low C3A content (2.0 wt%) and satisfies the requirements for sulfate resistance of SR 3 type cement in EN 197-1:2011.
- It satisfies the requirements for cement with moderate heat development in accordance with the Swedish SS 134202:2006 and for low alkali cement in accordance with SS 134203:2014.

CEM II/A-V Portland cement was also proposed for the SFL construction, which complies with EN 197-1:2011 standard requirements for Portland cement with a siliceous fly ash content of up to 20 wt.% [17].

Table 3. Permitted cements, additions and limit values of concrete composition and properties with design working life of 100 years for the selected exposure classes in Section 1.5.

Selected exposure classes for the reinforced concrete structure in the LILW repositories					
	Corrosion induced by carbonation [XC2]	Chlorides from other source than sea water [XD2]	Aggressive chemical attack		
			[XA1]	[XA2]	[XA3]
Permitted cement types	CEM I	CEM I	CEM I	In sulphate-rich environment, sulphate-proof cement (CEM I-SR3) conforming to SFS-EN 197-1 shall be used or the binder shall contain a minimum of 70% of blast-furnace slag of the total quantity of the binder.	
	CEM IIA/-S	CEM IIA/-S	CEM IIA/-S		
	CEM II/B-S	CEM II/B-S	CEM II/B-S		
	CEM II/A-D	CEM II/A-D	CEM II/A-D		
	CEM II/A-V	CEM II/A-V	CEM II/A-V		
	CEM II/B-V	CEM II/B-V	CEM II/B-V		
	CEM II/A-LL	CEM II/A-LL	CEM II/A-LL		
	CEM II/A-M	CEM II/A-M	CEM II/A-M		
	CEM II/B-M	CEM II/B-M	CEM II/B-M		
	CEM III/A	CEM III/A	CEM III/A		
CEM III/B	CEM III/B	CEM III/B			
Mineral additives content (weight %) of the total amount of the binder					
Silica fume	≤ 10%	≤ 10%	≤ 10%	The designer shall select the mineral additives according to the current chemical attack.	
Fly Ash	≤ 30%	≤ 30%	≤ 30%		
GGBFS – slag	≤ 80%	≤ 80%	≤ 80%		

Based on the SKB cement selection for the construction of the SFL repository and BY 65 – Concrete code 2021 (Table 3.2 Permitted cements and additions in different exposure classes) presented in appendix 2, three cement types are selected:

- 1) CEM I 42.5 N – SR 3 (sulphate-resistant cement)
- 2) CEM III/A 52,5 L (Kolmossementti)
- 3) CEM III/B 42,5 L – LH/SR – Blast furnace cement (Kolmossementti)

According to BY 65 – Concrete code 2016 and 2021, mineral additives to be added to the concrete include silica fume, slag and fly ash presented in appendix 2. As the fly ash availability in Finland will be very low after the year 2030, the following mineral additives were selected:

- Silica fume, maximum of 10% of the binder weight

- Slag (GGBFS – Ground Granulated Blast Furnace Slag), maximum of 80% of the binder weight (50% is recommended [18]).

2.2 Water to cement ratio and minimum strength class

The limit values for concrete properties with design working life of 100 years for the selected exposure classes are given in Table 4.

Table 4. Limit values of concrete properties with design working life of 100 years for the selected exposure classes in Section 1.5.

Selected exposure classes for the reinforced concrete structure in the LILW repositories					
	Corrosion induced by carbonation [XC2]	Chlorides from other source than sea water [XD2]	Aggressive chemical attack		
			[XA1]	[XA2]	[XA3]
Max. w/c ratio	0,80	0,50	0,50	0,45	0,4
Min. compressive strength class	C20/25	C30/37	C30/37	C35/45	C40/50
Air content (%)	2%	2%	2%	2%	2%

The maximum water to cement ratio to fulfil the requirement for the reinforced concrete structures in LILW repositories is 0.40 and the minimum compressive strength class is C40/50 as presented in Appendix 3. Based on the previous requirements, the selected values for the durable concrete mixtures are:

- Water to binder ratio = 0,44 or lower
- Compressive strength class = C40/45

2.3 Aggregate to binder ratio

According to Ipatti (2010) and Vesikari (2012) reports [19], [20], the aggregate to binder ratio was 5.0 for the water to cement ratio of 0,425.

- Aggregate to binder ratio = 5.0 for w/b ratio of 0.44

3 Preparation of specimens

3.1 Concrete mixes

The proposed concretes mixes are proportioned with constant water-binder ratio of 0.40 and aggregate-binder ratio of 5.0. The proportioning of the concrete mixes is presented in Table 5.

Table 5. Proposed mix design of concrete.

Concrete code	Cement type	Cement content /binder	Slag content of cement	Slag content of binder	Silica fume/ binder	W/B ratio ^(*)	Aggregate to binder ratio
SR-mix	SR – cement	100%		0	–	0,44*	5,0
SR-Si-mix	SR – cement	90%		0%	10%	0,44	5,0
KA-mix	Kolmossementti	100%	40%	40%	–	0,44	5,0
KB-mix	KolmosBertta	100%	70%	70%	–	0,44	5,0
KB-Si-mix	KolmosBertta	90%	63%	63%	10%	0,44	5,0

SR-Cement = CEM I 42.5 N – SR 3

Kolmossementti = CEM III/A 52,5 L (High-strength blast furnace cement)

KolmosBertta = CEM III/B 42,5 L – LH/SR (Blast furnace cement).

Si = Silica fume

(*) the water to binder ratio is selected based on workability class of the concrete used by TVO and Fortum (reference: Timo Kukkola and Tapani Eurajoki)

3.2 Preparation of hardened concrete specimens

Preparation of hardened concrete specimens are performed according to the European standard “EN 12390-1: Testing hardened concrete. Part 1: Shape, dimensions and other requirements for specimens and moulds”. For each shape of test specimen, cube, cylinder and prism, the nominal size (d) should be chosen to be at least three and a half times the maximum aggregate size (D_{max} according to EN 206) in the concrete.

1. Cylinder specimens

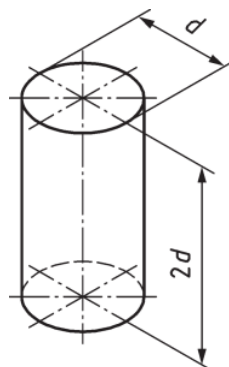


Figure 5. Cylinder specimen

Nominal size: $d = 150 \text{ mm}$ and $d = 100 \text{ mm}$.

Designated size: Designated sizes may be selected within $\pm 10 \%$ of the nominal size.

Tolerances:

- 1) The tolerance on the designated diameter (d) is 1,0 %.
- 2) The tolerance on the flatness of the load-bearing surface is 0,000 6d mm.
- 3) The tolerance on the perpendicularity of the side, with reference to the end faces, is 0,00 7d mm.
- 4) The tolerance on the height ($2d$) is 5 %.

2. Prisms specimens

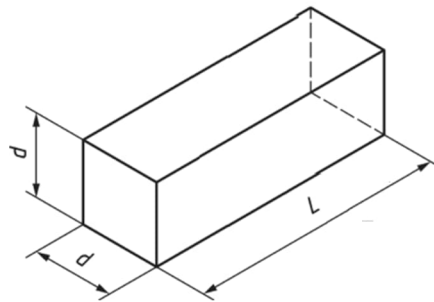


Figure 6. Prism specimen.

Nominal size: $d = 100$ mm and $L = 500$ mm

Designated size: Designated sizes may be selected within ± 10 % of the nominal size.

Tolerances:

- 1) Between moulded surfaces, the tolerance on the designated size (d) is 1,0 %.
- 2) Between the top trowelled face and the bottom moulded face, the tolerance on the designated size is 1,5 %.
- 3) The tolerance on the perpendicularity of the sides of the prism with reference to the base, as cast, is 0,5 mm.

3. Corrosion monitoring specimens

As an objective to assess achieving intended service life on LILW concrete structures, the corrosion of reinforcement is to be monitored. Corrosion of the steel reinforcement is monitored on the proposed laboratory specimens for several years. The specimens are prepared with 300 mm x 300 mm and 50 mm of concrete cover. Four reinforcement bars $\phi 16$ mm spaced at 200 mm are used. Concrete cover depth and reinforcement rebar details are simulating the reinforcement of the reinforced concrete silo structure at Olkiluoto. Linear polarization, concrete resistivity and corrosion potential tests will be monitored. With these corrosion rate values it would be possible to obtain estimations on how long it would take before cracks appears

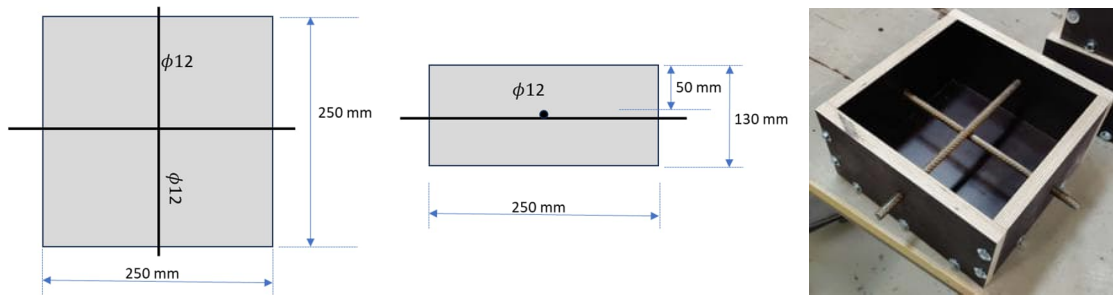


Figure 7. Corrosion monitoring specimens.

A list of the proposed hardened concrete tests and the used specimens is presented in Table 6. Details of the hardened concrete test specimens are presented in Appendix 4.

Table 6. Proposed hardened concrete tests and their used specimens.

Hardened concrete test	Test specimen
Compressive strength of test specimens	Cylinder specimens, d=150 mm and h = 300 mm
Modulus of elasticity in compression	Cylinder specimens, d=100 mm and h = 200 mm
Tensile splitting strength of test specimens	Cylinder specimens, d=100 mm and h = 200 mm
Density of hardened concrete	Cylinder specimens, d=150 mm and h = 300 mm
Determination of the chloride migration coefficient	Cylinder specimens, d=100 mm and h = 200 mm
Determination of the shrinkage of concrete	Prism specimens, d = 100 mm and L = 500 mm
Accelerated and natural carbonation	Prism specimens, d = 100 mm and L = 500 mm
Micro X-ray Fluorescence (μ XRF) and petrographic analysis	Prism specimens, d = 100 mm and L = 500 mm
Assessing concrete corrosion with non-destructive testing methods (NDT)	Corrosion monitoring specimens, 250 x 250 x 130 mm

Table 7. Proposed plan for the hardened concrete and durability test over 30 years for each concrete mixture.

