DaCS
Durable advanced Concrete Solutions

Report No. 06

Requirements and recommendations for frost durable concrete. Test methods.

Overview of national and international standards, codes, committees, representative projects.

WP 2. Production and documentation of frost durable concrete: air entrainment, cracking and scaling in performance testing

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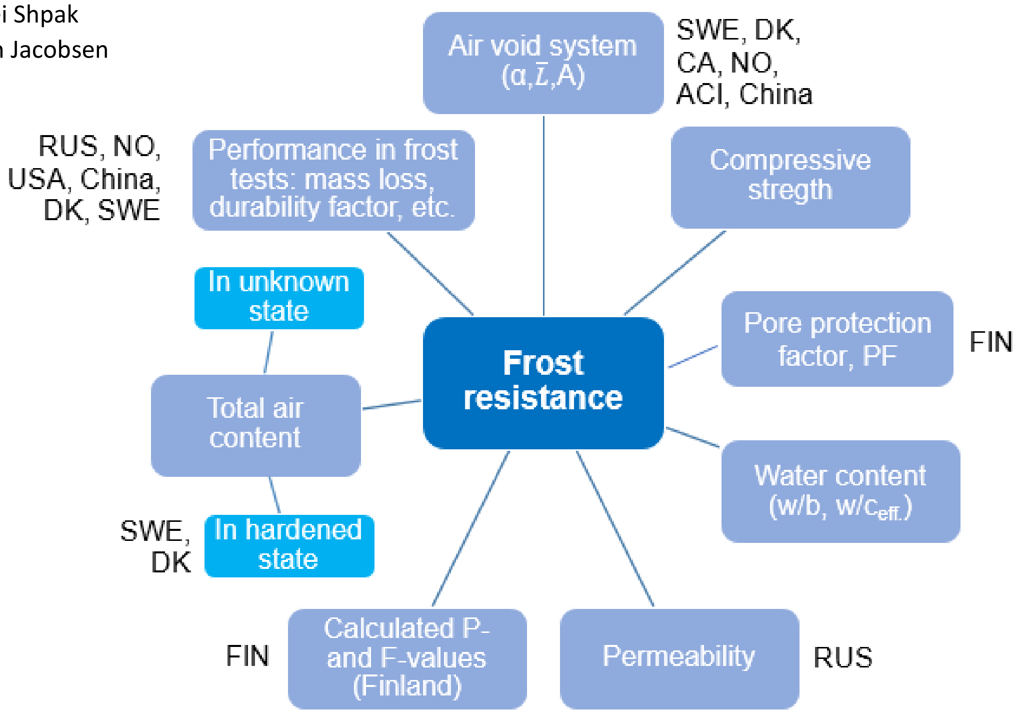

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ABSTRACT

The complexity of the ways the standards are organized in most of the reviewed countries contributes to immense efforts that the design and construction institutions should take on for selecting the requirements for a structure in a particular environment.

Requirements and recommendations to frost durable concrete can be roughly divided into Exposure or Load, Material requirements or Resistance, Execution, Tests and Acceptance Criteria. Each component is discussed in the present report, which is entirely based on more than 60 available to the author regulatory and recommendative documents in Europe, Russia, and North America and partly China as well as specific requirements in selected organizations and projects.

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Preface

This report and the related work have been carried out within the research project "Durable advanced Concrete Solutions" (DaCS). The project started in 2015 and is a 4-years' research program with a focus on concrete structures for severe conditions. The main R&D objective is to enable the production of sustainable and durable concrete structures for coastal and offshore arctic applications, considering both production and service life phases.

Multiple researchers from the Norwegian University of Science and Technology, SINTEF and industry partners, together with 3 PhD-students and a number of MSc-students, work on four focus areas:

WP 1: Early age cracking and crack calculation in design
WP 2: Production and documentation of frost-resistant concrete
WP 3: Concrete ice abrasion
WP 4: Ductile, durable Lightweight Aggregate Concrete

The industry partners are leading multinational companies in the cement and building industry, together with Norwegian engineering companies and offshore industry. Together our aim is to improve the concrete material quality to produce environmentally friendly and durable concrete structures for future arctic offshore and coastal applications. Combining the existing knowledge and experience across industries with the recognized research capabilities of NTNU and SINTEF provides a good basis for both high quality and industry relevant research. Achieving the overall research objectives will strengthen the Norwegian industry's relevance, attractiveness, and competitiveness.

The DaCS project partners are: Kværner AS (project owner), Axion AS (representing Stalite), AF Gruppen Norge AS, Concrete Structures AS, Mapei AS, Multiconsult AS, NorBetong AS, Norcem AS, NPRA (Statens Vegvesen), Norges Teknisk-Naturvitenskapelige Universitet (NTNU), SINTEF Byggforsk, Skanska Norge AS, Unicon AS and Veidekke Entreprenør AS. The project has received a financial contribution from the Norwegian Research Council.
For more information, see https://www.sintef.no/projectweb/dacs/.

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The present report would not exist without help and technical support of Peng Zhang from Qingdao University of Technology in China, Kjell Tore Fosså from Kværner AS and UniS in Norway, Frank Spörel from Bundesanstalt für Wasserbau/BAW in Germany, Matthias Müller from Bauhaus-Universität Weimar in Germany, Ole Mejlhede Jensen from DTU in Danmark, Martin Strand from Lund University in Sweden, Miguel Ferreira from VTT in Finland and Mette Rica Geiker from NTNU in Norway.

Summary

The report gives an overview of requirements and recommendations to frost durable concrete in standards and specifications, available to the author from a limited selection of standardization and engineering organizations in Europe, Russia and North America, and partly China.

In order to compare requirements and recommendations from different documents we have decided to divide them into Load, Resistance, Execution, Tests and Acceptance Criteria. Each criteria is organized in detailed tables for the best possible comparison. The results provide an overview for how the frost durability is perceived in standards and regulatory documents in different parts of the world. The results show a great variability in the definition of freeze-thaw resistance Most of the countries limit requirements to the mass-ratio, binder type and content, and the total air content in fresh or hardened concrete. Some set requirements to the air-void system and air content in hardened concrete, while others use requirements based on freeze-thaw tests optionally combined with permeability-related tests and remaining compressive strength.

Requirements and recommendations from different international projects show that the industry normally uses the most stringent freeze-thaw test methods (scaling with 3% salt solution, internal cracking with rapid freeze-thaw cycles in water) to meet Clients' requirements. Yet it is not clear how these types of test methods correlate with real exposure in actual structures. The differences could lie in mismatch between, for example, age of concrete before the test and age of the structure, exposure to salt and water during freeze-thaw cycles of specimen in the test and of real structure, test surface (sawn or formed) and finished surface for actual covering of a roadway, or sidewalk, or formed surface or similar.

There is a valuable exposure station project in Sweden, which has provided with a relatively well-correlated data comparison between the European salt-scaling test and frost damage after exposure of samples along salted motorway[1]. However, based on Canadian experience (Thomas[2]), the results from North-American salt-frost scaling test and performance of the same concretes at field did not correlate, especially for concrete with high volume of fly ash. In addition to the abovementioned differences between the test and exposed structure, scaling in salt-frost testing has shown to be sensitive to curing, pre-conditioning and ageing before testing. Compared to OPC concrete, carbonation can cause increased scaling for concrete with high content of slag, whilst concrete with fly ash requires longer curing period in order to perform as good as OPC concrete.

