Nordic Concrete Research – Publ. No. NCR 73 – ISSUE 2/ 2025 – Article 7, pp. 121-138

sciendo

Nordic Concrete Federation

ISSN online 2545-2819
ISSN print 0800-6377

DOI: 10.2478/ncr-2025-0021

Received: Sept.25, 2025
Revision received: Dec. 12, 2025
Accepted: Dec. 15, 2025

Mechanical Properties and Microstructural Analysis of Concrete Designed for Low and Intermediate Level Nuclear Waste Repositories

Fahim Al-Neshawy
D.Sc. (Tech.), Staff Scientist
Aalto University School of Engineering,
Department of Civil Engineering
Rakentajanaukio 4 A, 02150 Espoo, Finland
fahim.al-neshawy@aalto.fi

Abobaker Ba Ragaa
M.Sc., Doctoral Researcher
Aalto University School of Engineering
Department of Civil Engineering
Rakentajanaukio 4 A, 02150 Espoo, Finland
abobaker.baragaa@aalto.fi

ABSTRACT
This study investigates the mechanical properties and microstructural characteristics of five concrete mixtures specifically designed for application in low and intermediate-level nuclear waste repositories. These repositories necessitate construction materials that not only offer durability and strength but also maintain a long service-life under the underground environmental conditions over extended period. The concrete mix design was formulated with a focus on optimizing durability and sustainability, incorporating supplementary cementitious materials such as silica fume and slag to enhance the concrete durability. Comprehensive microstructural analyses using petrographic analysis and Micro x-ray fluorescence (μ-XRF) provided insights into

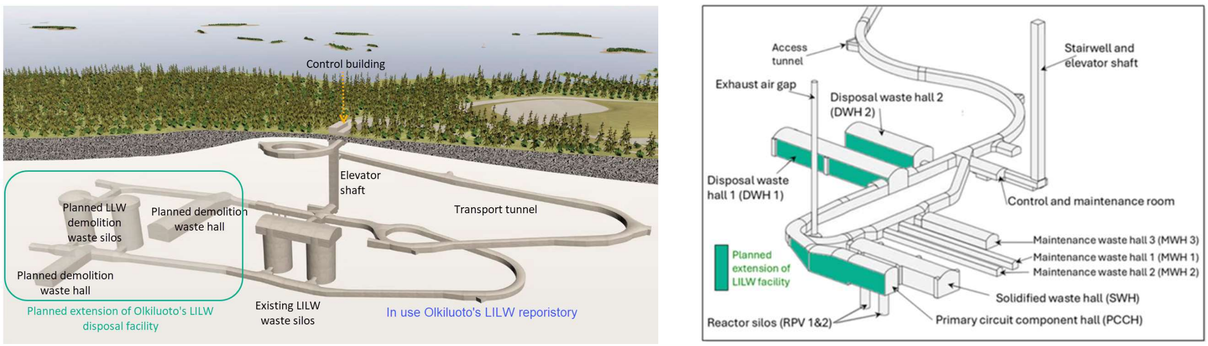
the hydrate phases and pore structure evolution, revealing that the concrete exhibits dense microstructures and low permeability, essential for reducing leaching and sulfate attack risks. Mechanical testing demonstrated high compressive strength and modulus of elasticity, showing the suitability of concrete mixtures for structural components in repository environment. Overall, the findings highlight the potential of this designed concrete mixture in meeting the demands of low and intermediate level nuclear waste storage, ensuring safety and stability while also supporting environmental sustainability using eco-friendly materials.

Key words: Mix Design, Mineral Additives, Testing, Nuclear Waste, Durability.

1. INTRODUCTION

1.1 Low- and intermediate level nuclear waste repositories in Finland

Low and intermediate level waste is produced at nuclear facilities, particularly nuclear power plants, during the processing of radioactive liquids and gases, as well as during repair and maintenance activities within controlled areas, among other operations. This category of waste is also known as operational waste. Most of the operational waste contains radioactive materials at levels that require it to be processed, stored, and disposed in accordance with radiation protection standards [1]. Currently, Finland operates two repositories for low- and intermediate-level waste (LILW) located near the Olkiluoto and Loviisa nuclear power plants (NPP), as shown in Figure 1. Both repositories are planned to be extended to contain the decommissioning waste generated during the dismantling of the plant units. The expansion is planned to be completed in the late 2050s, prior to the decommissioning of the power plant [2] [3].



(a) (b)

Figure 1 – Operating and planned extension of (a) Olkiluoto and (b) Loviisa LILW nuclear waste repositories [3], [4], [5].

1.2 Cement-based reinforced concrete for LILW repositories

The use of cement-based materials, particularly reinforced concrete, for constructing engineering barriers at Low and Intermediate Level Waste (LILW) repositories presents significant challenges due to the multi-century target service life. These challenges encompass aspects of design, material behavior, construction, inspection, and aging assessment. Although durability is a critical property emphasized in modern concrete design standards, existing guidelines generally pertain to structures with a target service life of less than 100 years. Consequently, for LILW repositories, the fundamental principle to adopt is "defense in depth." This approach involves multiple barriers, robust design with inherent structural redundancy and material property redundancy, rigorous inspection protocols, comprehensive monitoring systems, condition assessment strategies, and retrofit options [6].

Cement-based materials are widely used in low- and intermediate-level radioactive waste (L/ILW) management. These cementitious materials can serve as hydraulic and transport barriers, and most importantly, they are designed to create a chemical environment that minimizes steel corrosion, slows waste degradation, and consequently reduces the release and migration of radionuclides. The service life of cement-based materials can vary significantly depending on their intended function. For instance, cementitious tunnel supports may only be required during the construction and operational phases of a repository, whereas cement-based materials intended as barriers for radionuclide retention and chemical stability must maintain their properties over extended periods [7].

Concrete requirements for nuclear waste repositories focus on extreme long-term durability, low leachability (low pH), high structural integrity (strength), and radiation shielding, using special low-pH mixes with supplementary binders (slag, fly ash, silica fume) to immobilize radionuclides, inhibit corrosion, and create impermeable barriers for thousands of years, far beyond normal construction standards [8].