Test name	2024	2025	2026	2027	End of FAFER 2028	2034	2039	2044	2054	# of specimens / Mix
Age of specimens	0	1	2	3	4	10	15	20	30	
EN 12390-3: Compressive strength test EN 12390-7: Density of hardened concrete • Storage under water • Cylinder specimens (d=100 and h=200)	9 specimens – tested at 7/28/91d	3 specimens	3 specimens	3 specimens	3 specimens	3 specimens	3 specimens	3 specimens	3 specimens	33
EN 12390-6: Tensile splitting strength • Storage under water • Cylinder specimens (d=100 and h=200)	3 specimens – tested at 91d	3 specimens	3 specimens	3 specimens						12
EN 12390-13: Modulus of elasticity in compression • Storage under water • Cylinder specimens (d=100 and h=200)	3 specimens – tested at 91d	3 specimens	3 specimens	3 specimens	3 specimens	3 specimens	3 specimens	3 specimens	3 specimens	27
EN 12390 - 16: Shrinkage of concrete ^(a) • Storage in standard environment • Prism specimens (100x100x500 mm)	12 measurements	4 measurements yearly								2
EN 12390 - 12: Accelerated carbonation test ^(b) • Storage in standard environment • Prism specimens (100x100x500 mm)	16 measurements	2 measurements / year until the cross section is carbonated								4
Micro XRF and thin section analysis Chloride ion penetration test of concrete • Storage in salt solution pins • Prism specimens (100x100x500 mm)	3 ^(c) x0.5 specimens – tested at 28d	1.5 specimen	1.5 specimen	1.5 specimen	1.5 specimen	1.5 specimen	1.5 specimen	1.5 specimen	1.5 specimen	14
NT Build 492 - Chloride migration coefficient from non-steady-state migration experiments • Storage in salt solution pins • Cylinder specimens (d=100 and h=200)	1 specimen – tested at 28d	1 specimen	1 specimen	1 specimen	1 specimen	1 specimen	1 specimen	1 specimen	1 specimen	9
iCor corrosion measurement (NDT) method • Storage in RH = 75% and T = 13 °C • Reinforced concrete slabs (250x250x130 mm)	4 measurements yearly									4
Natural carbonation test ^(b) • Storage in RH = 75% and T = 13 °C • Prism specimens (100x100x500 mm)	2 measurements / first year and thereafter 1 measurement / year until the cross section is carbonated									3
Accelerated leaching test of concrete – test samples are 50x50x50 mm cube MORTAR specimens stored in ammonium nitrate solution, needed for the concrete degradation modelling.										
Temperature development monitoring of the concrete (semi adiabatic calorimeter test) for two weeks (336h)										

^(a) The shrinkage measurement is performed according to the standard EN 12390-16. After mould removing, (i) the length of the specimens is measured with a shrinkage measurement device daily for one week, (ii) weekly measurements during six month, and then (iii) yearly measurements.

^(b) Measurements: (i) starts at age of 28d, (ii) weekly measurements for one month, (iii) monthly measurements for one year and (iv) two measurements yearly until the cross section is carbonated (50 mm samples)

^(c) Specimen 100x100x250 mm is used for tests, specimens are stored in three different solutions simulating Olkiluoto, Loviisa and XA3 exposure class ground water conditions.

The investigation of hardened concrete for acquisition of real data on long-term performance of the reinforced concrete barriers (silos and vaults) in nuclear waste repositories is carried out over 30 years. The long-term tests for concrete specimens in various chemical water solutions resembling the operation phase and the immersion ground water of Olkiluoto and Loviisa are performed. A plan of the testing program over 30 years (2024 – 2054) is presented in Table 7.

4 Testing of concrete

4.1 Testing of fresh concrete

Fresh concrete tests include slump, air content, unit weight and temperature. Data from these tests is helpful in assessing mix production and consistency in performance. A list of the proposed fresh concrete tests is presented in Table 8.

Table 8. Proposed fresh concrete tests and their European standards.

Standard	Fresh concrete test
EN 12350-1	Testing fresh concrete – Sampling and common apparatus
EN 12350-2	Testing fresh concrete – Part 2: Slump test
EN 12350-7	Testing fresh concrete – Air content. Pressure methods
EN 12350-6	Testing fresh concrete Density
	Temperature monitoring of freshly mixed concrete

4.1.1 Slump test (EN 12350-2)

It is the most common test since 1922 for workability of fresh concrete, which can be performed either at the working site/field or in the laboratory. A concrete slump test should be performed for each batch of fresh concrete for maintaining the consistency between each batch.

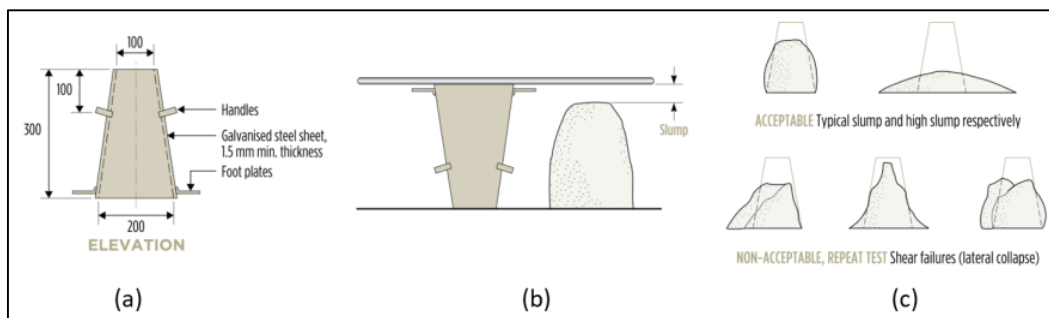


Figure 8. Slump test: (a) typical mold for slump test, (b) measuring the slump and (c) examples of concrete slump.

Slump test is widely used across the globe due to its simplicity, low cost, and immediate results. Slump test is regulated by EN: 12350-2. This testing method consists of a cone with a base diameter of 200 mm, a top diameter of 100 mm and a height of 300 mm. The cone is filled with concrete in 3 layers and compacted by 16 mm dia steel rod, 25 strokes for each layer. After filling the cone and levelling of top surface, cone is removed without jerk. The shape of the concrete after the removal is assessed to determine the workability.

4.1.2 Air content test – pressure method (EN 12350-7)

The air content of fresh concrete is determined as per EN 12350 (Part 7). Sample of fresh concrete is collected in a rigid, watertight, metal container and compacted either through

internal vibrator, or vibration table. Air content of concrete is measured by the pressure air measurement method (Figure 9) which is based on the principles of Boyle's law. Boyle's law states that the volume of the gas is inversely proportional to the pressure. By the application of pressure on a concrete of known volume (that consists of air voids), compression takes place which results in the reduction of the volume. This volume change is measured and related to the original initial volume. The difference between original and reduced volume of concrete provides the air content in concrete.



Figure 9. Determination of Air Content in Fresh Concrete: Pressure gauge method.

4.1.3 Testing fresh concrete density (EN 12350-6)

It is important to find the density of fresh concrete to know the volume and yield as per the batch. The procedure for determination of density of fresh concrete is given in EN 12350 (Part-6). The fresh concrete is compacted (by vibrator or vibration table) into a calibrated, rigid and watertight container (Figure 10) and then is weighed (The same container of Air Content Test is used). Volume (V) of container is obtained. The empty container weight is deducted to know the weight of the compacted concrete inside the container. The density is calculated by dividing the weight (W) of compacted concrete by the volume (V) of the container.

$$\rho_{\text{concrete}} = \frac{W}{V} \quad (1)$$



Figure 10. Example of the rigid and watertight container.

4.1.4 Temperature monitoring during concrete curing

In order to ensure the quality and durability of larger projects, it is important to monitor and record the temperature of the concrete. It is also necessary to control the mix temperature, ambient temperature, and differential temperature in mass concrete elements. Temperature differences can cause stress that leads to thermal cracks and loss of structural integrity, thus shortening the life and decreasing the strength of the mass concrete element. If the temperature goes below a certain limit, the hydration of water can slow or stop meaning the concrete won't set properly and won't achieve optimal strength. When concrete temperatures are properly monitored, appropriate adjustments are able to be made when needed. Temperature monitoring is also necessary to verify:

- Temperature differentials did not go beyond safe limits. The temperature of hardening concrete should not exceed 60°C (BY 65, 2021)
- Concrete did not cool more than 2.8°C per hour during the first 24 hours.
- The core temperatures at various stages, in order to determine any necessary temperature control strategies to put in place.

Data loggers with thermocouple temperature sensors (Figure 11) are used to accurately monitor and record concrete temperature throughout the curing process. Type K thermocouple probes are embedded within the concrete so that the actual core temperature of the mixture is logged, rather than just the ambient air temperature.

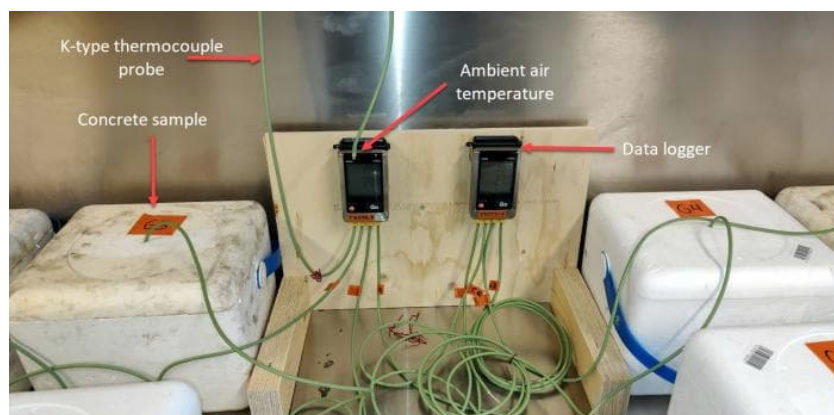


Figure 11. Temperature monitoring of a concrete sample.

4.2 Testing of hardened concrete

Test on Hardened Concrete is performed to check and control the quality of the concrete works used in the structure. Systematic testing of raw materials, fresh concrete and hardened concrete are a part of any quality control programme for concrete, which helps to achieve higher efficiency of the material used and greater assurance of the performance of the concrete with regard to both strength and durability. In addition to quality control, various test on hardened concrete also plays an important role in determining different physical properties such as strength and elastic properties of concrete. These tests are necessary for checking whether concrete is suitable for its intended use [21]. A list of the proposed fresh concrete tests is presented in Table 9.

Table 9. Proposed hardened concrete tests and their European standards.

Standard	Hardened concrete test
EN 12390-3	Testing hardened concrete – Compressive strength of test specimens
EN 12390-6	Testing hardened concrete – Tensile splitting strength of test specimens
EN 12390-7	Testing hardened concrete – Density of hardened concrete
EN 12390-12	Testing hardened concrete – Determination of the carbonation resistance of concrete. Accelerated carbonation method.
EN 12390-13	Testing hardened concrete – Determination of secant modulus of elasticity in compression
EN 12390-16	Testing hardened concrete – Determination of the shrinkage of concrete
EN 14629	Products and systems for the protection and repair of concrete structures - Test methods - Determination of chloride content in hardened concrete
NT Build 492	Chloride migration coefficient from non-steady-state migration experiments
	Micro X-ray Fluorescence (μ XRF) – determination of Sulfate, Magnesium and Chloride profiles in concrete.
	Thin-Section analysis – Petrographic analysis of hardened concrete
	Assessing concrete corrosion with non-destructive testing methods (NDT) and monitoring the natural carbonation of concrete.