All in all, most standards are not updated with recent research results, do not account for the steady development of concrete materials (especially towards SCM) and technologies, machinery, construction, and testing techniques.

[1] Helsing E., Utgenannt P. The salt-frost resistance of concrete with supplementary cementitious materials (SCM), Nordic Concrete Research. Proceedings of the XXIII Nordic Concrete Research Symposium, 2017

[2] Thomas, M. Optimizing the use of fly ash in concrete. (2007)

Sammendrag

Rapporten gir en oversikt over krav og anbefalinger til frostbestandig betong i standarder og spesifikasjoner tilgjengelig for forfatteren fra et begrenset utvalg av standardiserings- og ingeniørorganisasjoner i Europa, Russland og Nord-Amerika og delvis Kina.

For å kunne sammenligne krav og anbefalinger fra ulike dokumenter har vi valgt å dele inn krav og anbefalinger til frostbestandig betong i last-, motstands-, utførelses-, test- og godkjennelseskriterier. Hvert av kriteriene er organisert i detaljerte tabeller for enklest mulig sammenligning. Resultatene gir dermed en oversikt over hvordan frostbestandighet oppfattes i standarder og kravdokumenter i ulike deler av verden. Resultatene viser stor variasjon i definisjonen av fryse-tine-motstand. De fleste land begrenser kravene til krav til masseforhold, bindemiddeltype og –innhold og totalt luftinnhold i fersk eller herdet betong. Noen stiller krav til luftporesystemet og luftinnholdet i herdet betong, mens andre bruker krav basert på fryse-tine-tester og eventuelt permeabilitets-relaterte tester og gjenværende trykkfasthet.

Krav og anbefalinger fra ulike prosjekter internasjonalt viser at industrien normalt bruker de strengeste fryse-tine-testmetodene (avskalling med 3 % saltløsning, oppsprekking ved raske fryse-tine-sykler i vann) for å møte kundenes krav. Hvordan denne typen testmetoder relaterer til virkelig eksponering i de aktuelle konstruksjonene er imidlertid ofte uklart. Forskjellene gjelder f.eks. aldring før fryse-tine-forsøket begynner sammenlignet med aldring i konstruksjonen før frosteksponering, tilgang til salt og vann i testprøven i forhold til konstruksjonen under frysing og tining, prøveflater i testprøven (sag- eller formflate) kontra bearbeidet overflate i veidekke, fortau, forskalingsflate i konstruksjon og lignende.

I Sverige finnes et verdifullt felteksponeringsprosjekt som har gitt en mengde data med relativ god korrelasjon mellom den europeiske salt-frost-avskallingstesten og frostskader etter eksponering av prøver langs en saltet motorvei[1]. Basert på kanadiske erfaringer (Thomas[2]) korrelerer imidlertid ikke den nord-amerikanske salt-frost-avskallingstesten med feltytelsene til de samme betongene, spesielt for betong med et høyt volum av flyveaske. I tillegg til forskjellene mellom testprøven og eksponert konstruksjon nevnt ovenfor, har avskalling i salt-frost-prøving vist seg å være følsom for herding, forbehandling og aldring før testing. Sammenlignet med OPC-betong kan karbonatisering gi økt avskalling på betong med høyt slagginnhold, mens betong med flyveaske trenger lengre herdetid for å klare seg like bra som OPC-betong.

Alt i alt, de fleste standarder er ikke oppdatert med nylige forskningsresultater, tar ikke hensyn til kontinuerlig utvikling av betongens delmaterialer (spesielt mot SCM) og teknologi, maskineri, konstruksjon, og testteknikker.

[1] Helsing E., Utgenannt P. The salt-frost resistance of concrete with supplementary cementitious materials (SCM), Nordic Concrete Research. Proceedings of the XXIII Nordic Concrete Research Symposium, 2017

[2] Thomas, M. Optimizing the use of fly ash in concrete. (2007)

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APPENDICES

List of abbreviations (Standards)

ACI 555	American Concrete Institute. Code or Standard Specification
ACI 555**R**	American Concrete Institute. Guide
ASTM	American Society for Testing and Materials. Standard
AASHTO LRFD	The American Association of State Highway and Transportation Officials. Specification, based on Load and Resistance Factor Design philosophy
CSA	Canadian Standards Association
BNQ	Bureau de normalisation du Québec / Bureau of standardisation in Québec, Canada
MTO	Ministry of Transportation, Ontario, Canada. Laboratory testing manual
NS-EN 206	Norwegian national annex to EN 206
SS EN 206	Swedish national annex to EN 206
SIS-CEN/TR	Swedish technical report
DS	Danish standard
DIN	German Institute for Standardization, National standards
GOST	Russian regulatory requirements (for all sorts of products, services)
SP (new SNiP)	Russian building rules (and regulations, for SNiP – is being superseded)

List of abbreviations (Concrete, parameters, and constituents)

SCM	Supplementary cementitious materials (silica fume, fly ash, blast furnace slag)
SF	Silica fume
FA	Fly ash
BFS	Blast furnace slag
AEA	Air-entraining admixture
SP	Water-reducing or super-plasticizing admixture
w/c	Water-to-cement ratio
w/b	Water-to-binder ratio
T.A.C	Total air-void content (Total air content), %
D_{max}	The highest diameter of the aggregate particle, mm
Rel. Dyn.E-Modul	Relative dynamic modulus of elasticity

1 Introduction

This DaCS project report represents an overview of requirements and recommendations for frost durable concrete, embracing the data from over 60 standards, regulatory and recommendatory documents (see Table 2). The collected data is included in the author's Ph.D. project "Production and documentation for frost durable concrete". Over the years many workers have reviewed the topic concrete frost durability from various perspectives; for Rilem committees, for textbooks, as part of PhDs, to understand or develop models to explain frost damage such as the critical degree of saturation and the glue-spall theory etc. We have in this document limited the review to standards and recommendations issued by standardization- and engineering organizations for production of frost durable concrete.

It is important to distinguish, that in that overview the documents under the category "Requirements" mean national (f.ex. NS-EN, SS, DIN), regional (CEN) and international standards (ISO, ASTM), whilst specifications, codes, technical standards, or any other documents, developed by technical committees (ACI, AASHTO, RILEM, HETEK, SVV, ZTV), will further be called for "Recommendations".

Note: The word "standard" (mentioned 120 times in this document) is understood differently as it can mean either a compulsory (norm or "law") or a recommendative document. For instance, ACI means that they issue standards, codes, specifications, all in one, but the organization has zero liability for the consequences their "standards" could lead to. Interesting to note that ASTM international standards often refer to requirements given in ACI documents.

The words "requirement" (repeated 110 times in the document) and "specification" (used 30 times) can also be misleading as it is clearly seen in the following example from the Wikipedia: Specification or Requirement specification is a technical standard, developed by a technical committee in a private organization for a product, a structure, or a particular work. So, depending on the perspective one interpret the document from, a specification is a requirement and a recommendation at the same time.