1.3 Degradation of concrete in low- and intermediate level waste repositories

Reinforced concrete structures are used in the technical barriers of final repositories for low and intermediate active nuclear wastes. The required service life for technical barriers is, however, much longer than the present experiences from reinforced concrete structures [9]. The concrete structures in the low and intermediate level waste (LILW) repositories are subjected to two completely different environmental conditions:

1) The operational phase covers the period before the closure of caverns, where dank air (relative humidity 70%, temperature around 12 °C) with carbon dioxide content (500–600 ppm) surrounds the facilities.
2) The post-closure period when the caverns will be filled by cool (temperature around 12 °C) and saline brackish groundwater. Slightly alkaline (pH 7–9) groundwater contains moderate amounts of ions harmful for concrete and the steel reinforcement such as sulphate and chloride ions [10].

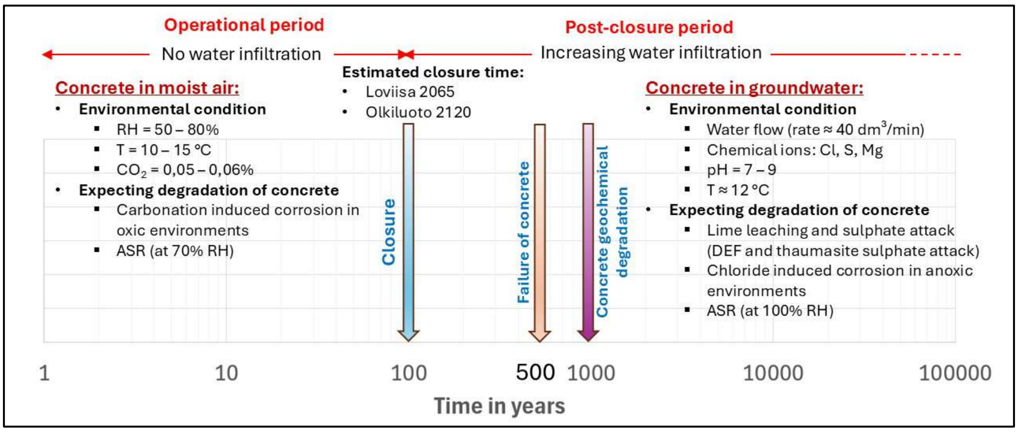


Figure 2 – Typical environmental conditions and concrete degradation mechanisms in relation to the timescale in LILW nuclear waste repositories [10].

As presented in Figure 2, reinforced concrete structures are subjected to various deterioration mechanisms, such as carbonation induced corrosion, chloride induced corrosion in anoxic environment, conventional and thaumasite sulfate attacks, portlandite leaching and alkali-silica reaction.

1.4 Research objectives and expected results

The objective of this research is to enhance our understanding of the long-term performance of concrete used in underground repositories. The research work in this study is divided into three tasks focusing on:

1) Mix design and testing of conventional concretes
2) Mix design and testing of concretes containing environmentally friendly components
3) Durability testing on concrete samples

The concrete mixtures are based on the new cementitious materials manufacturing technology and the recent concrete characteristic properties. Also, the use of new components for LILW repository concrete by partial replacement of cement clinker with supplementary cementitious materials (SCM). Due to the high price of silica fume and the sharp decrease of fly ash, the ground granulated blast furnace slag seems the most promising SCM for the selected concrete.

By testing the durability of concrete, construction professionals can gain valuable insights into its resistance to different deterioration factors affecting the reinforced concrete structures in the low- and intermediate-level radioactive waste repositories. This information enables them to select the right mix design, optimize construction techniques, and make informed decisions regarding maintenance and repair strategies. Ultimately, concrete durability testing helps enhance construction efficiency by reducing the risk of premature deterioration, minimizing costly repairs, and ensuring the longevity of structures.

2. EXPERIMENTAL PROGRAM

The initiation of the experimental program was carried out during March 2024. The experimental program is based on five concrete mixtures using different binders. A 100 different specimens per concrete mixture were prepared for hardened concrete tests. A total of 500 concrete specimens were stored in three different salt solutions, under water and in relative humidity of about 75 % RH.

2.1 Concrete mix design

The mix design of the concrete was based on the C40/50 compressive strength class, S3 consistency class and maximum water to binder ration of 0.45 by weight. The target air content of the concrete mixtures was assumed to be 1.5%. MasterGlenium SKY 600 superplasticizers, (BASF) was used to enhance the workability of the concrete mixtures.

Table 1 – The mix design on concrete.

Concrete mixtures	SR	SR-SI	KA	KB	KB-SI
Cement amount (kg/m³)	375	306	375	375	306
Silica fume amount (kg/m³)		34			34
Lahnajärvi 0/8 mm (kg/m³) - dry	1165	1177	1165	1165	1178
Inkoo 8/16 mm (kg/m³) - dry	703	711	703	703	711
Water (kg/m³)	165	165	165	165	165
MasterGlenium Sky 600 (kg/m³)	4.13	4.24	3.75	3.00	2.72
Density (kg/m³)	2409	2394	2409	2409	2394
Water to binder ratio	0.44	0.49	0.44	0.44	0.49

The binders [11] used in the concrete mixtures were:

1) SR – Sulfate resistance cement – CEM I 42.5 N SR3
2) SR-SI – Sulfate resistance cement – CEM I 42.5 N SR3 and 10% of binder weight of Elkem Microsilica – Grade 920
3) KA – Blast furnace cement – CEM III/A 52,5 L
4) KB – Blast furnace cement – CEM III/B 42,5 L – LH/SR
5) KB-SI – Blast furnace cement – CEM III/B 42,5 L – LH/SR and 10% of binder weight of Elkem Microsilica – Grade 920

2.2 Preparation of concrete test specimens

Preparation of hardened concrete specimens were performed according to the European standard “EN 12390-1” [12]. 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.

Figure 3 – Casting of the test specimens for each concrete mixture.

The following test specimens were cast from each concrete mixture as shown in Figure 3.

- Cylinder specimens Φ150 mm x H300 mm for compressive strength test.
- Cube specimens 150x150x150 mm for compressive strength test.
- Cylinders specimens Φ 100 mm x H200 mm for splitting tensile strength, and modulus of elsticity in compression and rapid chloride migration coefficient tests.
- Prism specimens 100x100x500 mm for shrinkage, accelerated carbonation, Micro X-ray Fluorescence (μXRF) and the microstructure (petrographic) analysis of concrete.
- Special moulds for corrosion measurements.
- Heat monitoring Box + thermocouple + logger.