4.2.1 Compressive strength test (EN 12390-3)

The determination of the compressive strength of concrete is described in EN 12390-3 (Testing hardened concrete – Compressive strength of test specimens). It makes provision for two sizes of concrete cylinder to be used – either 150 mm-diameter \times 300 mm-high, or 100 mm-diameter \times 200 mm-high (see Figure 12). The smaller cylinder may be used provided the maximum aggregate size does not exceed 20 mm and the designer's permission is obtained. Whilst the cylinder sizes tend to give the same average compressive strength, and hence may be used to determine compliance with the concrete specification, the coefficient of variation of the individual results may be different. Hence, results from the two specimen sizes cannot be combined when determining the average strength. Cylinder tests are quite sensitive to the planeness of the ends. Alternative methods for treating the

ends of cylinders are (i) to mill (grind) the cylinder ends, or alternatively (ii) to use standard rubber caps.

The testing of compressive strength of concrete can be used for laboratory specimens, as well as concrete cores. Specimens in the method are loaded until they fail, and their failure load is used to express the compressive strength of that specimen. The rate of loading is constant throughout the test.



Figure 12. (a) Moulds for the two standard sizes of concrete test cylinders and (b) compression test machine.

4.2.2 Tensile splitting strength test (EN 12390-6)

The tensile strength of concrete is one of the basic and important properties which greatly affect the extent and size of cracking in structures. Moreover, the concrete is very weak in tension due to its brittle nature. Hence, it is not expected to resist the direct tension. So, concrete develops cracks when tensile forces exceed its tensile strength. Therefore, it is necessary to determine the tensile strength of concrete to determine the load at which the concrete members may crack. Furthermore, splitting tensile strength test on concrete cylinder is a method to determine the tensile strength of concrete. The procedure based on the EN 12390-6 (Testing hardened concrete – Tensile splitting strength of test specimens).

The indirect tensile strength or splitting test, is conducted on a standard 150 mm × 300 mm concrete cylinder (see Figure 13) by placing it horizontally in a testing machine and applying a compressive force to it. When tested in this way, the cylinder splits, enabling the tensile strength of the concrete to be determined.

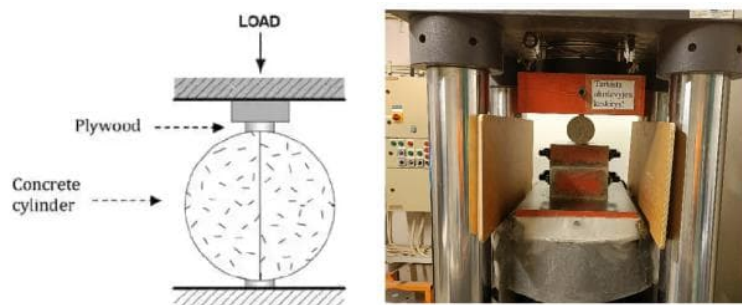


Figure 13. Concrete cylinder for indirect tensile strength testing (photo: Jukka Piironen).

4.2.3 Density of hardened concrete (EN 12390-7)

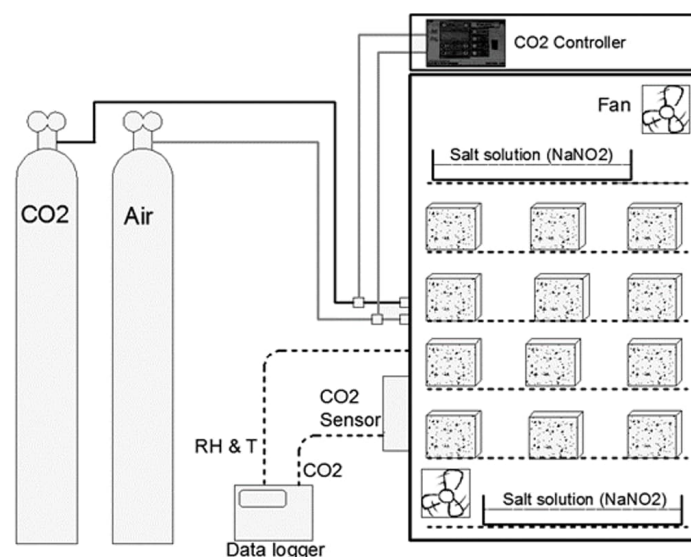
Hardened concrete density is determined either by simple dimensional checks, followed by weighing and calculation, or by weight in air/water buoyancy methods. The density of hardened concrete test is conducted on a standard 150 mm × 300 mm concrete cylinder that are used for the compressive strength test (see Figure 12). The procedure based on the EN 12390-7 (Testing hardened concrete – Density of hardened concrete).

4.2.4 Carbonation resistance of concrete

Concrete carbonation is one of the main causes of reinforcement corrosion. Determination of the rate of concrete carbonation can be made by exposing specimens in natural atmospheres; however, as this results in too slow a process, testing is usually made by accelerating the process using atmospheres of relatively high CO₂ concentration.

Accelerated carbonation tests are commonly used in the laboratory to test the resistance of cement-based materials to carbonation or to investigate its consequences. The accelerated carbonation resistance of concrete is determined according to EN 12390-12 (Testing hardened concrete – Determination of the carbonation resistance of concrete).

A 100 x 100x 500 mm prism specimen is used to perform the accelerated carbonation test for each mix recipe. When cured for 28 days, the specimens are brought into laboratory air environmental conditions (20°C, 65%RH) to dry for 14 days. Whereafter, the specimens are placed into the chamber (presented in Figure 14) for exposure to carbon dioxide. The target carbon dioxide content of 3,0% in the chamber was obtained by manually adjusting the air and CO₂ flow rates by the flow controller. The standard proposes a relative humidity around 57 %. However, throughout the operational phase of the LILW repository, the moisture air in proximity to the concrete structures maintains a relative humidity level of approximately 70% using NaCl solution. The carbon dioxide concentration and relative humidity as well as temperature are monitored throughout the exposure period.



Accelerated carbonation test chamber

Figure 14. Illustration of the system used for the accelerated carbonation method.

The accelerated carbonation depth is measured at (i) 7, 28, 56, 91, 182 and 365 days of storage in the test chamber and (iii) two measurements yearly until the cross section is carbonated (50 mm samples). The natural carbonation depth is measured at the same age as the accelerated carbonation test.

Carbonation depth is measured according to EN14630 (Products and systems for the protection and repair of concrete structures - Test methods - Determination of carbonation depth in hardened concrete by the phenolphthalein method). The testing is done to determine the depth of carbonation that took place in the concrete using phenolphthalein solution (adding 1 gram of phenolphthalein to 70mL of ethyl alcohol and diluting that to 100mL with distilled water). The mixed solution is then brushed onto the concrete surface and changes are observed. The color of concrete in which no carbonation has occurred will change to pink, while the concrete parts that did not exhibit any carbonation will not change. Figure 15 shows the color change of concrete after the phenolphthalein test, which shows the change of color of the specimen to pink on the inner part, whilst the outer edges which have been carbonated show no color change. The depth of carbonation in the sample can be obtained by measuring the distance from the surface to the points where the color of the sample turns pink.



Figure 15: Carbonation testing of a concrete specimen.

4.2.5 Modulus of elasticity in compression (EN 12390-13)

Modulus of elasticity of concrete is defined as the ratio of stress applied on the concrete to the respective strain caused. The accurate value of modulus of elasticity of concrete can be determined by conducting a laboratory test called compression test on a cylindrical concrete specimen. In the test, the deformation of the specimen with respect to different load variation is analyzed. These observations produce a Stress-Strain graph (load-deflection graph) from which the modulus of elasticity of concrete is determined. The slope of a line that is drawn in the stress-strain curve from a stress value of zero to the compressive stress value of $0.45 * f'_c$ (working stress) gives the modulus of elasticity of concrete.

The modulus of elasticity in compression test of hardened concrete test is conducted on a standard 100 mm × 200 mm concrete cylinder, as presented in Figure 16. The test is performed according to EN 12390-13 (Testing hardened concrete – Determination of secant modulus of elasticity in compression). Cylinder tests are quite sensitive to the planeness of the ends. Alternative methods for treating the ends of cylinders are (i) to mill (grind) the cylinder ends, or alternatively (ii) to use standard rubber caps.



Figure 16. modulus of elasticity in compression test of hardened concrete test (Photo: Jukka Piironen).

4.2.6 Shrinkage of concrete (EN 12390-16)

Shrinkage of concrete is a common issue in construction. Shrinkage occurs mainly as water evaporates from the mixture, weakening the concrete and potentially causing cracks, warping and deflection. There are various types of shrinkage of concrete, namely plastic, drying, autogenous and carbonation shrinkage. During the initial days, concrete undergoes rapid shrinkage, which progressively slows down over time. The most crucial factor affecting shrinkage of concrete is the drying conditions, i.e., humidity.

Two prisms with designated size of 100x100x500 [mm³] are used for investigating total shrinkage of each concrete mix. On each end of the prisms embedded gauge studs are cast. The distance between these embedded studs is defined as the gauge length, which was used as a reference for strain measurements. Moreover, in the EN 12390-16 (Testing hardened concrete – Determination of the shrinkage of concrete) standard for determination of the shrinkage of concrete, the gauge length using embedded gauge studs are calculated as:

$$L_0 = \text{Specimen length} - 2 * \text{length of the embedded part of the stud} \quad (2)$$

Despite the four different types of shrinkage, the EN 12390-16 standard is only followed for the determination of total shrinkage of concrete after demolding of the specimens. Thus,

possible shrinkage occurring within the first 24h is not in the scope of this research. Specimens are stored in a drying room (20°C and 65% relative humidity) where the initial length and weight are recorded. A length comparator instrument is used for determining the length of the prisms.

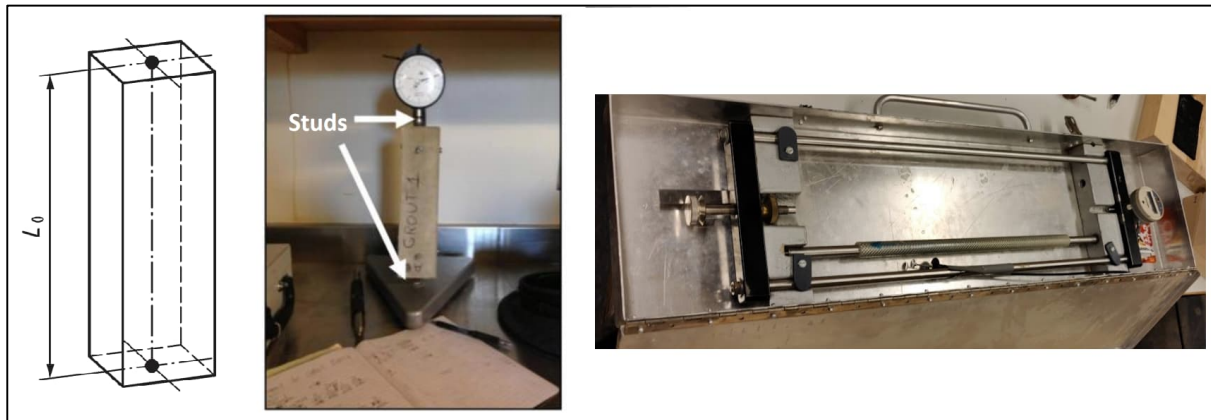


Figure 17. Shrinkage measurement recorded using length comparator.