The scope of this work is to give an overview over the documents (available to author) relevant for frost exposure requirements and recommendations with a slight focus on the introduction of supplementary cementitious materials (Fly Ash or FA in particular) in concrete, pointing to basic similarities and differences, ending with some examples of requirements to frost durable concrete structures.

Frost durability for concrete is its ability to withstand repetitive freeze-thaw cycles throughout a defined life of the structural element without damage due to surface scaling or internal cracking. The concrete is usually exposed to periodical wetting and drying, deicer salts and other different aggressive matters along with the freeze-thaw.

It is the country standards, norms and regulations for concrete that stipulate:

- the exposure (wetness/saturation, chlorides, frost etc.) to base the design on,
- the material requirements (air void requirements, w/b-ratio, binder composition, strength etc.) to select for that exposure,
- the production techniques and rules (placing arrangements, finishing, curing) to apply for making the concrete frost resistant and
- the test methods (air voids, frost tests, porosity, strength etc.) for the final product to confirm compliance.

The approach can vary significantly from country to country. Numerous committees and unions with their sets of recommendations in addition to national standards can make it difficult even within the country to agree on what the frost durable concrete is and how to produce it.

Selection of the reviewed documents in this course report is limited to available to author standards and recommendations from the USA (ACI, AASHTO, ASTM), Canada (CSA, BNQ), Norway (NS-EN), Sweden (SS, SIS), Danmark (DS), Germany (DIN, ZTV, BAW), Russia (SP, GOST, SNiP) and China (GB/T).

The present overview did not include among other documents a review of the concept of equivalent durability of concrete CEN/TR 16563. These technical recommendations were adopted by a number of European countries. It targets connecting field experience with laboratory results, developing a database of reference mixes and exposures. At present, the concept cannot be used in most of the European countries under the directive of EN 206 [20], as it requires some established national system for reference concretes.

Table 1. List of the main tables in the document

	Table 2	Overview of the documents included in the review
Load	Table 3a	Classification for freeze-thaw exposure conditions. LOAD
	Table 3b	Summary of exposure classes from the reviewed standards and specifications
Resistance	Table 4	Material requirements. RESISTANCE
Execution	Table 5	Production and execution of concrete works. Requirements and recommendations
Tests	Table 6a	Tests for frost durability – material characterization
	Table 6b	Tests for frost durability – freeze-thaw tests
	Table 7	Overview of requirements for frost durable concrete

Table 2. Overview of the documents included in the review

	Europe						Asia	North America	
	Norway	**Sweden**	**Denmark**	**Germany**	**Finland**	**Russia**	**China**	**USA**	**Canada**
Exposure classes, Material requirements	NS-EN 206+NA NS-EN ISO 19903	SS EN 206 SS 137003	DS 2426 (DS 411) DS/EN 1992-1-1 HETEK, Danish Road Directorate	DIN 1045-2	B4, Liite 3, SFS-EN 206-1	GOST 31384-2017 SP 35.13330.2011 GOST 26633-2012	GB 50476-2008	AASHTO LRFD Bridge design spec. ACI 201.2R-01 ACI 302.1R-96 ACI 318-14	CSA A23.1-09-A23.2-09
Production and execution of concrete works	EN 206:2013 EN 13670:2009					GOST 7473-2010 GOST 10181-2014 GOST 30459-2008 SP 70.13330.2012		ASTM C172/C172M ACI 304.2R-00 ASTM C94/C94M-16a	
	NS-EN 13670:2009/NA NS-EN 14487-1+NA NS-EN ISO 19903 NCA Pub. 25 SVV Prosesskode 2	SS 137003		DIN 1045-2 ZTV-ING				ACI 212.3R-2010 ACI 302.1R-96 ACI 304R-00 ACI 318-14 PCA. Volume 19/1 AASHTO LRFD Bridge constr. spec.	CSA A23.1-09-A23.2-09
Tests for frost durability – freeze-thaw tests	CEN/TS 12390-9					GOST 10060-2012	GB/T 50082—2009	ASTM C672 ASTM C666	
		SS 137244 SIS-CEN/TR 15177		Bunke cube test RILEM TC 117-FDC/CDF					MTO LS-412 BNQ NQ 2621-900

2 Exposure characteristics

Most of the standards begin with the description of exposure classes, emphasizing by that a great importance of selecting it properly. Exposure class represents an imposed environmental **Load** that a structural element or a whole structure will oppose to throughout its lifecycle.

Exposure class (further in the text – class) selection for designing of the concrete mix for the structures that undergo freeze-thaw cycles depends on varying saturation conditions, presence of de-icing agents (f.ex. chlorides) and sulfates (seawater).

Combination of environmental loads is often a case when selecting the most appropriate class of the load for a particular element. Some organizations develop free software (ex. Svensk Betong [59]) or guidelines (see an example in figure 1 below), helping end-users to choose the most suitable class for further design.

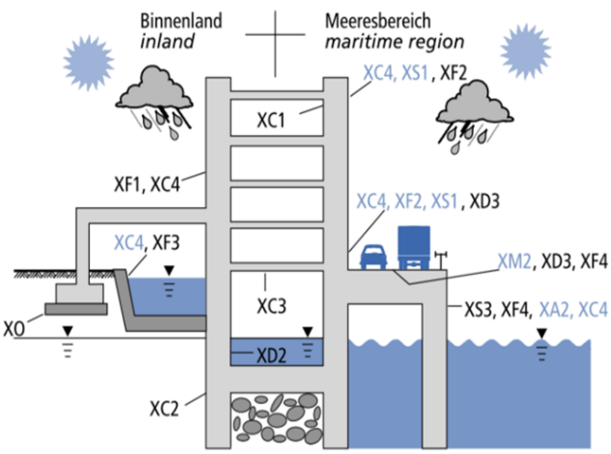

Figure 1. Guidelines for exposure class and material parameters selection [60]

Reprinted from "The new German concrete standards DIN EN 206-1 and DIN EN 1045-2 as basis for the design of durable constructions," by Horst Grube, Beatrix Kerkhoff., Concrete Technology Reports, VDZ, Düsseldorf, 2001-2003, p.22