2.3 Storing of concrete test specimens

Five storage conditions representing the ground water in Olkiluoto, Loviisa, exposure class XA3 and the environmental conditions at the operation phase of the repository were used as shown in Figure 4.

Figure 4 – Storage location of the specimens at the research tunnel of Aalto University.

1) A brine container simulating the groundwater surrounding the Olkiluoto repository.
2) A brine container simulating the groundwater surrounding the Loviisa repository.
3) A brine container simulating a chemical attack of exposure class XA3.

4) Moist air container (75 % RH): Saturated NaCl solution for producing 75 % RH containing 40 – 45 g NaCl/100 ml water content.
5) A tap water container for storage of the mechanical and durability testing specimens.

The brines' conditions for the storage of the test specimens are presented in Table 2. The temperature at the storage location (Aalto University underground research tunnel) where the temperature is 15±2°C and relative humidity varied between 65 – 75%.

Table 2 – The simulation of the environmental conditions during the operation phase.

Solution code	Chemical	Proposed aggressive component (mg/l)	Measured aggressive component (mg/l) 16.10.2024
Olkiluoto salt solution	Na2SO4	$SO4^{2+}$ = 160	210
	NaCl	Cl^- = 1400	1350
	MgCl2·6H2O	Mg^{2+} = 75	63,4
Loviisa salt solution	Na2SO4	$SO4^{2+}$ = 576	510
	NaCl	Cl^- = 5040	4130
	MgCl2·6H2O	Mg^{2+} = 270	242
XA3 salt solution	Na2SO4	$SO4^{2+}$ = 6400	6320
	NaCl	Cl^- = 56000	52000
	MgCl2·6H2O	Mg^{2+} = 3000	2770

3. RESULTS AND ANALYSIS

3.1 Properties of fresh concrete

All tests of fresh concrete included in this report were executed in the laboratory facilities of the Department of Civil Engineering, Aalto University. The fresh concrete tests were carried out in accordance with the standards for testing fresh concrete, SFS-EN 12350 [13]. The tests performed in this investigation were slump, density and air content, which corresponds to parts 2, 6, and 7, respectively, in the standard EN 12350.

Table 3 – Fresh concrete test results.

Mix-ID	SR	SR-SI	KA	KB	KB-SI
Immediately (10 minutes) after concrete delivery					
Slump, [mm]	250	170	170	240	150
Measured air content (%)	1,6	3,4	3,5	1,9	2,8
Measured density (kg/m³)	2320	2290	2310	2360	2320
One hour after concrete delivery					
Slump, [mm]	250	155	80	170	100
Measured air content (%)	1,3	2,8	3,0	1,7	3,0
Measured density (kg/m³)	2340	2360	2300	2370	2270

3.2 Mechanical properties of concrete

Performance of concrete is evaluated from mechanical properties which include compressive strength, splitting tensile strength, and modulus of elasticity.

3.2.1 Compressive strength of hardened concrete

The compressive strength of concrete mixes were tested at the age of 28, and 91, 365 days. The compressive strength test was performed on cylinder specimens with diameter of 150 mm and height of 300 mm in accordance with standard EN 12390-3 [14]. After removal the concrete specimens from moulds, they were stored in chamber at (20 ± 2) °C and relative humidity ≥ 95 % until tested in accordance with the procedure given in the standard.

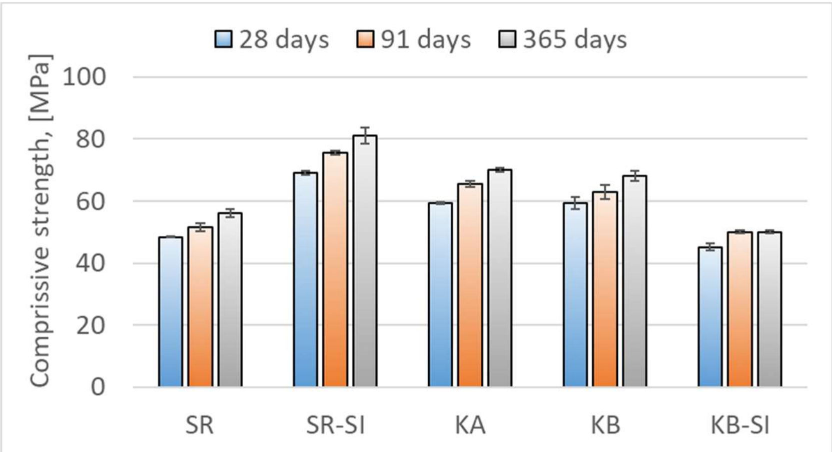


Figure 5 – Development of compressive strength with time for different concrete mixes.

As shown in Figure 5, the concrete mixtures showed a similar strength development profile. At the curing age of 28 days, the concrete specimens achieved over 100% of the 28-day compressive strength (C40/45). The addition of 10 % silica fume by binder weight to the SR-SI (CEM I 42.5 N SR3 and 10% silica fume) mix increased the 28, 91 and 365 days compressive strength compared to the SR mix. The compressive strength of the KB-SI mix (CEM III/B 42,5 L – LH/SR and 10 % silica fume) decreased at 28, 91 and 365 days compared to the KB mix, which could be because the air content of the mix. The air content of KB-SI was 3,0 % and the KB mix had 1,7% air content. It is also noticed that compressive strength of KA mix (CEM III/A 52,5 L cement included 40 – 64 % slag) and the KB mix (CEM III/B 42,5 L – LH/SR cement including 66 – 80 % slag) were almost the same, which could be because the air content of the mix. The air content of KA was 3,0 % and the KB mix had 1,7% air content.

3.2.2 Splitting tensile strength of hardened concrete

The splitting tensile strength test of concrete mixes was carried out at the age of 91 and 365 days. The splitting tensile strength test was performed on cylinder specimens with diameter of 100 mm and height of 200 mm in accordance with standard SFS-EN 12390-6 [15]. After removal the concrete specimens from moulds, they were stored in chamber at (20 ± 2) °C and relative humidity ≥ 95 % until tested in accordance with the procedure given in standard. Results of the splitting tensile strength of cylindrical concrete specimens tested at 91 and 365 days are presented in Figure 6.