For each specimen tested, the total shrinkage strain, expressed as 10^{-6} , is calculated at time t from:

$$\varepsilon_{cs}(t, t_0) = \frac{l(t_0) - l_{cs}(t)}{L_0} \quad (3)$$

$\varepsilon_{cs}(t, t_0)$ is the total shrinkage strain of the specimen at time t ,

L_0 is the gauge length in mm (Equation (2)),

$l(t_0)$ is the initial length at time t_0 in mm and

$l_{cs}(t)$ is the length at time t in mm.

4.2.7 Chloride migration coefficient (NT Build 492)

The service life and durability of reinforced concrete structures are affected by the degradation of concrete and corrosion of reinforcement. One of the main aspects of the durability design approach is to restrict the movement of the aggressive ions into the concrete (i.e. chloride ions). Chloride-initiated corrosion is one for the major causes of early age deterioration of concrete structures.

The NT Build 492 test method is based on the non-steady state migration of chloride ions. The test results are used as a durability indicator with respect to the resistance of the concrete to chloride penetration. Figure 18a presents the chloride migration test set-up (Proove'it system developed by Germann Instruments in Denmark).

Migration testing is performed on concrete cylindrical specimens of 100 mm diameter. The specimens are cured for 28 days before the performing the tests. After the required pre-conditioning, where necessary, the test specimen is placed in designed cells with reservoirs at each end. The reservoirs are filled with a chloride free and chloride containing solution (different solutions are prepared for different tests). An electric voltage is applied between two external electrodes to rapidly force the chloride ions into the concrete specimen. Figure 18b shows a typical cell arrangement according to the NT Build 492 test method.

After a defined period of time, the specimen is removed from the cells and split. The penetration depth of the free chloride ions is determined using a suitable colour indicator solution. The chloride migration coefficient is then calculated based on the measured depth of penetration in the concrete, the magnitude of the applied voltage and other measured parameters. Figure 18c shows the boundary of the free chloride (white / blueish colour) within the concrete specimen.

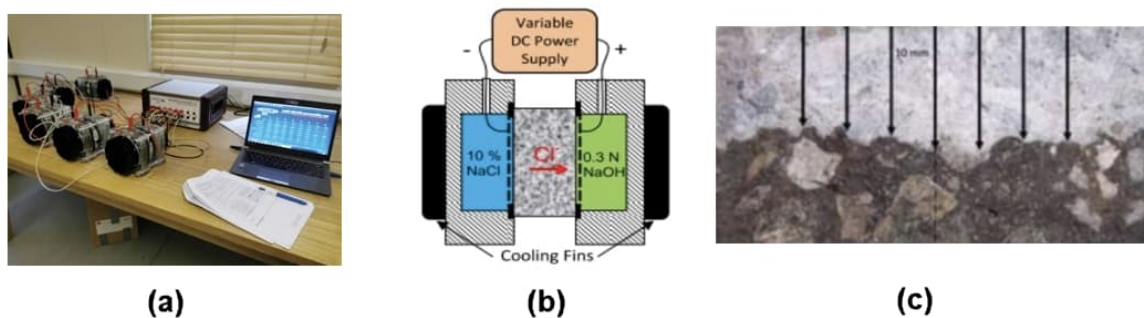


Figure 18. Chloride migration coefficient (NT Build 492) test. (a) Chloride Migration Test using Proove'it System determining the Migration coefficient on 6 samples of concrete, (b) A typical cell arrangement according to NT Build 492 test method using the Proove'it system and (c) Chloride penetration as indicated by the white/blueish colour change on the concrete.

4.2.8 Micro X-ray Fluorescence (μ XRF)

Micro X-ray fluorescence (μ XRF) is an elemental analysis technique which allows for the examination of very small sample areas. Like conventional XRF instrumentation, Micro X-ray Fluorescence uses direct X-ray excitation to induce characteristic X-ray fluorescence emission from the sample for elemental analysis. Unlike conventional XRF, which has a typical spatial resolution ranging in diameter from several hundred micrometres up to several millimetres, μ XRF uses X-ray optics to restrict the excitation beam size or focus the excitation beam to a small spot on the sample surface so that small features on the sample can be analysed.

X-ray energy forms the basis for insightful measurement techniques. Energy dispersive X-ray fluorescence identifies metals and elements in an object by detecting their signature XRF emission energies. Essentially, all elements have a fixed number of electrons arranged in atomic orbitals around their nuclei. When photons from the X-ray tube strike the object of interest with enough energy to expel the electrons out of the elements' innermost orbitals, the atoms become unstable.

To regain stability, electrons from the outer orbitals move into the newly vacant spaces in the inner orbitals. As an electron transitions from an outer orbital to an inner orbital, it emits photon energy known as X-ray fluorescence. This release of energy is illustrated in Figure 19. This energy is determined by the different energies between the initial and final orbitals of the individual's electron transitions. The amount of element present in an object is determined by the intensity of the signal detected at its signature energy.

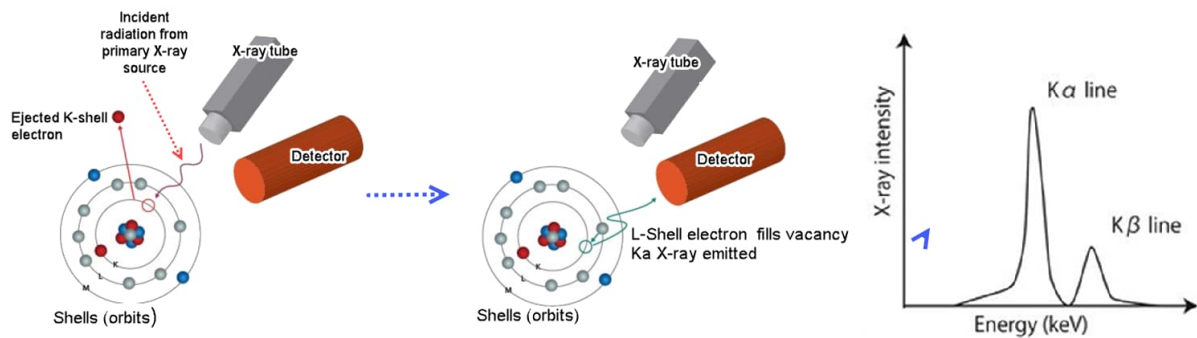


Figure 19. The mechanism of characteristic X-ray generation.

Standard μ XRF configuration is presented in Figure 20. The sample can be scanned to measure the elemental distribution within a sample with a spatial resolution as small as 10 μ m (energy dependent).

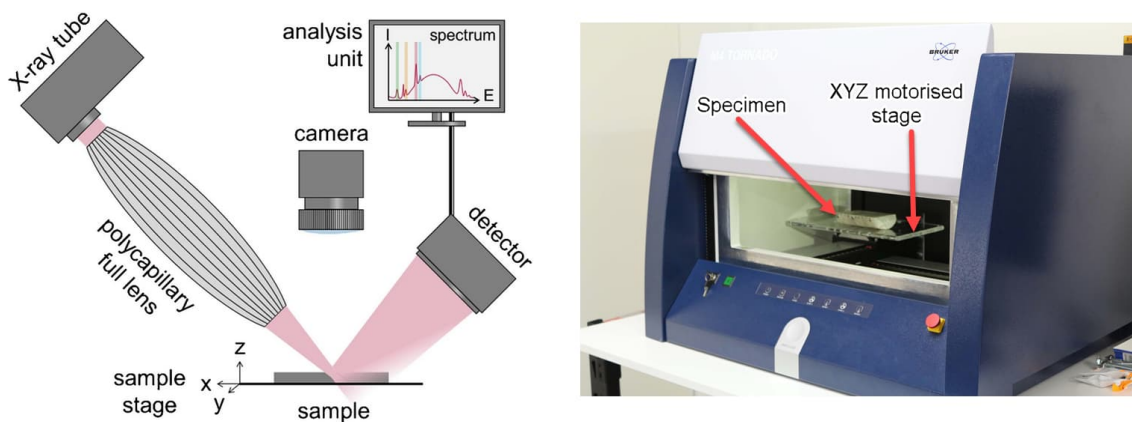


Figure 20. Schematic showing the main components of the Micro X-ray Fluorescence (μ XRF) [22].

Micro-XRF allows for fast measurements of large areas, with high spatial resolution in short times. The individual element distributions can be visualized and extracted quickly. Fundamental parameter-based quantification allows for a quick assessment of the composition of the sample. Smart analysis of mapping allows for semi-quantitative analysis of complex chemical compounds concentration in the concrete matrix.

As an example presented in Figure 21, drawing out a series of objects allows for semi-quantitative analysis: The HyperMap data can be used to tell the aggregates apart from the cement and quantify the cement composition into the depth of the sample. In this example, the Cl concentration goes from 1 wt.% to 0 wt.% within the first 10 mm. The K concentration is anticorrelated to the Cl (leaching). The sum of SiO₂ and CaCO₃ is stable at about 85 wt.%.

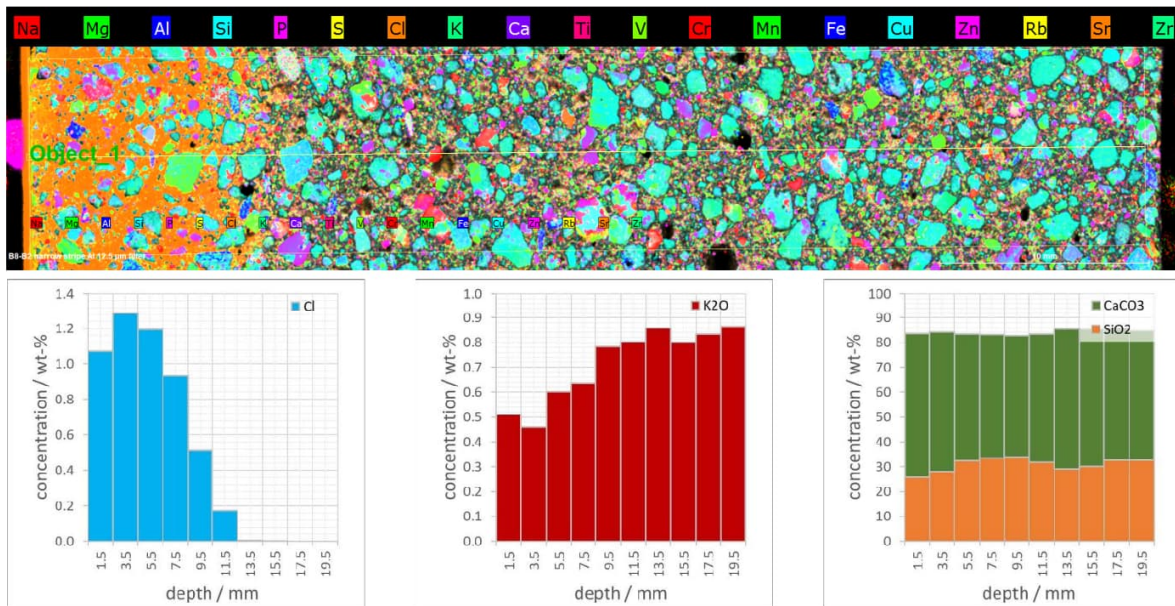


Figure 21. Examples of the Micro X-ray fluorescence (μ XRF) distribution maps of some chemical compounds in concrete.