Expositionsklassen (Umwelteinwirkungen, „Angriffe") *Exposure classes (environmental effects, "attacks")*				Betontechnische Maßnahmen („Widerstände") *Concrete technology measures ("resistances")*		
Klassenbez. *class designation*		Einwirkung *effect*	und *and* Beanspruchung *stress*	Max. w/z *max. w/c*	Min. z *min. c*	f_{ck}, cube f_{ck}, cube
XO		kein Angriff *no attack*	kein Betonangriff *no concrete attack*	keine Anforderung *no requirement*	keine Anforderung *no requirement*	C8/10 *C8/10*
XC	1	Carbonatisierung *carbonation* (H_2O, CO_2)	trocken *dry*	0,75	240	C16/20
	2		ständig nass *constantly wet*	0,75	240	C16/20
	3		mäßig feucht *moderately moist*	0,65	260	C20/25
	4		nass / trocken *wet / dry*	0,60	280	C25/30
XD/ XS	1	Chlorid *chloride* (Cl, H_2O)	mäßig feucht moderately moist	0,55	300	C30/37
	2		ständig nass *constantly wet*	0,50	320	C35/45
	3		nass / trocken *wet / dry*	0,45	320	C35/45
XF	1	Frost /+ Salz *freeze-thaw /+ salt*	mäßige Wassers. o. T. *moderate water saturation (o.T.)*	0,60	280	C25/30
	2		mäßige Wassers. m. T. *moderate water saturation (m.T.)*	0,55 + LP	300	C25/30
				0,50	320	C35/45
	3		hohe Wassers. o. T. *high water saturation (o.T.)*	0,55 + LP	300	C25/30
				0,50	320	C35/45
	4		hohe Wassers. m. T. *high water saturation (m.T.)*	0,50 + LP	320	C30/37
XA	1	Säure *acid* Chem. Angriff *chemical attack*	schwach angreifend *weakly corrosive*	0,60	280	C25/30
	2		mäßig angreifend *moderately corrosive*	0,50	320	C35/45
	3		stark angreifend *strongly corrosive*	0,45	320	C35/45
XM	1	Verschleiß *wear*	mäßiger Verschleiß *moderate wear*	0,55	300	C30/37
	2		starker Verschleiß *severe wear*	0,45	320	C35/45
	3		sehr starker Verschleiß *very severe wear*	0,45	320	C35/45

For example, if we design a structure in Sweden, exposed to seawater, and freezing and thawing cycles, the governing exposure classes would be XS3 and XF4 – for the splash zone and XS1 and XF2 – above the area of active splashes (exposed to seawater spray). Consequently, the requirements for concrete should meet the limits described in the national standard for both classes in either case. Normally XF-classes (in Europe) set stricter requirements and, hence, serve as dominant exposure classes for selection of the mix design parameters.

However, there are other practices, regulating requirements and recommendations towards application for some particular structures or its components, which overrule in a loose sense the use of standard requirements. That could be an industrial specification or code of various committees, for instance, for road and highway structures (ex. [14], [15], [24], [38], etc.).

In addition, particular projects like some of the concrete offshore platforms or bridges may have their own set of requirement specifications to concrete (and its constituent materials) in the face of either extensively harsh environment, prolonged design life or construction solutions beyond any other specifications, or simply taking into account stringent Clients' design considerations.

Table 3a presents an overview of how standards in different countries specify exposure classes. **Table 3b** shows an example of a criterion-based comparison of the overviewed standards.

Observations based solely on Tables 3a and 3b (see the Tables below):

1. Europe. EN 206 and modifications of this European standard, i.e. NOR [20], SWE [28], GER [35], DK [33], RUS [48]:

- Neither Norwegian nor Danish standards consider high saturation condition for De-icer-free exposure, differentiating class XF1 from XF3 only by exposed surface orientation. Recommendations from HETEK [34] solve the mismatch for Danish Road Directorate. Norwegian road authorities follow the letter of the standard.
- Both German and Swedish standards do not specify saturation conditions for class XF1
- Only Danish and Swedish standards seem to provide with a full description of exposed surfaces and structures for the classes, while other three national standards give very vague and general definitions.
- German standard display no division to horizontal and vertical surfaces between the classes of exposed structures
- Sweden – the only standard distinguishing the transition from a vertical to a horizontal surface by introducing the threshold requirement for the slope (30deg.).

2. North America

- A substantial difference can be observed in exposure classes characterization between reviewed ACI [1,3,6] and AASHTO [14,15] documents, despite the fact that exposure characteristics of the latter two specifications should logically fall under broader ACI 201.2R Guide for durable concrete and ACI 318 Building Code Requirements for structural concrete.
- ACI 201 [1] and ACI 302 [2] are well aligned.
- AASHTO specifications [14,15] introduce the classes for air-entrained (AE) and high-performance concretes (HPC) of elements in bridge construction. There are many requirements given particularly for class A (HPC) (see Table 4), but the exposure conditions are not defined.
- Canadian standard [17] offers two pure frost classes for horizontal and vertical surfaces without exposure to chlorides (similar to XF1 and XF3 in variations to EN 206 standard). Pertaining exposure to chlorides and to other aggressive matters, like manure, the standard does not put emphasis on the impact of freeze-thaw on requirements for concrete, meaning that other exposure criteria overrule it (see Appendix A, Table A.1).
- There is a mismatch between ASTM C94/C94M [7] for fresh concrete and the building code ACI 318 [6]. When referring to ACI code, ASTM standard wrongly categorizes exposure class F2 as a severe exposure (see Note 5, section 6.1.4 in ASTM C94) with exposure to de-icing salts, while in the ACI F2 is for exposure to only fresh water.

3. Asian approach:

- Both Chinese [51,53] and Russian [48] standards define exposure by lowest temperatures in the freeze-thaw cycle. The temperature ranges vary significantly, depending on the target structural groups: SP 35.13330 is for the bridges and pipes whereas GB/T 50476 is for general civil construction.
- Russian GOST standards are being revised and updated. The new versions resemble European standards, and they refer to them more often. However, the building norms SP (or SNiP) seem to remain independent of that tendency.

None of the standards gives a definition of moderate saturation conditions, splash zone, sea spray exposure, airborne de-icing agent.

Table 3a. Classification for freeze-thaw exposure conditions. LOAD

Country	Standard, Code, Guide	Exposure class	Exposed structures, surfaces classification	Water saturation, exposure	De-icing agents (incl. chlorides)	Temperature	Reference
Norway, NO	NS-EN 206:2013+NA:2014	XF1	Vertical concrete surfaces	Rain, moderate saturation		Freezing and thawing cycles	Table 1, p. 21 [20]
		XF2	Vertical concrete surfaces of road structures	Moderate saturation	De-icing agent (airborne)		
		XF3	Horizontal concrete surfaces	Rain, moderate saturation			
		XF4	Road and bridge decks, splash zone of marine structures and other concrete surfaces	High saturation	De-icing agent or direct spray with de-icer, Sea water		
	NS-EN ISO 19903:2006	Severe	Reinforced and pre-stressed concrete above splash zone	Moderate saturation	Sea spray, rain	Freezing and thawing cycles	Clause 8.3.3.1 [23]
		Very severe	Reinforced and pre-stressed concrete in splash zone	High saturation	Sea water		
Canada, CA	CSA A23.1-09-A23.2-09	F-1	Pool decks, patios, tennis courts, freshwater pools, and freshwater control structures.	Saturated condition		Freezing and thawing cycles	Table 1, p.121 [17]
		F-2	Exterior walls and columns.	Unsaturated condition			
		C-1	Structurally reinforced concrete. Bridge decks, parking decks and ramps, portions of marine structures located within the tidal and splash zones, salt-water pools and other concrete structures		Chlorides, seawater spray		
		C-2	Non-structurally reinforced. Garage floors, porches, steps, pavements, sidewalks, curbs, and gutters.		Chlorides		
		C-XL	Structurally reinforced, highly durable concrete (with higher durability performance expectations than the C-1, A-1, or S-1 classes)		Chlorides or other severe environments		
		A-1	Structurally reinforced concrete exposed to severe manure and/or silage gases. Concrete exposed to the vapor above municipal sewage or industrial effluent. Reinforced elements over manure pits/silos or in contact with effluents				
		A-2	Structurally reinforced concrete exposed to moderate to severe manure and/or silage gases and liquids. Exterior walls and slabs of manure tanks.				
		A-3	Structurally reinforced concrete exposed to moderate to severe manure and/or silage gases and liquids in a continuously submerged condition.				