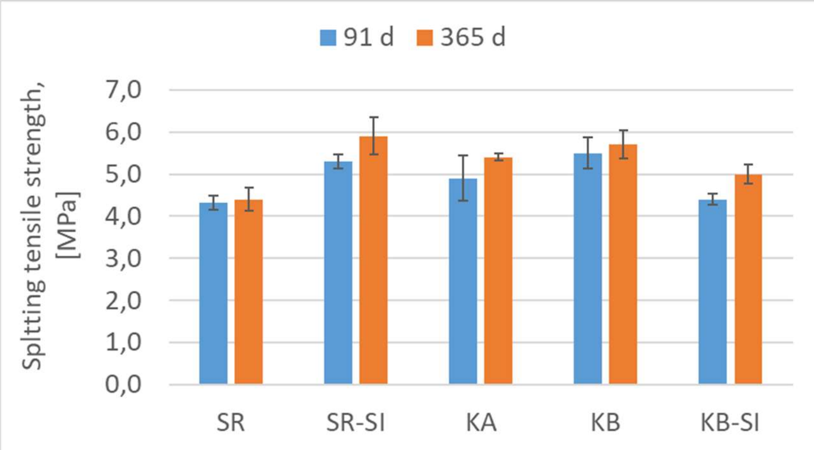


Figure 6 – Development of splitting tensile strength with time for different concrete mixes.

The addition of 10 % silica fume by binder weight to the concrete mixtures affects the splitting tensile strength in the same way as the compressive strength. The ratio of splitting tensile strength to compressive strength varied between 7.0 % to 8.8 % at 28 days, and from 7.3 % to 10.8 % at 365 days.

3.2.3 Modulus of elasticity in compression of hardened concrete

There are two types of elastic modulus.

1) The static modulus is measured by plotting the deformation of a cylinder under an applied load, usually 30–40 % of the ultimate load. Most design codes include methods to estimate the static modulus from the compressive strength, but these may not work for unusual concrete, such as very high strength mixes. EN 12390-13 [16] standard for determination of secant modulus of elasticity in compression is here used to measure the modulus of elasticity of concrete.
2) The dynamic modulus is determined by resonance methods or by the measurement of ultrasonic pulse velocity (UPV). Ultrasonic pulse velocity (UPV) of concrete specimens at the age of about 300 days was measured. In these experiments, cube specimens with a size of 150×150×150 mm were used. Three specimens from each concrete mixture were tested and mean values were calculated.

$$E_d[GPa] = \rho * V^2 * \left(\frac{(1+\nu)(1-2\nu)}{(1-\nu)}\right) \quad (1)$$

where E_d is the dynamic (Young's) modulus of elasticity (GPa), V is the ultrasonic pulse velocity (km/s), ρ is the density of concrete (kg/m^3) and ν is the Poisson's ratio. According to EN1992-1-1 [17] the value of Poisson's ratio ν may be taken equal to ν = 0.2 for uncracked concrete and ν = 0 for cracked concrete.

The static modulus of elasticity (E_c) measures concrete's stiffness under slow, sustained loads (like deflection), determined by destructive stress-strain tests, while the dynamic modulus (E_d)

measures it via vibrations (ultrasound/resonance), giving higher values because it avoids creep and reflects concrete's stiffness at very small strains, typically 20-40 % higher than static, varying with concrete quality, age, and type (normal vs. high strength) [18].

The two test procedures did not give the same measured value of the modulus. Static modulus is the value usually quoted by concrete producers [19], [20], [21]. The average static modulus of elasticity (E_c) of the various concrete specimens was approximately 40 GPa at 91 days and increased to 43 GPa after 365 days. The dynamic modulus of elasticity at age of 300 days was approximately 10 to 25% higher than the static modulus of elasticity at 365 days. Overall, the average dynamic modulus of elasticity for the different concrete specimens was around 52 GPa at 300 days. The results for both the static modulus of elasticity and dynamic modulus of elasticity are shown in Figure 7.

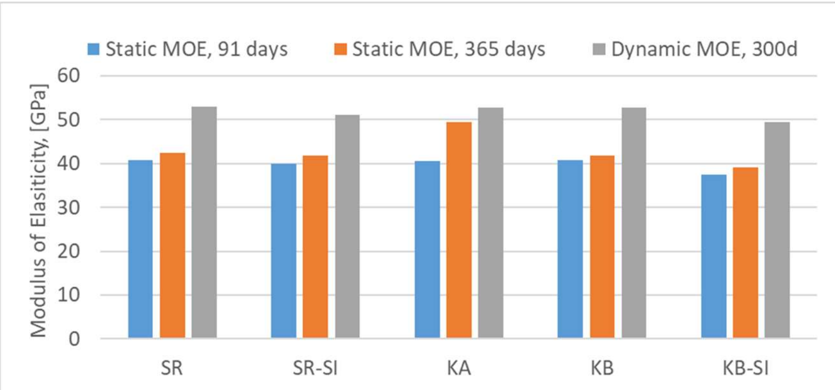


Figure 7 – Modulus of elasticity of concrete mixes.

3.3 Concrete durability testing

Reinforced concrete durability issues can be caused by many different factors that occur during the life of the concrete structures. In this research we performed the following durability tests: (i) drying shrinkage, (ii) accelerated carbonation tests and (iii) chemical analysis of the sulphate, chloride and magnesium ions using Micro XRF and (iv) microstructural analysis using petrographic thin-section analysis. In this paper, we present only the drying shrinkage and the accelerated carbonation test results because the chemical and petrographic analysis are still undergoing.

3.3.1 Drying shrinkage of concrete

The dry shrinkage of concrete was measured according to the EN 12390-16 [22] on two prisms with designated size of 100x100x500 [mm]. Specimens were stored in a testing chamber with relative humidity of 65% RH and temperature of 20 ± 2°C. As shown in Figure 8, it is evident that the KB-SI-MIX specimens had shrunk significantly more than the other specimens. The results indicate that the addition of silica fume has a little adverse effect on the dry shrinkage property of concrete composites. With the increase of silica fume content, the dry shrinkage strain is increasing.