4.2.9 Petrographic analysis of hardened concrete – Thin Section Analysis (TSA)

Thin Section Analysis (TSA) is a form of petrographic testing that is done to analyze the physical and chemical properties of materials. It is a typical testing procedure for rock and geological purposes, which was then integrated for soils, concrete, and other materials. It is a microscopic test, in which an image is taken and analyzed. This form of testing is widely used to identify the mineralogy of the tested samples in a small scale. The testing is conducted on thin slices obtained from the concrete specimen or drilled core, and the image taken is then analyzed to get a visual insight into the concrete's internal condition. The results of the TSA can be both quantitative and qualitative.

Concrete testing with TSA is done by slicing off very thin sections (around 30 μ m) of concrete from the specimen, which are then grinded and (if necessary) polished. The samples are then observed with a microscope to determine its physical properties. The obtained results, however, mainly depend on the experience of the tester, since a lot of the obtained information are qualitative. Figure 22 shows some preparation steps for the TSA analysis.

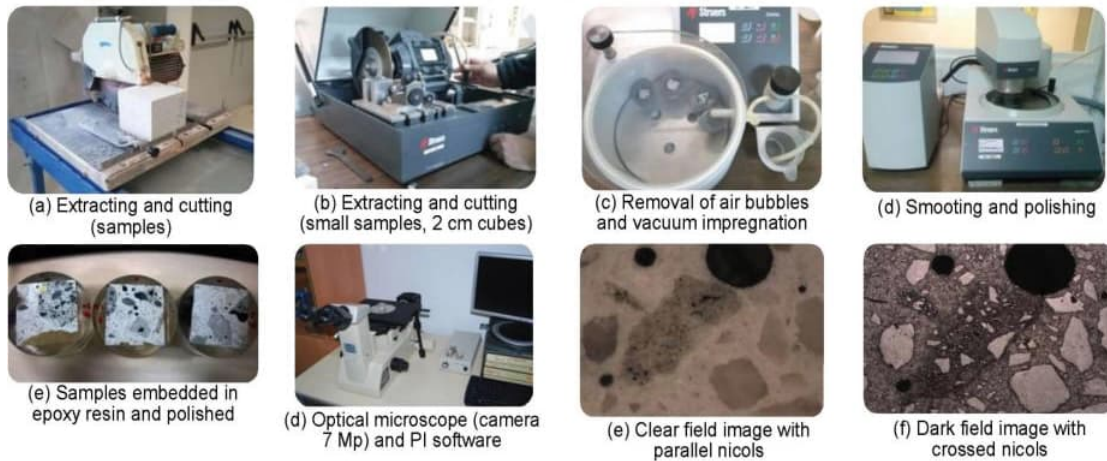


Figure 22: Sample preparation for optical petrographic analysis [23].

Based on the analysis of thin sections a long series of parameters and properties can be described, among those:

- aggregate distribution inside the concrete (as well as size and quality of those aggregates),
- the existence of cracks in the concrete's microstructure (their size, and the cause of the cracks),
- the presence and extent of damage in the concrete as well as the cause of that damage
- the air content in the concrete's pore structure
- the existence of different binder materials, as well as signs of expansive ettringite formation, AAR, and sulfate damage.
- w/c-ratio and homogeneity of cement paste
- Cement type and content
- Cement hydration and content of microcracks
- Bleeding and paste stability while the concrete was still plastic
- Bonding quality and ITZ for paste-sand and paste-stone.
- Degree of carbonation

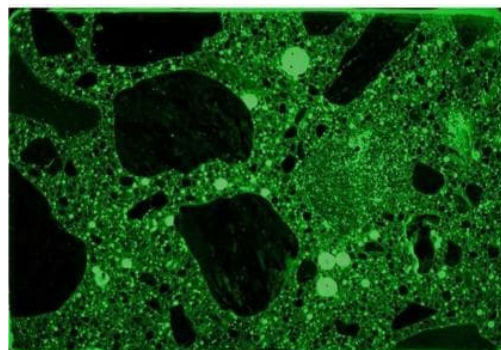


Figure 23. Example of this-section analysis. A 20 μ m thick fluorescence impregnated thin section in uv-light. The dimensions are 45mm x 30mm x 0.020mm.

4.2.10 Electrochemical measurement of steel rebar corrosion (NDT)

The electrochemical measurement of steel rebar corrosion explores the behaviour of embedded steel reinforcement corrosion under anoxic conditions in the presence of sodium chloride solution. Corrosion potential, corrosion rate and electrical resistivity of concrete values are obtained using an NDT device (iCOR™) provided by Giatec Scientific presented in Figure 24 and Figure 25. The iCor device implements a four-point array with an electrode spacing of 50 mm; with the surface-mounted array being parallel to the rebar. The outer probes apply a narrow DC/AC step voltage for a short period of time (3 to 10 seconds) and simultaneously record the voltage of the system with a relatively high sampling rate.

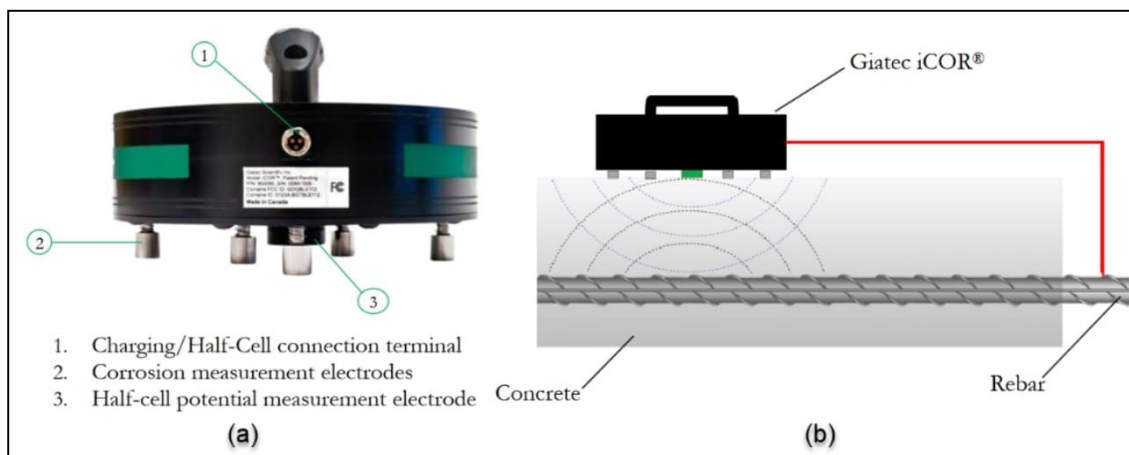


Figure 24. (a) side view of the iCor device and (b) principle of the Half-cell potential measurement using iCor.

iCOR measures the electrical response of the rebar inside the concrete, which is determined from the surface of the concrete with the use of four probes, which make it able to measure the corrosion rate and concrete electrical resistivity without the need of rebar connection. iCOR is also equipped with a reference electrode for half-cell corrosion measurement (Figure 24b). The purpose of the half-cell potential measurement was to determine the electrical potential on the surface of concrete which is an indication of corrosion potential of rebar in concrete.



Figure 25. Example of using the iCor device for measuring the electrochemical corrosion of steel.

4.2.11 Measurement of chloride profiles – Potentiometric titration

Chloride titrations are carried out to determine the ingress of chloride ions of the concrete surface. The measurement of chloride profiles is determined by applying the standard m EN 14629 (Products and systems for the protection and repair of concrete structures - Test methods - Determination of chloride content in hardened concrete, method B, potentiometric titration). The potentiometric titration belongs to chemical methods of analysis in which the endpoint of the titration is monitored with an indicator electrode that records the change of the potential as a function of the amount (usually the volume) of the added titrant of exactly known concentration.



Figure 26. Example of the potentiometric titrators used in the titration method.

Chloride content analyses is performed from specimens by grinding powder samples as presented in Figure 27. The titration samples are ground from the concrete specimens at the following depths:

- Sample 1. From a depth of 0 to 3 mm
- Sample 2. From a depth 5 to 8 mm
- Sample 3. From a depth of 10 to 13 mm
- Sample 4. From a depth of 15 to 18 mm
- Sample 5. From a depth of 20 to 23 mm
- Sample 6. From a depth of 28 to 31 mm
- Sample 7. From a depth of 38 to 41 mm
- Sample 8. From a depth of 48 to 50 mm

The Profile Grinder, presented in Figure 27, is used to obtain concrete powder samples at small depth increments for accurate determination of chloride ion profiles. The Profile Grinder grinding machine, pulverizes the concrete into a fine powder at exact depth

increments, which can be selected between 0.5 mm to 2.0 mm. The grinding area is 73 mm in diameter and the maximum depth is 40 mm. For every depth increment of 1 mm, approximately 9 grams of powder is obtained for analysis.



Figure 27. Concrete sampling for chloride measurement – Profile grinder.

According to the standard, the minimum weight of the powder sample should be approx. 10 g. The chloride content is determined with 0,1 M silver nitrate solution in a potentiometric titration. Consumption of silver nitrate solution (V_3) in the titration is noted. The first derivative method is to be used. First derivative is a technique of adding small aliquots of titrant to the sample, recording the potential changes, and applying a first derivative analysis to the data, from which the endpoint is calculated. The technique assumes that the change in mV reading per volume of titrant added will be greatest at the endpoint. The chloride content of the concrete as percent of chloride ion is calculated by mass of sample using the following formula:

$$Cl\% - wt\ of\ concrete = \frac{3,545 * f * V_3}{m} * 100 \quad (4)$$

Where (f) is the molarity of silver nitrate solution, (V_3) is the volume of the silver nitrate solution used in the titration [ml] and (m) is the mass of the concrete sample [g].