Country	Standard, Code, Guide	Exposure class	Exposed structures, surfaces classification	Water saturation, exposure	De-icing agents (incl. chlorides)	Temperature	Reference
USA	ACI 201.2R-01	Moderate	Certain exterior walls, beams, girders, and slabs not in direct contact with soil	Occasional contact with moisture		Freezing and thawing cycles	Clause 1.4, Table 1.1 [1]
		Severe	Concrete of thin sections (bridge decks, railings, curbs, sills, ledges, and ornamental works)	Almost continuous contact with moisture	De-icing salts	Freezing and thawing cycles	
	ACI 302.1R-96	Moderate	Concrete floors and slabs			Freezing and thawing	Clause 6.2.3 [3]
		Severe	Concrete floors and slabs	High saturation	De-icing chemicals		
			Reinforced concrete		Brackish water, seawater, de-icing chemicals, other aggressive materials		
	AASHTO LRFD Bridge design and construction specifications	Class A (AE),	Concrete for all elements of structures		Saltwater (in or above), De-icing salts	Alternate freezing and thawing	C5.4.2.1 [14], Table 8.2.2-1 [15]
		Class A (HPC)	Cast-in-place construction where performance criteria should be specified separately				
		Class B (AE)	Concrete for footings, pedestals, massive pier shafts, and gravity walls		De-icing salts, saltwater		
		Class C (AE)	Concrete for thin sections, such as reinforced railing less than 10cm thick, for filler in steel grid floors				
	ACI 318-14	F1	Exterior walls, beams, girders, and slabs not in direct contact with soil.	Limited exposure to water.		Freezing-and-thawing cycles	Tables 19.3.1.1 and R.19.3.1 [6]
		F2	Members that will be subject to snow and ice accumulation, such as exterior elevated slabs. Horizontal and vertical members in contact with soil. Foundation or basement walls extending above grade.	Frequent exposure to water, possible saturation. Snow and ice accumulation against surface			
		F3	Horizontal members in parking structures. Foundation or basement walls extending above grade.	Frequent exposure to water, possible saturation. Snow and ice accumulation against surface	De-icing chemicals		
Germany	DIN 1045-2	XF1	Outdoor components			Freezing and thawing cycles	Table 1 [35]
		XF2	Elements in spraying or splashing areas of treated traffic areas that do not fall under XF4. Concrete elements in the seawater spray area	Moderate saturation	De-icing agent, Sea water spray		

Table 3a continued

Country	Standard, Code, Guide	Exposure class	Exposed structures, surfaces classification	Water saturation, exposure	De-icing agents (incl. chlorides)	Temperature	Reference
Germany	DIN 1045-2	XF3	Structural components in the area with varying fresh water level (direct translation - "water exchange zone")	High saturation		Freezing and thawing cycles	Table 1 [35]
		XF4	Traffic areas treated with de-icing agents. Mainly horizontal surfaces in the spraying area of treated traffic areas. Reservoirs of clear water; Marine structures in the tidal zone	High saturation	De-icing agents, sea water		
Sweden	SS EN 206:2013 (with additional clarification from Heidelbergcement group)	XF1	Vertical surfaces exposed to rain or freezing. Outdoors with slopes greater than 30 degrees. Facades, indoors in uninsulated buildings, escape routes, as well as heated and ventilated side spaces in road tunnels			Freezing and thawing cycles	[28]
		XF2	Vertical surfaces exposed to freezing Parts of bridges under the ground. Otherwise traffic space in road tunnels.	Moderate saturation	De-icing agent (airborne)		
		XF3	Horizontal surfaces exposed to rain and freezing. Outdoors with slopes lower than 30 degrees. Constructions in fresh water with / without one-sided pressure or exposed to splash. Outdoor water pools, balconies without risk for de-icers, dam structures, parts of bridges / tunnels that are not in the road environment	Rain, high saturation			
		XF4	Road and bridge decks, surfaces directly exposed to splashes of de-icing agents. Splash zone of marine structures. Decks and joints of outdoor parking houses, garage driveways, ground concrete, concrete pavements, stairs / ramps, decks in timber drying areas, upper surface of the bridge deck parts of bridges / tunnels that belong to road environment	High saturation	De-icing salts, sea water		
Denmark	DS 2426 (DS/EN 1992-1-1 DK NA:2011, which replaced DS 411)	XF1 (moderate)	Vertical concrete surfaces. Foundation piles and foundations partly above ground, external walls, columns and facades, external beams with structurally protected upper side, balcony railings, installation channels, elevator pits.	Rain, moderate saturation		Freeze-thaw cycles	Clause 4.2 [33]
		XF2 (aggressive)	Vertical concrete surfaces of road structures. Retaining walls, exterior stairs, basement exterior walls partially above ground	Moderate saturation	De-icing agent (airborne)		

Table 3a continued

Country	Standard, Code, Guide	Exposure class	Exposed structures, surfaces classification	Water saturation, exposure	De-icing agents (incl. chlorides)	Temperature	Reference
Denmark	DS 2426 (DS/EN 1992-1-1 DK NA:2011, which replaced DS 411)	XF3 (aggressive)	Horizontal concrete surfaces Outside deck, external beams without structurally protected upper side, exterior stairs	Rain, moderate saturation		Freeze-thaw cycles	Clause 4.2 [33]
		XF4 (extra aggressive)	Road and bridge decks, splash zone of marine structures and concrete surfaces, exposed to direct spray containing de-icer and freezing. Balconies and their elements, parking decks, swimming pools, bridge columns, edge beams on bridges.	High saturation	De-icing agent or direct spray with de-icer, Sea water		
	HETEK committee, Danish Road Directorate	1	Splash zone structures, pavement slabs, edge beams, decks, continuously moisture exposed columns and vertical walls, back-filled support and retention walls and decks without membrane	Exposed to water, high saturation	With or without salt	Freezing and thawing cycles	Report No. 97, 1997, p.13 [34]
		2	Decks with intact membranes, crash barriers, columns and vertical walls, not exposed to capillary suction, but less than 1,5m from splash zone	Periodical water exposure	With or without salt		
		3	Vertical surfaces – back-filled retention walls with membranes, sheltered columns	Rare exposure to water			
Russia	GOST 31384-2017[1]	XF1	Vertical surfaces of the buildings and structures	Rain, moderate water saturation		Freezing and thawing cycles	Table A.1 [48]
		XF2	Vertical surfaces of transport works	Moderate water saturation	De-icing agents		
		XF3	Horizontal surfaces of the roads and other structures	High water saturation			
		XF4	Horizontal surfaces of roads and bridges, outdoor staircases, etc. Marine structures	High water saturation	De-icing agents, incl. sea water		
	SP 35.13330.2012[2]	Severe	Surfaces of massive structures and thin walls (less than 0.5m thick)	Underwater (0.5m below ice exposed surfaces), under- and over-ground flood-free zones		-10...-20 C°	Table 7.5 [50]
		Extra severe	Surfaces of massive structures, thin walls, external and internal concrete blocks	Varying water level (splash / tidal zone)	Sea water?	Below -20 C°	
		De-icing salts	Elements listed for severe and extra severe exposure		De-icing agents	Below -10 C°	