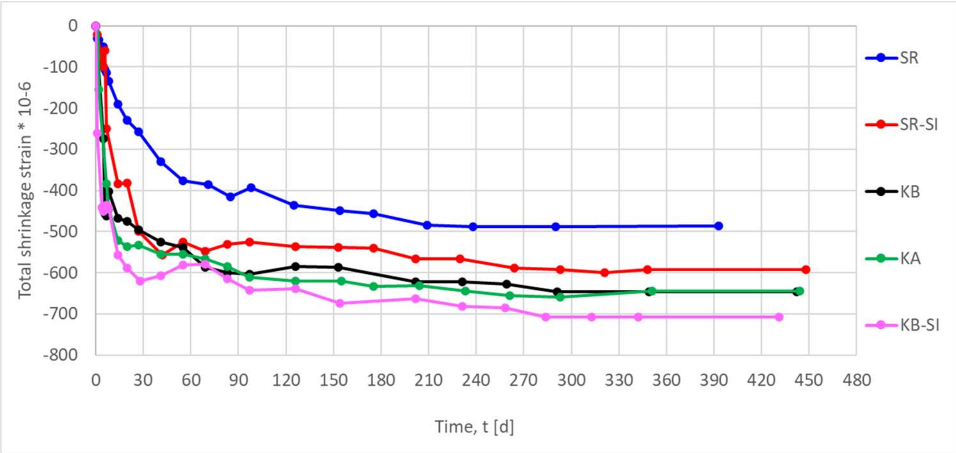


Figure 8 – Mean total dry shrinkage strain expressed in mm/m.

3.3.2 Accelerated carbonation

The accelerated carbonation test results were obtained by measuring the carbonation depth of an approximately 50 mm wide part of a prism of designated dimensions of 100x100x500 mm. The average temperature, CO_2 content and relative humidity in the chamber were 22.0 ^{o}C, 3.0 % and 68.7 %, respectively. As shown in Figure 9, the concrete mixtures with sulphate resistance cement (CEM I 42.5 N SR3) had the lowest (less than 12 mm) carbonation depth while the concrete mixtures with blast furnace cement with addition of silica fume (CEM III/B 42,5 L – LH/SR and 10% of binder weight of Elkem Microsilica) had the highest carbonation depth (36 mm) after 365 days in the accelerated carbonation chamber.

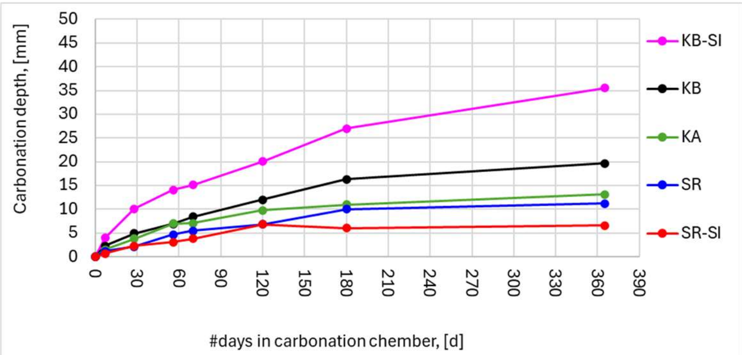


Figure 9 – Measured carbonation depth based on the accelerated carbonation method.

3.3.3 Non-destructive tests in the detection of corrosion

Special reinforced concrete specimens, presented in Figure 10, were prepared for monitoring the corrosion potential of the reinforcement steel. Hot rolled reinforcing steel bars B500B with diameter of Ø 12 mm were used. Concrete specimens were stored at air environmental conditions (20 ^{o}C, 65%RH) to dry for 28 days. Whereafter, the specimens were placed into the container with environmental condition of 75 % relative humidity and about 15°C temperature.

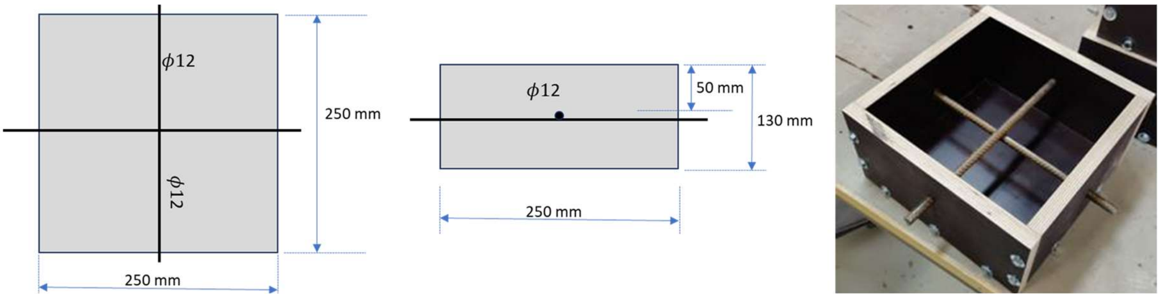


Figure 10 – Molds for the corrosion monitoring specimens.

For evaluation the corrosion activities in the concrete specimens, the corrosion potential, the electrical resistivity of concrete and the corrosion rate were measured using the iCOR device provided by Giatec Scientific [23]. 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 makes it possible 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. 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 a rebar in the concrete. The results of corrosion potential, electrical resistivity of concrete and corrosion rate are presented in Table 4.

Table 4 – Statistical analysis of the measurement results of corrosion activities.

Mix code	**Corrosion potential, (mV/CSE)**			**Average concrete resistivity, (Ω.m)**			**Average corrosion rate, (µA/cm²)**		
	Average	Standard deviation	CoV, (%)	Average	Standard deviation	CoV, (%)	Average	Standard deviation	CoV, (%)
SR	-73	17,4	23,7	183	0,4	31	1,4	0,4	31
SR-SI	-36	8,5	23,9	1025	0,2	58	0,4	0,2	58
KA	-37	6,5	17,3	961	0,6	51	1,3	0,6	51
KB	24	4,4	18,9	1715	0,3	37	0,8	0,3	37
KB-Si	210	24,7	11,8						

The non-destructive tests (NDT) results in the detection of the reinforcement steel corrosion show that:

- The corrosion potential values are higher than -200 (mV/CSE), which mean that there is less than 10% probability of steel corrosion activity according to the limit values presented in Table 5a.
- The electrical resistivity of the SR varies between 164 to 201 (Ω.m), which indicate a high resistance of concrete to the steel corrosion. It is also noticed that the addition of silica fume increases the resistivity of concrete as presented for SR-SI and KB-SI mixtures.
- The corrosion rate results show that the average of corrosion rate was 0,4 and 0,8 (µA/cm²) for mixtures SR-SI and KB respectively, which means there was no corrosion risk expected for these mixtures. The other mixtures had an average corrosion rate higher than 1,0 (µA/cm²) which means that corrosion damage is possible in 10 – 15 years for these concrete mixes.

Table 5 – Corrosion evaluation criteria and limit values based on iCor device without sensor control [24], [25].