The chloride content by mass of cement is calculated using the following formula

$$Cl\% - wt\ of\ cement = Cl\% - wt\ of\ concrete * \frac{mass\ of\ concrete\ ingredients\ in\ kg}{mass\ of\ cement\ in\ kg} \quad (5)$$

5 Storage of concrete specimens

Four storage conditions representing the ground water in Olkiluoto, Loviisa, exposure class XA3 and the environmental conditions at the operation phase of the repository. Details about the chemical analysis of the ground water at Olkiluoto and Loviisa are presented in appendix 5 and appendix 6.

i. Olkiluoto ground water simulation

Aggressive component	unit	Minimum measured contents (PVA2)	Maximum measured contents (PVA3)	Average measured contents	Proposed limit
Sulfaatti, SO ₄ ²⁻	mg/l	130	320	230	160
Chloride, CL ⁻	mg/l	320	2030	1400	1400
Magnesium, Mg ²⁺	mg/l	15	71	43	75

ii. Loviisa ground water simulation

Aggressive component	unit	Minimum measured contents (LPVA4)	Maximum measured contents (LPVA5)	Average measured contents	Proposed limit
Sulfaatti, SO ₄ ²⁻	mg/l	470	590	530	576
Chloride, CL ⁻	mg/l	4000	5250	4625	5040
Magnesium, Mg ²⁺	mg/l	200	265	232,5	270

iii. XA3 exposure classes for chemical attack from ground water

Aggressive component	unit	Minimum limit	Maximum limit	Average limit	Proposed limit
Sulfaatti, SO ₄ ²⁻	mg/l	3000	6000	4500	6400
Chloride, CL ⁻	mg/l				56000
Magnesium, Mg ²⁺	mg/l	≥ 3000	up to saturation		3000

iv. Simulation of the environmental condition during the operation phase

Sodium chloride (NaCl) particles absorb water vapour at a relative humidity above 75% at 23 °C and then they form NaCl solution. NaCl solution desorbs water vapour when the relative humidity in the immediate nearness decreases below the equilibrium relative humidity of that salt solution. Therefore, this system is able to regulate the relative humidity in its immediate nearness [27].

As the relative humidity of the moist air around the concrete structures is about 70% RH in the operation phase of the LILW repository, a saturated sodium chloride solution is

prepared to produce relative humidity of 75%. The saturated sodium chloride solution contains 40 – 45 g NaCl/100 ml water content.

As the temperature varies between 10 to 13 °C inside the LILW repository, the temperature at the storage location (Otaniemi underground tunnel, temperature is about 15±2°C) is accepted as an exposure temperature. The relative humidity and the temperature of the storage location will be monitored during the storage time.

Three water solutions and moist air condition are prepared for the storage of the test specimens. The solutions were aimed to simulate the ground water in Olkiluoto, Loviisa and chemical attack exposure class XA3. The test solutions are presented in Table 10. Details of different solutions are presented in Appendix 7.

Table 10. The proposed simulation of the environmental condition during the operation phase

Solution code	Chemical	Aggressive component (mg/l)
OL-solution	Na ₂ SO ₄ +NaCl+MgCl ₂ ·6H ₂ O	SO ₄ ²⁺ = 160
		Cl ⁻ = 1400
		Mg ²⁺ = 75
LV-solution	Na ₂ SO ₄ +NaCl+MgCl ₂ ·6H ₂ O	SO ₄ ²⁺ = 576
		Cl ⁻ = 5040
		Mg ²⁺ = 270
XA3-solution	Na ₂ SO ₄ +NaCl+MgCl ₂ ·6H ₂ O	SO ₄ ²⁺ = 6400
		Cl ⁻ = 56000
		Mg ²⁺ = 3000
75%RH	Saturated NaCl solution	-

6 References

- [1] World Nuclear Association, "Radioactive Waste Management - Nuclear Waste Disposal." Accessed: Aug. 23, 2023. [Online]. Available: <https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx>
- [2] OECD/NEA, "Radioactive Waste Management and Decommissioning - Storage of Radioactive Waste and Spent Fuel," 2020. Accessed: Aug. 23, 2023. [Online]. Available: https://www.oecd-nea.org/upload/docs/application/pdf/2020-09/7406_-_storage_of_radioactive_waste_final_030620.pdf
- [3] L. Kumpula, I. Huhtanen, S. Palander, M. Ylä-Mella, and V. Kuhmonen, "Management of spent nuclear fuel and radioactive waste in Finland Second national programme under Article 12 of Directive 2011/70/EURATOM of the Council of the European Union", Accessed: Aug. 21, 2023. [Online]. Available: <https://urn.fi/URN:ISBN:978-952-327-855-4>
- [4] J. Vehmas, A. Rentto, J. Luukkanen, B. Auffermann, and J. Kaivo-oja, "The Finnish Solution to Final Disposal of Spent Nuclear Fuel," Springer VS, Wiesbaden, 2023, pp. 287–317. doi: 10.1007/978-3-658-40496-3_11.
- [5] Teollisuuden Voima Oyj (TVO), "TVO - Operational waste." Accessed: Aug. 21, 2023. [Online]. Available: <https://www.tvo.fi/en/index/production/nuclearwastemanagement/operationalwaste.html>
- [6] Fortum, "Nuclear waste management." Accessed: Aug. 21, 2023. [Online]. Available: <https://www.fortum.com/energy-production/nuclear-power/nuclear-waste-management?vtab=accordion-item-28736>
- [7] J. Kořátková, J. Zatloukal, P. Reiterman, and K. Kolář, "Concrete and cement composites used for radioactive waste deposition," *J Environ Radioact*, vol. 178–179, pp. 147–155, Nov. 2017, doi: 10.1016/J.JENVRAD.2017.08.012.
- [8] M. Garamszeghy, "Disposal of Low-and Intermediate-Level Waste: International experience," Feb. 2018. Accessed: Aug. 23, 2023. [Online]. Available: https://radwasteplanning.ca/sites/default/files/lilw_white_paper_final.pdf
- [9] Stuk, "Radiation and Nuclear Safety Authority Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management," Oct. 2017, Accessed: Aug. 23, 2023. [Online]. Available: https://www.iaea.org/sites/default/files/national_report_of_finland_for_the_6th_review_meeting_-_english.pdf
- [10] I. A. E. AGENCY, "Status and Trends in Spent Fuel and Radioactive Waste Management," *Status and Trends in Spent Fuel and Radioactive Waste Management*, pp. 1–57, 2018, Accessed: Aug. 23, 2023. [Online]. Available: <https://www.iaea.org/publications/11173/status-and-trends-in-spent-fuel-and-radioactive-waste-management>

-
- [11] P. Keto *et al.*, "KYT SURFACE Near Surface Repositories in Finland," Feb. 2020. Accessed: Aug. 23, 2023. [Online]. Available: http://kyt2022.vtt.fi/kyt2022_seminar_sept_2019.htm.
- [12] J. Pitkäoja, J. Kumpulainen, O. Nummi, and H. Oy, "Long-term safety assessment for disposal of VTT's decommissioning wastes in Loviisa LILW repository," 2019, Accessed: Aug. 24, 2023. [Online]. Available: <https://jyx.jyu.fi/bitstream/handle/123456789/67068/1/URN%3ANBN%3Afi%3Aaju-202001021003.pdf>
- [13] NGWA National Ground Water Association, "Groundwater | Dissolved mineral sources and significance." Accessed: Aug. 24, 2023. [Online]. Available: <https://www.ngwa.org/what-is-groundwater/About-groundwater/dissolved-mineral-sources-and-significance>
- [14] F. Al-Neshawy, A. Ba Ragaa, and J. Punkki, "Comprehensive state-of-the-art report for long-term behaviour of concrete structures in repository environment," Espoo, 2023. Accessed: Aug. 24, 2023. [Online]. Available: <https://aaltodoc.aalto.fi/handle/123456789/119823>
- [15] SFS-EN 206, "SFS-EN 206:2014 + A2:2021:en Concrete. Specification, performance, production and conformity." Accessed: Aug. 24, 2023. [Online]. Available: <https://sales.sfs.fi/en/index/tuotteet/SFS/CEN/ID2/2/979489.html.stx#>
- [16] F. P. Glasser, "Cements in Radioactive Waste Disposal," 2011. Accessed: Aug. 24, 2023. [Online]. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1701_add-CD/PDF/UK%20Aberdeen%20University.pdf
- [17] A. Idiart, J. Olmeda, and M. Laviña, "Modelling of concrete degradation-influence of concrete mix design - Report for the safety evaluation SE-SFL," 2019, Accessed: Aug. 24, 2023. [Online]. Available: <https://www.skb.se/publikation/2493347/R-19-14.pdf>
- [18] A. Iqbal, "Durability Properties of Low-Carbon Concrete," Aalto University School of Engineering, 2022. Accessed: Aug. 25, 2023. [Online]. Available: https://aaltodoc.aalto.fi/bitstream/handle/123456789/117151/master_Iqbal_Ahsan_2022.pdf
- [19] A. Ipatti, "Betonin pitkäikäisäilyvyys loppusijoitusolosuhteissa. Työvaihe: yhteenveto koebetoin betoniteknisistä perusominaisuuksista.," Vantaa, Dec. 2010.
- [20] E. Vesikari and P. Koskinen, "Durability of Concrete Barriers in Final Depositories of Nuclear Waste," Espoo, Feb. 2012. Accessed: Aug. 27, 2023. [Online]. Available: http://kyt2014.vtt.fi/julkaisut/koskinen_et_vesikari_VTT_R_01185_12.pdf
- [21] "Testing of Hardened Concrete - Compression, flexural, non destructive test." Accessed: Aug. 26, 2023. [Online]. Available: <https://civilcrews.com/testing-of-hardened-concrete/>
- [22] F. A. Wahid, "Characterising concrete using micro X-ray fluorescence (μ XRF)," Imperial College London, London, 2016. Accessed: Jan. 26, 2024. [Online]. Available:

<https://spiral.imperial.ac.uk/bitstream/10044/1/55139/1/Abdul%20Wahid-F-2017-PhD-Thesis.pdf>

- [23] Z. Sánchez-Roldán, I. Valverde-Palacios, I. Valverde-Espinosa, and M. Martín-Morales, "Microstructural analysis of concretes manufactured with recycled coarse aggregates pre-soaked using different methods," *Materiales de Construcción*, vol. 70, no. 339, Sep. 2020, doi: 10.3989/MC.2020.16919.
- [24] S. Helland and M. Maage, "Chloride penetration into concrete with lightweight aggregates," Mar. 1999, [Online]. Available: https://www.researchgate.net/publication/336879504_Chloride_penetration_into_concrete_with_lightweight_aggregates_-_Brite_EuRam_III_project_BE96-3942R3
- [25] K. van Tittelboom, N. de Belie, and R. Doug Hooton, "Test methods for resistance of concrete to sulfate attack - A critical review," *RILEM State-of-the-Art Reports*, vol. 10, pp. 251–288, 2013, doi: 10.1007/978-94-007-5413-3_10/FIGURES/3.
- [26] T. Aye, C. T. Oguchi, and Y. Takaya, "Evaluation of sulfate resistance of Portland and high alumina cement mortars using hardness test," *Constr Build Mater*, vol. 24, no. 6, pp. 1020–1026, Jun. 2010, doi: 10.1016/J.CONBUILDMAT.2009.11.016.
- [27] S. Sänglerlaub *et al.*, "Functional properties of foamed and/or stretched polypropylene-films containing sodium chloride particles for humidity regulation," 2017, doi: 10.1016/j.polymertesting.2017.12.002.