Table 3a continued

Country	Standard, Code, Guide	Exposure class	Exposed structures, surfaces classification	Water saturation, exposure	De-icing agents (incl. chlorides)	Temperature	Reference
China	GB/T 50476-2008 [51]	II-C	Components of water level variation zone, horizontal surfaces	High. Frequent rain, water level variation zone	/	-3…+2,5	Peng Zhang [53]
			Vertical surfaces	Moderate. Rain	/	-3…-8 and below -8	
		II-D	Components of water level variation zone, horizontal surfaces	High. Frequent rain, water level variation zone	/		
			Components of water level variation zone, horizontal surfaces	High. Frequent rain, water level variation zone	Chlorides	-3…+2,5	
			Vertical surfaces	Moderate. Rain		-3…-8 and below -8	
		II-E	Components of water level variation zone, horizontal surfaces	High. Frequent rain, water level variation zone			

Table 3a continued

[1] Exposure classes for concretes in the aggressive environment, inducing corrosion by the action of alternating freezing and thawing.

[2] Standard specifies the requirements for minimum frost resistance class in particular exposure conditions

Table 3b. Summary of exposure classes from the reviewed standards and specifications

<table>
<tr><th rowspan="3">Saturation and additional criteria</th><th colspan="14">Standard, Code, Guide</th><th rowspan="3">De-icing agents</th></tr>
<tr><th>Hetek</th><th>NS-EN ISO 19903</th><th>DS 2426</th><th>NS-EN 206</th><th>GOST 31384</th><th>SS EN 206</th><th>DIN 1045-2</th><th colspan="2">ACI 318</th><th>ACI 302</th><th>ACI 201</th><th>CSA A23</th><th>GB/T 50476</th><th>AASHTO</th><th>SP 35.13330</th></tr>
<tr><th>DK</th><th>NOR</th><th>DK</th><th>NOR</th><th>RUS</th><th>SWE</th><th>GER</th><th colspan="4">US</th><th>CAN</th><th>CHI</th><th>US</th><th>RUS</th></tr>
<tr><td>High saturation, sea splash</td><td rowspan="2">Class 1</td><td>Very severe</td><td colspan="2">XF4</td><td></td><td></td><td></td><td colspan="2"></td><td></td><td>Severe</td><td>C-XL</td><td>II-D, II-E</td><td>Class A (HPC)</td><td></td><td>De-icing salts</td></tr>
<tr><td>High saturation</td><td></td><td></td><td></td><td colspan="3">XF3</td><td colspan="2">F2</td><td></td><td></td><td>F1</td><td rowspan="2">II-C, II-D</td><td></td><td rowspan="2">Severe</td><td rowspan="2">No de-icing salts</td></tr>
<tr><td>Moderate. Horiz. surfaces</td><td rowspan="3">Class 2</td><td></td><td colspan="2">XF3</td><td></td><td></td><td></td><td>F1</td><td>F2</td><td colspan="2">Moderate</td><td>F2</td><td></td></tr>
<tr><td>Moderate saturation, sea spray</td><td>Severe</td><td colspan="5">XF2</td><td colspan="2">F3</td><td></td><td></td><td>C1</td><td>II-D</td><td>Class A, Class B</td><td></td><td>De-icing salts</td></tr>
<tr><td>Moderate saturation Vertic. surfaces</td><td></td><td></td><td colspan="2">XF1</td><td></td><td></td><td colspan="2">F1</td><td></td><td rowspan="2">Moderate</td><td></td><td>II-C</td><td></td><td rowspan="2">Severe</td><td rowspan="2">No de-icing salts</td></tr>
<tr><td>Rare contact with water</td><td>Class 3</td><td></td><td></td><td></td><td></td><td colspan="2">XF1</td><td colspan="2"></td><td>Moderate</td><td></td><td></td><td></td></tr>
<tr><td>Parking (garage floors), ground concrete</td><td></td><td></td><td>XF4</td><td></td><td colspan="3">XF4</td><td colspan="2">F3</td><td></td><td></td><td>C2</td><td></td><td>Class B</td><td></td><td rowspan="2">De-icing salts</td></tr>
<tr><td>Thin walls, sections</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2"></td><td></td><td>Severe</td><td></td><td></td><td>Class C</td><td>Extra severe</td></tr>
<tr><td>NA</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2"></td><td>Severe</td><td></td><td>A1-A3</td><td></td><td></td><td></td><td>Other aggressive matters</td></tr>
</table>

Note: The table attempts to summarize collected information in a simple manner. More criteria could be included into that comparison table: direct contact with ground, reinforced or not, etc.

3 Material requirements

It is not that ambiguous that the main parameters for designing frost durable concrete remain the same as for regular concrete: water-to-cement (w/c) or water-to-binder (w/b) ratios with or without efficiency factors for SCM, compressive strength and air-void content. However, when we mean frost–durable or –resistant concrete, there are other material requirements to be involved – air-void spacing factor, binder proportions, and limitations, permeability and frost resistance for aggregate and concrete.

All the above-mentioned material requirements represent **Resistance** of the structure or the element against the **Load** in the form of environmental exposure, determined in accordance with Table 3a.

Table 4 shows the presence of given controlled parameters for concrete (mix design, its fresh and hardened state) in various national standards and specifications. The requirements are given to ensure a minimum of 50 years service life (or more, depending on concrete cover), unless other specified.

Observations:

1. Air-void parameters:

- In Europe, it is only Sweden and Denmark, who set the importance of air void parameters (spacing factor) in the main concrete standard (EN 206).
- It is unclear in which state of the concrete (fresh or hardened) it should meet the requirements for air content. T.A.C is documented in hardened concrete only in Denmark, among all the reviewed standards; however, Sweden presumably does the same despite no clarity in the standard text. Both standards also measure T.A.C in the fresh state.
- Swedish standard avoids setting a requirement for T.A.C and air-void spacing factor for the most severe exposure XF4.
- Even though the Canadian standard [17] sets general requirements for the average air void spacing factor of 230 µm (no single result greater than 260µm), it recommends (I.3.8, Clause 4.3.1) especially for highly workable HPC concretes using a target maximum allowed spacing factor of 170 µm.
- The Air Void Analyzer or AVA (acc. to chapter C4.6. [57]) can be considered for use in monitoring the variability of the air void system in fresh concrete during production. Although its correlation with other test methods is still to be proven, AVA stands as an alternative test method for air content (Table C1.0-2 [57]) in line with standards ASTM C231 and ASTM C457.
- Russia.
  Interesting that GOST 26633-2012 for heavyweight concrete [46] had clear requirements to air-void content varied with D_{max} and w/c-ratios (see the Table below), accepting only the concrete with F/T-resistance over $F_1$200 (F_1 – in acc. with Basic first method< see Table 6b). Whereas the newest revision, called GOST 26633-2015, exhibits far less information and sets a general requirement for air content at 4% for all concretes with $F_1$200 ($F_2$100) independent of D_{max} and w/c, and the table below is no longer there or in any other standards.