Corrosion potential	Potential value, (mV/CSE)	> -200	-200 to -350	< -350	
	Probability of corrosion activity	Less than 10%	Uncertain	More than 90%	
Resistivity of concrete	Resistivity (Ω.m)	> 200	100 to 200	50 to 100	< 50
	Classification	Ver high	High	Moderate	Low
Corrosion rate	Corrosion Rate (μA/Cm²)	< 1,0	1,0 to 3,0	3,0 to 10,0	> 10,0
	Corrosion rate classification	Passive/Low	Moderate	High	Severe
	Severity of damage	No corrosion damage expected	Damage possible in 10 – 15 years	Damage expected in 2 – 10 years	Damage expected in 2 years or less

3.3.4 Sulfate, Magnesium and Chloride contents in concrete

The μ-XRF testing has been performed to determine the quantity of both sulfate and magnesium ions in the concrete samples. The initial average concentration of magnesium and sulfate ions by weight percentage of concrete is presented in Figure 11.

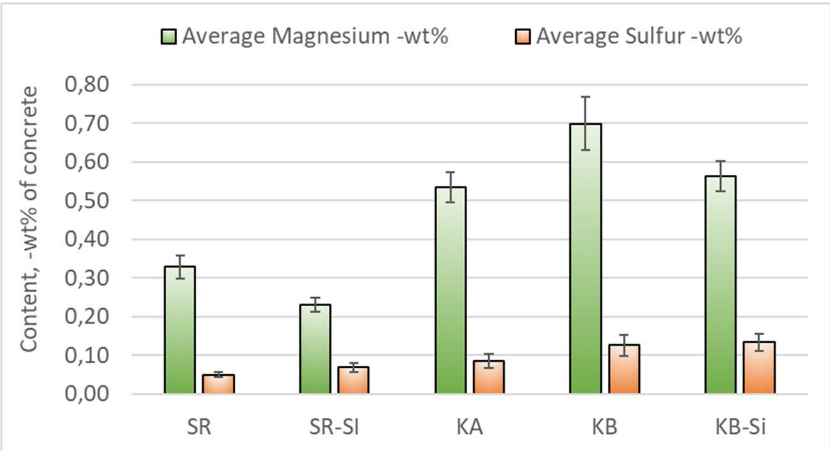


Figure 11 – Average initial concentration of magnesium and sulfate by weight -% of concrete.

The average values of the sulphate content varied between 0,05 to 0,13 % of concrete. The minimum sulphate concentration was found in the concrete mixture produced with the CEM I sulphate resistance cement and higher sulphate content was found in the concrete mixture produced by CEM III/B with addition of 10 % silica fume by weight of the binder. The highest magnesium content was found in the concrete mixtures produced by slag cements (KA, KB and KB-SI). The lowest magnesium content was found in the concrete mixtures produced by the CEM I sulphate resistance cement with addition of 10 % silica fume by weight of the binder.

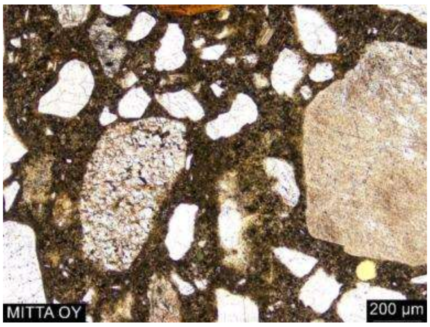
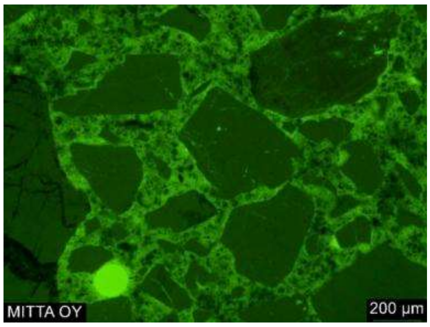
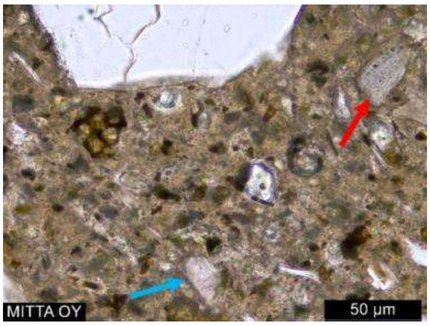
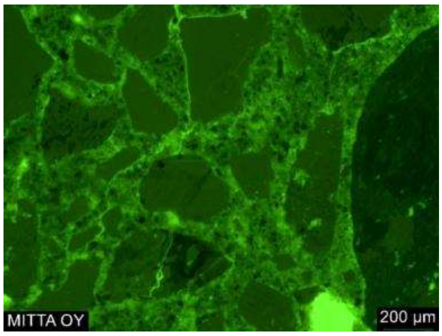
The chloride content was measured using the potentiometric titration method of standard EN 14629:2007 [26], using powdered samples which were drilled from the concrete prism specimens. The specimens were prepared and stored in a conditioning room of a constant RH of 65 % and a temperature of 20 ±2 °C before drilling the powdered samples. The results are reported as weight percentages of the dry weight of the concrete sample. The chloride content in the concrete at a depth of 0–5 mm for all mixtures was less than 0.01% by weight, which is below the detection limit.

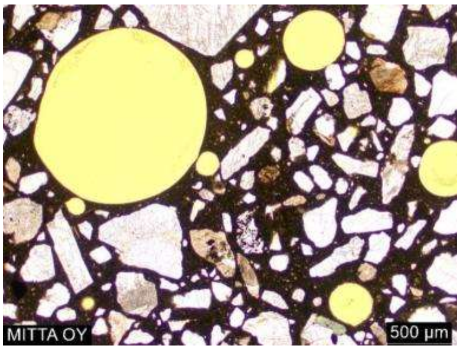
3.3.5 Petrographic analysis of hardened concrete

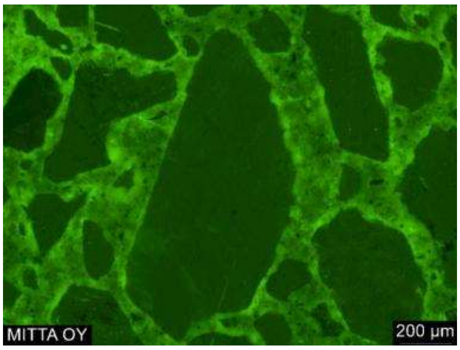
The concrete samples were extracted from 100×100×500 mm prism specimens at 28 days of age. Prior to cutting, the specimens were removed from their molds and stored in a chamber maintained at (20 ± 2) °C with a relative humidity of at least 95%. After cutting, the samples were wrapped in plastic sheets and kept in a chamber at (20 ± 2) °C with a relative humidity of at least 65% until the thin sections were prepared for petrographic analysis. The preparation of the thin sections and the petrographic analysis were carried out by a third-party laboratory.