7 Appendices

7.1 Exposure classes related to environmental actions on reinforced concrete structures – EN 206-1.

Class Designation	Description of environment	Informative examples where exposure may occur
No risk of corrosion attack		
XO	For concrete without reinforcement or embedded metal: All exposures except where there is a freeze/thaw, abrasion or chemical attack. For Concrete with reinforced or embedded metal: Very Dry	Concrete inside buildings with very low air humidity
Corrosion induced by carbonation		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity, e.g. floor slabs. Concrete permanently submerged in water.
XC2	Wet, rarely dry	Concrete surfaces subject to long term water contact, many foundations.
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity. External concrete sheltered from rain.
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2.
Corrosion induced by chlorides		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides.
XD2	Wet, rarely dry	Swimming pools, Concrete exposed to industrial waters containing chlorides.
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides, pavements, car park slabs.
Corrosion induced by chlorides from sea air		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast.
XS2	Permanently submerged	Parts of marine structures.
XS3	Tidal and spray zones	Parts of marine structures.
Freeze/thaw attack with or without de-icing agents		
XF1	Moderate water saturation without de-icing agent	Vertical concrete surfaces exposed to rain and freezing.
XF2	Moderate water saturation with de-icing	Vertical concrete surfaces of road structures exposed to freezing & agent airborne de-icing agents.
XF3	High water saturation without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing.
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents. Concrete surfaces exposed to direct spray containing de-icing agents and freezing. Splash zones or marine structures exposed to freezing.
Chemical attack		
XA1	Slightly aggressive chemical environment according to EN 206.	
XA2	Moderately aggressive chemical environment according to EN 206.	
XA3	Highly aggressive chemical environment according to EN 206.	

7.2 Permitted cements and additions in different exposure classes.

	No-risk of corrosion or attack	Exposure classes																		
		Carbonation-induced reinforcement corrosion				Chloride-induced reinforcement corrosion						Freeze/thaw attack				Aggressive chemical attack				
						Chlorides from sea water			Chlorides other than sea water											
X0	XC1	XC2	XC3	XC4	XS1	XS2	XS3	XD1	XD2	XD3	XF1	XF2	XF3	XF4	XA1	XA2	XA3			
Permitted cement types	No restrictions caused by durability. All EN 197-1 compliant cement grades permitted	I	I	I	I ¹⁾	I ¹⁾	I ¹⁾	I ¹⁾	I ¹⁾	I ¹⁾	I ¹⁾	I	I	I	I	I	I ²⁾	I ²⁾		
		IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	IIA/-S	
		II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	II/B-S	
		II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	II/A-D	
		II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	II/A-V	
		II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V	II/B-V
		II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL	II/A-LL ⁴⁾	II/A-LL	II/A-LL	
		II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M	II/A-M ⁴⁾	II/A-M	II/A-M	
		II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	II/B-M ⁵⁾	
		III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	III/A	
III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B	III/B			
Clinker content of binder ⁶⁾	≥ 5	≥ 5	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20	≥ 20			
	Mineral additives content of the binder ⁶⁾																			
Mineral additives weight % of the total amount of binder	Mineral additives weight % of the total amount of binder																			
	Silica fume	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10	≤ 10		
Fly ash	≤ 50	≤ 50	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30	≤ 30			
GGBFS - slag	≤ 95	≤ 95	≤ 80	≤ 80	≤ 80	≤ 80	≤ 80	≤ 80	≤ 80	≤ 80	≤ 80	≤ 50	≤ 80	≤ 50	≤ 80	≤ 80	≤ 80			

1) In case of using CEM I, it is recommended to determine other methods for improving the durability of concrete based on the severity of the attack. Examples of those methods include the use of mineral additives for improving the chloride resistance of concrete and increasing the thickness of concrete.

2) In aggressive sulfate attack environment, SFS-EN 197-1 recommends the use of Sulfate Resistant cement (CEM I-SR3) or binder which contain GGBFS slag ≥70% of the total amount of binder.

3) Other than the sulfate attack environment, the designer chooses a binder based on the dominant aggressive chemical attack class (e.g. XA1, XA2 or XA3)

4) The limestone powder content ≤ 20%

5) The Portland clinker content of the binder is a mass percentage (mass %)

6) When using cement containing secondary cementitious materials more than allowed in CEM I (max. 5%), the content of the secondary cementitious materials is needed to take into account when calculating the amount of the additives.

7.3 Recommended limiting values for concrete composition and properties with design working life of 100 years.

	No risk of corrosion or attack	Exposure classes																
		Corrosion induced by carbonation				Corrosion caused by chlorides						Freeze-thaw stress ¹⁾				Aggressive chemical attack		
						Chlorides from sea water			Chlorides from other source than sea water									
X0	XC1	XC2	XC3	XC4	XS1	XS2	XS3	XD1	XD2	XD3	XF1	XF2 ²⁾⁴⁾	XF3	XF4 ²⁾⁴⁾	XA1	XA2	XA3	
Max. w/c		0.90	0.80	0.60	0.60	0.45	0.40	0.40	0.50	0.50	0.40	0.55		0.50		0.50	0.45	0.40
Min. strength class	C12/15	C20/25	C20/25	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45					C30/37	C35/45	C40/50
Min. cement content (kg/m ³)		160	160	250	250	300	320	340	300	300	320	270		300	300	320	330	
Air content (%)												5.5 ³⁾		5.5 ³⁾				

¹⁾ Additional frost resistance requirements as per Appendix 4, Table A4.1.

²⁾ The frost-salt resistance of the concrete shall be proved by means of functional methods as per Appendix 4, Section 3.

³⁾ The air content requirement applies to concrete in which the upper aggregate size is at least 16 mm. When the upper aggregate size is 12 mm, the air content requirement is raised by 0.5 percentage point, and when the upper aggregate size is 8 mm, the air content requirement is raised by 1.0 percentage point.

⁴⁾ The P-factor requirement is 50 in exposure class XF2 and 70 in exposure class XF4. The P-factor is determined as per InfraRYL, Part 3, Section 42020.1.2.

7.4 Details of the hardened concrete test specimens for each concrete mix

Hardened concrete – Durability tests:

- 1) Compressive strength
- 2) Tensile splitting strength
- 3) Modulus of elasticity
- 4) Drying shrinkage
- 5) Accelerated carbonation test
- 6) Micro XRF, Chloride penetration and Thin-sections analysis
- 7) Natural carbonation and NDT monitoring of corrosion
- 8) NT Build 492 – The rapid chloride permeability

1. Compressive strength (D150 x H300 cylinders), 33 specimens / mixture		
Age of concrete	Exposure environment	Action / test
0 – 1d	Cover with plastic sheets	Unmoulding of specimens
7d	Stored in RH \geq 95% and 20 \pm 2°C [A]	7d compressive test / 3 specimens
28d	Stored in RH \geq 95% and 20 \pm 2°C [A]	28d compressive test / 3 specimens
91d	Stored in RH \geq 95% and 20 \pm 2°C [A]	91d compressive test / 3 specimens
1 year	Stored in water [A]	1 year's compressive test / 3 specimens
2 years	Stored in water [A]	2 years compressive test / 3 specimens
3 years	Stored in water [A]	3 years compressive test / 3 specimens
4 years	Stored in water [A]	4 years compressive test / 3 specimens
10 years	Stored in water [TVO]	10 years compressive test / 3 specimens
15 years	Stored in water [TVO]	15 years compressive test / 3 specimens
20 years	Stored in water [TVO]	20 years compressive test / 3 specimens
30 years	Stored in water [TVO]	30 years compressive test / 3 specimens

[A] Stored at Aalto
[TVO] Stored at TVO

2. Tensile splitting strength (D150 x H300 cylinders), 12 specimens / mixture		
Age of concrete	Exposure environment	Action / test
0 – 1d	Cover with plastic sheets	Unmoulding of specimens
1d – 91d	Stored in RH \geq 95% and 20 \pm 2°C [A]	91d tensile splitting strength test / 3 specimens
1 year	Stored in water [A]	1-year tensile splitting strength test / 3 specimens
2 years	Stored in water [A]	2-year tensile splitting strength test / 3 specimens
3 years	Stored in water [A]	3-years tensile splitting strength test / 3 specimens

3. Modulus of elasticity (D100 x H200 cylinders), 27 specimens / mixture

Age of concrete	Exposure environment	Action / test
0 – 1d	Cover with plastic sheets	Unmoulding of specimens
91d	Stored in water [A]	91d MOE test / 3 specimens
1 year.	Stored in water [A]	1 year MOE test / 3 specimens
2 years	Stored in water [A]	2 years MOE test / 3 specimens
3 years	Stored in water [A]	3 years MOE test / 3 specimens
4 years	Stored in water [A]	4 years MOE test / 3 specimens
10 years	Stored in water [TVO]	10 years MOE test / 3 specimens
15 years	Stored in water [TVO]	15 years MOE test / 3 specimens
20 years	Stored in water [TVO]	20 years MOE test / 3 specimens
30 years	Stored in water [TVO]	30 years MOE test / 3 specimens

[A] Stored at Aalto

[TVO] Stored at TVO

4. Drying shrinkage (100 x 100 x 500 Prisms), 2 specimens / mixture

Age of concrete	Exposure environment	Action / test
0 – 1d	Cover with plastic sheets	Unmoulding of specimens
1d	Stored in RH = 65% and 20±2°C [A]	1d shrinkage measurement / 2 specimens
4d	Stored in RH = 65% and 20±2°C [A]	4d shrinkage measurement / 2 specimens
7d	Stored in RH = 65% and 20±2°C [A]	7d shrinkage measurement / 2 specimens
14d	Stored in RH = 65% and 20±2°C [A]	14d shrinkage measurement / 2 specimens
28d	Stored in RH = 65% and 20±2°C [A]	28d shrinkage measurement / 2 specimens
56d	Stored in RH = 65% and 20±2°C [A]	56d shrinkage measurement / 2 specimens
91d	Stored in RH = 65% and 20±2°C [A]	91d shrinkage measurement / 2 specimens
182d	Stored in RH = 65% and 20±2°C [A]	182d shrinkage measurement / 2 specimens
1 year	Stored in RH = 65% and 20±2°C [A]	1 year shrinkage measurement / 2 specimens

[A] Stored at Aalto

5. Accelerated Carbonation (100 x 100 x 500 Prisms), 2 specimens / mixture		
Age of concrete	Exposure environment	Action / test
0 – 1d	Cover with plastic sheets	Unmoulding of specimens
28d	Stored in water [A]	Moving to the curing room
42d	14d Stored in RH = 65% and 20±2°C [A]	Moving to the CO2 chamber
49d	Stored in CO2 chamber (4±0.5% CO2, RH = 65% and 20±2°C) [A]	7d storage – carbonation depth measurement / 50 mm slices
70	Stored in CO2 chamber (4±0.5% CO2, RH = 65% and 20±2°C) [A]	28d storage – carbonation depth measurement / 50 mm slices
112d	Stored in CO2 chamber (4±0.5% CO2, RH = 65% and 20±2°C) [A]	70d storage – carbonation depth measurement / 50 mm slices
224d	Stored in CO2 chamber (4±0.5% CO2, RH = 65% and 20±2°C) [A]	182d storage – carbonation depth measurement / 50 mm slices
408d	Stored in CO2 chamber (4±0.5% CO2, RH = 65% and 20±2°C) [A]	1 year storage – carbonation depth measurement / 50 mm slices
Measurements continue every 6 months or yearly until the total cross section is carbonated.		