Copy of Table B.7 (Б.7 - in Russian) [46]

Max size of aggregate particles (D_{max}), mm	Air-void content for fresh concrete, %		
	w/c ≤0,41	w/c = 0,41…0,50	w/c > 0,50
10	3…4	3…5	5…7
20	1…3	2…4	4…6
40		1…3	3…5
80			2…4

Worth mentioning that valid standards in Russia often refer in the text to old expired documents. Therefore, it makes it harder to pick a right selection of standards to follow and makes it easier to make a mistake.

Looking at the numbers, the Russian standard from 2012 does not seem to require air-entraining agents for concretes with w/c below 0.41, which is, best to our knowledge, the only standard, defining the lowest w/c-ratio limit for the need of air entrainment. This particular case requires rather thorough review of Russian standards.

Same GOST 26633-2015 limits w/c to 0.45 and the air content – to 5-7 % for topcoat for roads and airfield pavements [46 – 2015 version].

- Chinese standard focuses on requirements for air content (for certain aggregate size) and the spacing factor as a function of the degree of water saturation and the presence of de-icing salts (see Appendix B.1)

2. Supplementary cementitious materials (SCM):
   - German standard DIN 1045-2 sets requirements for a separate category of slow hardening concretes (with fly ash) when identifying limiting values for concrete that is to be exposed to freeze-thaw (see Table 6).
   - Canadian standard suggests using SCM in case of combined sulfate and chloride attacks.
   - Russian GOST R 55224-2012 [64] (Clause 5.11.2) accepts blast furnace slag as the only main mineral addition or cement replacement in concretes for road topping and airfield pavements, for reinforced elements and bridge structures.

3. Durability parameters:
   - Norwegian national annex introduces durability classes, which unify requirements for concrete under six (6) different sets for corresponding exposure classes (Table NA.11 in [20]). It makes it possible to simplify the process of selecting the requirements in the event of combined actions.
   - Finnish standard [63] uses unique P- and F-values as key parameters for concretes in the presence of de-icing agents (XF2, XF4) and without (XF1, XF3) respectively. The F-value depends on w/c-ratio and T.A.C (for D_{max} -16mm), while for P-value, in addition, binder composition and curing (see Appendix B.2) have meaning.
   - In Russia, the frost resistance class is assigned to particular types of structures and exposure conditions with special focus on the severity of freeze-thaw cycles (different requirements for lowest temperatures), see GOST 31384-2017 [48] (Table E.1 in the standard) and Appendix C2, Table C2.1. Building regulations and rules (known as SNiP or superseding it - SP), which the design of new works is based upon, provide own guidance on which parameters the concrete should meet (see Note 3 for Table C2.1, Appendix C2).

4. Other requirements:
   - Efficiency factors:
     - Both in Canada and in the USA, there are no efficiency factors (k_{eff}) used for SCMs. W/CM = Mass of Water / Total mass of PC + SCM.
     - There is no agreement in Europe on k_{eff} value for fly ash, used when calculating the so-called effective water-to-cement ratio (w/c_{eff}) or mass-ratio. However, most of the standards suggest using w/c_{eff} as a key parameter for concrete mix design (see a definition of c_{eff} in a footnote 1 under Table 4)
   - Only German and Russian *main concrete standards* specify particular acceptance criteria for frost resistance of aggregate.

DIN 1045-2 [35] (tables F 2.2. and U1), however, introduces two different frost resistance categories, referring to DIN EN 12620 (Tables 18 and 19 in that standard). Aggregates for XF1 and XF3 exposure is tested in fresh water (EN 1367-1), while for the exposures XF2 and XF4 (de-icing agents and seawater) aggregates are tested either by a procedure for determination of magnesium sulfate value (EN 1367-2), so-called “direct method”, or in the presence of de-icing salts (1%NaCl or urea). However, it should be mentioned that no clear relationship exists between the frost resistance of the aggregate as determined by EN 1367-1 and how the aggregate will perform in concrete during freeze/thaw.

- Norway puts an emphasis on the need for frost-resistant aggregate only for XF4 class, while Danish standard does not mention this requirement at all in the *main country concrete standard* [32].
- Russian SP 41.13330.2012 [81] recommends which type of admixtures for concrete to use as a function of structure type and exposure characteristics (see Annex B, Tables B.1 and B.2 in the standards).

Note:

It is often the calculated physical load that influences the material requirements, making concrete mix design process rather complicated and comprehensive.

For example, when we have a combined environmental load XF4 (European standard) and physical abrasive load from ice drift, the requirement for concrete strength increases from a standard value of C30/37 for XF4 to C70/85 (class B70). However, frost exposure demands certain air content, say 5%, which by thumb rule for high strength concrete would reduce compressive strength (in comparison with non-air entrained concrete – around 2.5% T.A.C.) without any extra measures by 5-10% for each volume % of additional air. In order to compensate for that strength loss, concrete technologist should reduce w/b-ratio to 0.26-0.28 or use different measurements to meet the required strength level.

Another point is the difficulty could be when one should combine multiple material and execution requirements.

For example, for an offshore structure the frost exposure adds up a challenge for mix design, having at the same time requirements for 500 cycles F/T resistance in ASTM C666 (proc. A) [61], high corresponding compressive strength of C60/75, 5-8% for total air-void content, increased open time of fresh concrete, massive casts, suitability for slipforming, hence highly workable and SCM containing concrete with low w/c [62].

Examples above show that keeping high quality (=high degree of fulfillment of all the requirements) during the production of this kind of concretes is very demanding in practice without a comprehensive, time-consuming and expensive prequalification program.