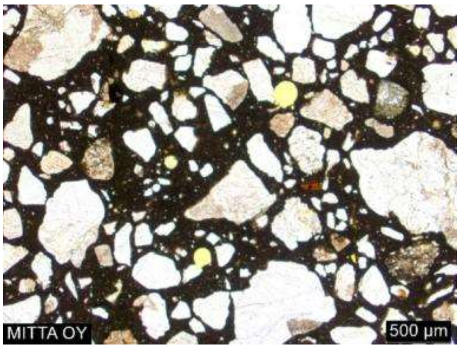
The petrographic analysis was done according to the ASTMC856/C856M-20 standard [27]. The quality evaluation of the concrete is based on the observations of e.g. homogeneity of the paste, water/cement-ratio, degree of hydration, quality, segregation, size and shape of aggregates, aggregate-paste adhesion, early-stage cracking, water separation, and drying shrinkage. The condition evaluation of the concrete is based on the observations of e.g. aggregate cracking related to deterioration, paste alteration, carbonation, secondary deposits, and cracking. Examples of the petrographic evaluation of the concrete mixtures are presented in Table 6.

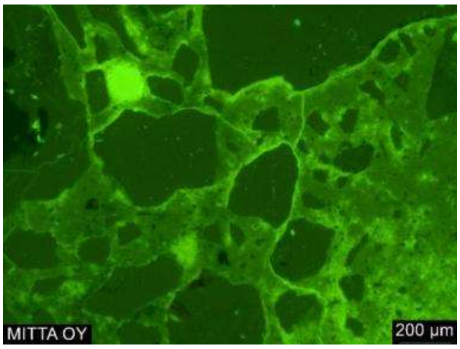
Table 6 – Examples of the petrographic evaluation of different concrete mixtures.

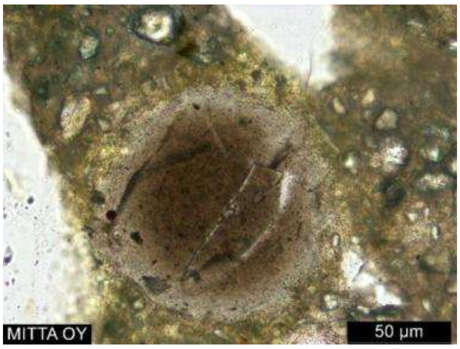
Concrete	Plane Polarized Light (PPL)	Ultraviolet Light (UVL)
SR	 The microporosity of the paste is slightly heterogenous.	 The paste shows very weak microcracking
SR-SI	 The paste contains Portland cement clinker, silica fume lumps (red arrow) and limestone filler (blue arrow).	 The paste shows weak microcracking

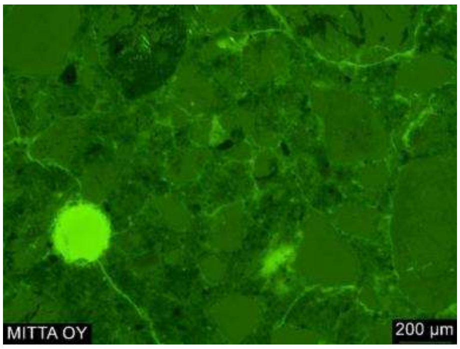
<table>
<tr><td>KA</td><td>

The amount of air voids is moderate</td><td>

The paste shows hardly any microcracking</td></tr>
<tr><td>KB</td><td>

The amount of air voids is low</td><td>

Weak, unoriented microcracking</td></tr>
<tr><td>KB-SI</td><td>

There are also silica fume lumps in the paste</td><td>

Weak microcracking in the paste</td></tr>
</table>

The petrographic examination of thin sections of different concrete mixtures indicated the following observations:

- All the samples are in normal condition, and no distinct deterioration was detected.
- The aggregate consists mostly of crushed granitoids, a few sandstones and amphibolites. Also, smaller silicate mineral grains were observed. The quality of the aggregate is normal.
- Sporadic adhesion cracks and air voids were observed between the aggregate and paste within most of the samples, but the adhesion of the aggregates is tight in the SR-SI sample.
- The grain size of the Portland cement clinker varies from fine to coarse. The composition of the paste appears to be different in every sample, which all contain slag and lime filler, but the amount of slag varies and appears to be the highest in the sample KB-SI. Silica fume occurs in the samples KB-SI and SR-SI, and especially as quite large lumps in the sample KB-SI. The microstructure of the paste is mostly homogenous, the microporosity is mostly quite low. There is only a diminutive carbonation near the cut surface, and it is most likely formed after cutting the cubes.

- Secondary ettringite related to water exposure was not observed.
- Calcium hydroxide crystals were observed in the smallest air voids in the sample KA.
- Unoriented microcracking was observed in all the samples. The intensity of the cracking is mostly weak, in the samples KA and SR are almost non-existent. The cracking is most likely caused by shrinkage.
- No deterioration was observed in any of the samples.

SUMMARY AND CONCULSIONS

The aim of this research was to investigate the properties of hardened concrete for acquisition of real data on long-term performance of the reinforced concrete over 30 years (2024 – 2054). This paper presents the experimental results of mechanical properties and durability studies conducted on concrete composite containing different cement types and addition of silica fume.
The performance of concrete is evaluated from mechanical properties which include compressive strength, splitting tensile strength, and modulus of elasticity.

Concrete and reinforcement durability issues can be caused by many different factors that occur during the life of the concrete. In this research we performed the following durability tests: (i) drying shrinkage, (ii) accelerated carbonation tests and (iii) chemical analysis of the sulphate, chloride and magnesium ions using Micro XRF and (iv) microstructural analysis using petrographic thin-section analysis.

The results indicate that the use of sulphate resistance cement with addition of silica fume enhances the mechanical properties of concrete as compressive strength, splitting tensile strength and modulus of elasticity. Addition of silica fume has an adverse effect on the drying shrinkage and carbonation property of concrete composites.