[A] Stored at Aalto

6. Micro XRF [75 mm slice] Chloride penetration [100 mm slice] Thin-sections analysis [75 mm slice] (100 x 100 x 250 Prisms), $8 \times 3 + 1 = 25$ specimens / mixture		
Age of concrete	Exposure environment	Action / test
0 – 1d	Cover with plastic sheets	Unmoulding of specimens and Moving to the curing room
28d	Stored in RH \geq 95% and 20 \pm 2°C [A]	Specimens are drying for 5 hours then coated by the water proofing epoxy coating. After 5 hours of drying, the specimens are immersed in different salt solutions. Micro XRF and chloride penetration – zero values are measured
1 year	Stored in Different (Oikiluoto, Loviisa & XA3) salt solutions [A]	<ul style="list-style-type: none"> • Micro XRF • Chloride penetration • Thin-sections analysis
2 years	Stored in Different (Oikiluoto, Loviisa & XA3) salt solutions [A]	<ul style="list-style-type: none"> • Micro XRF • Chloride penetration • Thin-sections analysis
3 years	Stored in Different (Oikiluoto, Loviisa & XA3) salt solutions [A]	<ul style="list-style-type: none"> • Micro XRF • Chloride penetration • Thin-sections analysis
5 years	Stored in Different (Oikiluoto, Loviisa & XA3) salt solutions [A]	<ul style="list-style-type: none"> • Micro XRF • Chloride penetration • Thin-sections analysis
10 years	Stored in Different (Oikiluoto, Loviisa & XA3) salt solutions [TVO]	<ul style="list-style-type: none"> • Micro XRF • Chloride penetration • Thin-sections analysis
15 years	Stored in Different (Oikiluoto, Loviisa & XA3) salt solutions [TVO]	<ul style="list-style-type: none"> • Micro XRF • Chloride penetration • Thin-sections analysis
20 years	Stored in Different (Oikiluoto, Loviisa & XA3) salt solutions [TVO]	<ul style="list-style-type: none"> • Micro XRF • Chloride penetration • Thin-sections analysis
30 years	Stored in Different (Oikiluoto, Loviisa & XA3) salt solutions [TVO]	<ul style="list-style-type: none"> • Micro XRF • Chloride penetration • Thin-sections analysis

[A] Stored at Aalto

[TVO] Stored at TVO

7. Natural carbonation (100 x 100 x 500 Prisms), 3 specimens / mixture		
NDT monitoring of corrosion (slab 250x250x130, 12 mm bar), 3 specimens / mixture		
Age of concrete	Exposure environment	Action / test
0 – 1d	Cover with plastic sheets	Unmoulding specimens and Moving to the curing room
28d	Stored in RH \geq 95% and 20 \pm 2°C [A]	Zero values are measured
49d	Stored in RH \geq 75% and 13 \pm 2°C [A]	Natural carbonation depth (50 mm slice)
70	Stored in RH \geq 75% and 13 \pm 2°C [A]	Natural carbonation depth (50 mm slice)
112d	Stored in RH \geq 75% and 13 \pm 2°C [A]	Natural carbonation depth (50 mm slice)
224d	Stored in RH \geq 75% and 13 \pm 2°C [A]	Natural carbonation depth (50 mm slice)
1 year	Stored in RH \geq 75% and 13 \pm 2°C [A]	Natural carbonation depth (50 mm slice) NDT corrosion monitoring (iCor device)
2 years	Stored in RH \geq 75% and 13 \pm 2°C [A]	Natural carbonation depth (50 mm slice) NDT corrosion monitoring (iCor device)
3 years	Stored in RH \geq 75% and 13 \pm 2°C [A]	Natural carbonation depth (50 mm slice) NDT corrosion monitoring (iCor device)
5 years	Stored in RH \geq 75% and 13 \pm 2°C [A]	Natural carbonation depth (50 mm slice) NDT corrosion monitoring (iCor device)
10 years	Stored in RH \geq 75% and 13 \pm 2°C [TVO]	Natural carbonation depth (50 mm slice) NDT corrosion monitoring (iCor device)
15 years	Stored in RH \geq 75% and 13 \pm 2°C [TVO]	Natural carbonation depth (50 mm slice) NDT corrosion monitoring (iCor device)
20 years	Stored in RH \geq 75% and 13 \pm 2°C [TVO]	Natural carbonation depth (50 mm slice) NDT corrosion monitoring (iCor device)
30 years	Stored in RH \geq 75% and 13 \pm 2°C [TVO]	Natural carbonation depth (50 mm slice) NDT corrosion monitoring (iCor device)

8. NT Build 492 - The rapid chloride permeability (D100 x H200 cylinders), 9 specimens / mixture

Age of concrete	Exposure environment	Action / test
0 – 1d	Cover with plastic sheets	Unmoulding of specimens
28d	Stored in RH \geq 95% and 20 \pm 2°C [A]	28d – initial values are measured / 1 specimens
1 year	Stored in RH \geq 75% and 13 \pm 2°C [A]	1-year measurements / 1 specimen
2 years	Stored in RH \geq 75% and 13 \pm 2°C [A]	2-year measurements / 1 specimen
3 years	Stored in RH \geq 75% and 13 \pm 2°C [A]	3-year measurements / 1 specimen
4 years	Stored in RH \geq 75% and 13 \pm 2°C [A]	4-year measurements / 1 specimen
10 years	Stored in water [TVO]	10-year measurements / 1 specimen
15 years	Stored in water [TVO]	15-year measurements / 1 specimen
20 years	Stored in water [TVO]	20-year measurements / 1 specimen
30 years	Stored in water [TVO]	30-year measurements / 1 specimen

[A] Stored at Aalto

[TVO] Stored at TVO

7.5 Example of the chemical analysis of the ground water at Olkiluoto.

	PVA2		PVA3	average
TDS (mg/L)	1200	-	4000	2600
pH	7.5	-	7.9	7.7
Na (mg/l)	320	-	1100	690
Ca (mg/l)	42	-	260	150
Mg (mg/L)	15	-	71	43
SO ₄ (mg/l)	130	-	320	230
Cl (mg/l)	320	-	2030	1200
HCO ₃ (mg/l)	320	-	240	280
Conductivity (mS/m)	200	-	700	450

7.6 Example of the chemical analysis of the ground water at Loviisa.

Parametri	Yksikkö	Määrittys- raja	LPVA4	LPVA5
pH		2	7,7	7,6
Sähkönjohtavuus	mS/m	0,5	1195	1520
Liuenneiden aineiden kokonaispitoisuus, TDS	mg/l	50	7870	9970
Tiheys	g/ml		1,0036	1,0051
Alkaliteetti	mmol/l	0,02	2,0	2,0
Asiditeetti	mmol/l	0,02	0,23	0,05
Aggressiivinen hiilidioksidipitoisuus	mg CO ₂ /l	2	<2	<2
Kokonaiskovuus	mmol/l	0,05	21,4	28,0
Bikarbonaatti (HCO ₃ ⁻)	mg/l	1,2	120	120
Liennut epäorgaaninen hiili (DIC)	mg/l	0,5	25	22
Liennut haihtumaton orgaaninen hiili (D-NPOC)	mg/l	0,5	1,5	1,0
Strontium	µg/l	10	4622	5984
Natrium	µg/l	60	1700000	2150000
Kalium	µg/l	40	21500	21500
Kalsium	µg/l	100	535000	685000
Magnesium	µg/l	10	200000	265000
Mangaani	µg/l	3	1600	1750
Alumiini	µg/l	10	<10	<10
Barium	µg/l	0,5	40,5	32,0
Rauta	µg/l	50	2300	1300
Fe ²⁺	mg/l	0,02	0,08	1,20
Boori	mg/l	0,05 ⌘	0,21	0,29
Silikaatti	µg/l	20	10393	9812
Kloridi	mg/l	0,3	4000	5250
Bromidi	mg/l	0,4	12,5	15,5
Fluoridi	mg/l	0,2*	<2,0	<2,0
Sulfaatti	mg/l	0,3	470	590
Helposti vapautuva sulfidi	mg/l	0,03	<0,03	<0,03
Fosfaattifosfori, PO ₄ -P	µg P/l	3	<3,0	3
Ammonium, NH ₄	µg/l	6,5	785	830
Ammoniumtyppi, NH ₄ -N	µg N/l	5	610	645

⌘) vaadittu vähimmäismäärittäysraja boorille 100 µg/l eli 0,1 mg/l *) lisätietoja kappaleessa 3.3.5

7.7 Details of the storage salt solutions.

Ions	Molar mass [g/mol]	Na ₂ SO ₄	NaCl	MgCl ₂ ·6H ₂ O	SO ₄ ²⁻	Cl ⁻	Mg ²⁺
Na	22,99	45,98	22,99	-	-	-	-
S	32,065	32,065	-	-	32,065	-	-
O	15,999	63,996	-	95,994	63,996	-	-
Cl	35,453	-	35,453	70,906	-	35,453	-
Mg	24,305	-	-	24,305	-	-	24,305
H	1,0079	-	-	12,0948	-	-	-
Total =		142,04	58,44	203,30	96,06	35,45	24,31

OLKILUOTO - Groundwater simulated solution

Solute	Molar mass of solute, [g/mol]	Ion	Molar mass of ion, [g/mol]	Proposed ion's concentration, [mg/L]	Volume of H ₂ O, [L]	Amount of solute, [g]/1L	Total amount of solute needed, [kg] for 500L solution
Na ₂ SO ₄	142,04	SO ₄ ²⁻	96,06	157,41	1	0,233	0,116
NaCl	58,44	Cl ⁻	35,45	1377	1	2,270	1,135
MgCl ₂ ·6H ₂ O	203,33	Mg ²⁺	24,31	67,5	1	0,565	0,282

LOVIISA - Groundwater simulated solution

Solute	Molar mass of solute, [g/mol]	Ion	Molar mass of ion, [g/mol]	Proposed ion's concentration, [mg/L]	Volume of H ₂ O, [L]	Amount of solute, [g]/1L	Total amount of solute needed, [kg] for 500L solution
Na ₂ SO ₄	142,04	SO ₄ ²⁻	96,06	583	1	0,862	0,431
NaCl	58,44	Cl ⁻	35,45	5100	1	8,407	4,204
MgCl ₂ ·6H ₂ O	203,33	Mg ²⁺	24,31	250	1	2,091	1,046

Exposure calss XA3 - Aggrssive simulated solution

Solute	Molar mass of solute, [g/mol]	Ion	Molar mass of ion, [g/mol]	Proposed ion's concentration, [mg/L]	Volume of H ₂ O, [L]	Amount of solute, [g]/1L	Total amount of solute needed, [kg] for 500L solution
Na ₂ SO ₄	142,04	SO ₄ ²⁻	96,06	6413	1	9,483	4,741
NaCl	58,44	Cl ⁻	35,45	56100	1	92,482	46,241
MgCl ₂ ·6H ₂ O	203,33	Mg ²⁺	24,31	2750	1	23,001	11,501