The following conclusions can be drawn from the experimental results:

- The use of sulphate resistance cement (CEM I 42.5 N SR3) with addition of silica fume enhances the mechanical properties of concrete as compressive strength, splitting tensile strength and modulus of elasticity compared to concrete with only sulphate resistance cement.
- The lowest mechanical properties were obtained in concrete mixtures using the blast furnace cement CEM III/B 42,5 L – LH/SR and 10% of binder weight of Elkem Microsilica.
- Addition of silica fume has an adverse effect on the drying shrinkage property of concrete composite. The dry shrinkage strain in the concretes containing silica fume was more than that in the concrete without silica fume.
- Presence of silica fume in concrete composites increases the carbonation depth considerably in concrete mixtures using the blast furnace cement CEM III/B 42,5 L – LH/SR and 10 % of binder weight of Elkem Microsilica.
- The addition of silica fume can improve the carbonation resistance of the concrete composite using sulphate resistance cement and 10% silica fume.

REFERENCES

1. STUK: "Predisposal management of low and intermediate level nuclear waste and decommissioning of a nuclear facility". Radiation and Nuclear Safety Authority of Finland. Helsinki, 2019.
2. Fortum Oy: "Finnish Government grants operating licence for Fortum's final disposal facility for Loviisa nuclear power plant's low- and intermediate-level radioactive waste". Fortum corporation press release 30 March 2023.
3. Pitkäoja J: "Long-term safety assessment for disposal of VTT's decommissioning wastes in Loviisa LILW repository" .University of Jyväskylä, Jyväskylä, Finland 2019.
4. Kumpula L, Huhtanen I, Palander S, Ylä-Mella M, and Kuhmonen V: " Management of spent nuclear fuel and radioactive waste in Finland". *Publications* of the Ministry of Economic Affairs and Employment, Helsinki, Finland, 2022. (In Finnish).
5. Saanio T: "Spent fuel and radioactive waste management in Finland". Nuclear Espana – *Journal of Spanish nuclear professionals*, October. 2025.
6. Žarnič R, Bosiljkov V B, and Giacomelli M: "Safety Evaluation Methodology of Engineering Barriers at Repository for Low and Intermediate Level Radioactive Waste". *Proceedings*, Nuclear energy for new Europe, Portoroz, Sloveni. 11 – 13 September, 2007.
7. Ma B, Provis J L, Wang D, and Kosakowski G: "The essential role of cement-based materials in a radioactive waste repository". *Materials Sustainability* , Vol. 2, No. 1, 2024, pp. 1–8.
8. Holt E, Leivo M, and Vehmas T: "Low-pH concrete developed for tunnel and plugs used in nuclear waste containment". *Proceedings*, Concrete Innovation Conference 2014, CIC2014, Oslo, Norway, 2014.
9. Ba Ragaa A, Al-Neshawy F, Jolis E M, Kuva J, and Punkki J: "Long-term durability assessment of concrete in Low and Intermediate Level Waste repositories". *Proceedings*, 27th International Conference on Structural Mechanics In Reactor Technology - SMiRT 27 Yokohama, Japan, March 3-8, 2024.
10. Al-Neshawy F and Punkki J: "Comprehensive state-of-the-art report for long-term behaviour of concrete structures in low and intermediate level radioactive waste (LILW) repository environment". *Report,* Department of Civil Engineering, Aalto University, 2022.
11. Finnsementti Oy: "Cement types according to SFS-EN 197-1". Finnsementti Oy, Espoo, Finland.
12. EN 12390-1 (2019): "Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds". CEN- European Committee for Standardization, Brussels, Belgium.
13. EN 12390-7 (2019): "Testing hardened concrete. Part 7: Density of hardened concrete". CEN- European Committee for Standardization, Brussels, Belgium.
14. EN 12390-3 (2001): "Testing hardened concrete - Part 3: Compressive strength of test specimens". CEN- European Committee for Standardization, Brussels, Belgium.
15. EN 12390-6 (2000): "Testing hardened concrete - Part 6 - Tensile splitting strength of test specimens". CEN- European Committee for Standardization, Brussels, Belgium.

16. EN 12390-13 (2013): "Testing hardened concrete - Part 13: Determination of secant modulus of elasticity in compression". CEN- European Committee for Standardization, Brussels, Belgium.
17. EN1992-1-1 (2015): "Eurocode 2*:* Design of concrete structures. Part 1-1: General rules and rules for buildings". CEN- European Committee for Standardization, Brussels, Belgium.
18. Popovics J S, Zemajtis J, and Shkolnik I: "A Study of Static and Dynamic Modulus of Elasticity of Concrete". *ACI-CRC Final Report*, October 2008.
19. Bamforth P, Chisholm D, Gibbs J, and Harrison T: "Properties of Concrete for use in Eurocode 2 – How to optimise the engineering properties of concrete in design to Eurocode 2". A cement and concrete industry publication, The Concrete Center, 2008.
20. Salam M and Al-Amawee A H: "The Ratio between Static and Dynamic Modulus of Elasticity in Normal and High Strength Concrete". Journal of Engineering and Development, Vol. 10, No. 2, 2006.
21. Chavhan P P and Student M E: "Correlation of Static and Dynamic modulus of Elasticity for Different SCC Mixes". *International Journal on Recent and Innovation Trends in Computing and Communicatio*n, Vol. 3, No. 7, 2015.
22. EN 12390-16 (2019): "Testing hardened concrete - Part 16: Determination of the shrinkage of concrete". CEN- European Committee for Standardization, Brussels, Belgium.
23. Giatec Scientific Inc.: "Concrete Corrosion Assessment Device."
24. Frølund T, Poulsen E, and Eng C: "Rebar Corrosion Rate Measurements for Service Life Estimates". *Proceedings*, ACI Fall Convention 2000, Toronto, Canada, Committee 365 "Practical Application of Service Life Models".
25. Giatec Scientific Inc.: "iCOR – User Manual V5.0."
26. EN 14629 (2007): "Products and systems for the protection and repair of concrete structures. Test methods. Determination of chloride content in hardened concrete". CEN- European Committee for Standardization, Brussels, Belgium..
27. Astm C856/C856M (2020): "Standard Practice for Petrographic Examination of Hardened Concrete". *Annual Book of ASTM Standards*, West Conshohocken, Pennsylvania, U.S.A.