Table 4. Material requirements. RESISTANCE

Country	Standard	Exposure class, exposed structure	Controlled parameters: Mix design, fresh concrete: Max w/c (effective w/c)	Min (effective C_{ef}[1]) binder content. kg	Min cement content (when SCM used)	Max (Min) SF content, %	Min strength class for cement	Min (Max) V+D+S[3], %	Max FA content[2] (Max Fa/C-ratio), %	Min air content (for aggregate D_{max}, mm), %	Durability class	Frost resistant aggregate (Class for aggregate)	Hardened concrete: Min comp. strength, MPa or class	Hardened air-void content, %	Max air-void spacing factor (specific surface)	Permeability class	Frost resistance (Class for frost resistance)
General, Europe, EU	EN 206:2013	XF1		(+)		+			(+)				+				
		XF2, XF3, XF4		(+)		+			(+)	+			+				
Norway, NO	NS-EN 206:2013+NA:2014	XF1	+	(+)		(+)		+	+		+		EU				
		XF2, XF3, XF4	+	(+)		(+)		+	+	+	+	+ (XF4)	EU				
	NS-EN ISO 19903:2006	Severe	(+)	+	+[6]	+			+	+, (+)			+				
		Very severe	(+)	+	+	+			+	+, (+)			+		+, (+)		
Sweden, SE	SS 137003:2015	XF1	(+)	(+)		+	+		+			+	EU				
		XF2, XF3	(+)	(+)		+	+		+	+, (+)		+	EU		+		+
		XF4	(+)	(+)		+	+		+			+	EU				+
Germany, GER	DIN 1045-2:2008-08	XF1	(+)		+, (+)							(+)[7]	+				
		XF3	(+)		+, (+)					+, (+)		(+)[7]	+				
		XF2,XF4	(+)		+, (+)					+, (+)		(+)[7]	+				+
Denmark, DK	DS 2426 (DS 411)	XF1	(+)		+	+	+		+, (+)	+			+				
		XF2, XF3, XF4	(+)	+	+	+	+		+, (+)	+			+	+	+		
Finland, FI	B4, Liite 3, SFS-EN 206-1	XF1, XF3	+		+	+		(+)	(+)								
		XF2, XF4				+		(+)	(+)								
Canada, CA	CSA A23.1-09-A23.2-09	A-1, A-2, A-3, F-1, F-2, C-1, C-2, C-XL	+[4]							+, (+)			+[5]		+		
Russia, RU	SP 35.13330.2011	Bridge										(+)				+	(+)
	GOST 26633-2015[8]	Road surface layer	+							+		(+)					

Country	Standard	Exposure class, exposed structure	Controlled parameters														
			Mix design, fresh concrete										Hardened concrete				
			Max w/c (effective w/c)	Min (effective C_{eff}[1]) binder content. kg	Min cement content (when SCM used)	Max (Min) SF content, %	Min strength class for cement	Min (Max) V+D+S[3], %	Max FA content[2] (Max Fa/C-ratio), %	Min air content (for aggregate D_{max}, mm), %	Durability class	Frost resistant aggregate (Class for aggregate)	Min comp. strength, MPa or class	Hardened air-void content, %	Max air-void spacing factor (specific surface)	Permeability class	Frost resistance (Class for frost resistance)
USA	AASHTO LRFD Bridge construction specification	Classes A(AE), B (AE), C (AE)	+		+	+		(+)	+	+, (+)			+				
		Class A (HPC)	+		+	+		(+)	+	+, (+)			+				
	ACI 201.2R-01		+							+, (+)					+, (+)		
	ACI 318-14	F1, F2	+							+, (+)		+	+				
		F3	+	+		+		(+)	+	+, (+)		+	+				
China	GB/T 50476-2008	II-C, II-D, II-E	+							+, (+)			+		+		+

Table 4 continued

Note: **(+)** means that a given standard uses a material requirement, written in **(**parentheses**)** in the table heading, f. ex. SS 137003:2015 specifies requirements for effective w/c, while ACI – for max acceptable w/c.

[1] C_{eff} =C+∑ki×pi, where Pi - puzzolana (FA, SF, GBFS)

[2] Requirements for FA content usually come along with the requirements for slag content.

[3] V - fly ash, D - silica fume, S – slag

[4] The maximum water-to-cementing materials ratio of the HVSCM-1 (high volume of supplementary cementitious materials) concrete, exposed to freezing and thawing, shall be reduced by 0.05 in all exposure classes.

[5] Minimum strength requirement for HVSCM-1 concrete (min 40% FA) and for exposure class C-XL should be given for 56 days.

[6] Requirement depends on D_{max}

[7] Standard specifies separate requirements for aggregates in concrete, depending on water saturation and exposure to chlorides or de-icing salts. Consequently, aggregates for concretes in classes XF2 and XF4 to be tested in salt (1%NaCl), XF1 and XF3 – in water. Limits of weathering or mass loss are different for each exposure class

[8] Retrieved from Appendix B. Additional requirements to concretes for various types of structures

4 Requirement to production and execution of concrete works

A general principle for the reviewed standards and recommendations can be embraced by the following quote from Hooton [65]: "Durable concrete can be made for most aggressive exposures provided appropriate materials, mix designs, and construction practices are followed. Blended cements and SCMs will improve the durability of concrete, but as with any cementing material, it cannot guarantee durability if it is not used in good quality concrete or if concrete is poorly placed and cured" (matured).

Practical understanding of how to obtain frost resistance and frost durability of severely exposed concrete boils down to composition and execution (mixing/workability/placement/execution/curing). Particularly the air entrainment is important. All the factors that may prevent the formation of the so-called adequate air-void system of the exposed parts of a concrete structure should be taken into consideration during production and execution phases.

Table 5 is focused on the production and execution parameters, which influence frost resistance of concrete.

Observations based on the reviewed standards:

0. General:

- The connection between a specification for production and execution and certain exposure characteristics depends on the specifics of the issuing organization. For instance, reviewed road authorities (AASHTO, SVV, ZTV) deal with similar exposure when they design roads, bridges, top coats, namely, saturated conditions, de-icing agents or sea spray. Therefore, their requirements are inseparably associated with exposure. Among the national standards reviewed, Canadian [17] and Russian [71] also connect production and execution with the exposure classes.

1. Mixing of concrete is scarcely mentioned in any of the standards.

- Recommendations to mixing time seem to exist only in North American standards [4,7,14]. AASHTO recommends increased mixing time for saltwater exposure, supposedly to ensure homogeneity of the mixture and activation of air-entraining agents used in their concrete mixes.
- Two documents of the selection [7, 38], namely ASTM standard and German construction guidelines from the road authorities, surprisingly offer a possibility for the addition of water after mixing without providing clear instructions on how to implement that. This we consider a lack of these two standards.
- None of the documents inform about effects of SCM in combination with admixtures, nor enlighten on the best practices for a combination of admixtures in the concrete mix. This is a lack since it is known that the effectiveness of the admixtures will vary with type and quality of pozzolans, with variation in the sequence of addition for admixtures and with their compatibility [4, clause 4.5]. It was clearly demonstrated in the study how varying the sequence of addition for admixtures can affect the air void system [75].

2. Transportation and delivery of fresh concrete.

- Russian standards [41,44,47] require that retention of workability is checked, compared to the actual transport time.
- Particular requirements do not seem to exist in the reviewed European documents.

- In North America, if we consider ASTM [7] requirement as a general limitation for transportation from A to B (max 1.5 hours), then for highways in AASHTO standard [15] it includes in the same timeframe placement and consolidation (practically reducing maximum allowed transportation time by ca 30 min). At the same time, the guide ACI 304R [4] sets even stricter requirements.

3. Fresh concrete measurements

<u>Air void content in concrete. Sampling</u>:

- European requirements for control of the air content were not found, either in concrete specification nor in the standard for execution. This lack of specification on where and when to measure fresh air content and workability can we consider a serious lack.
- The European standard for execution EN 13670, Chapter 8. Casting [ref. 21, with Norwegian National Annex], seems to be kept on a general level assuming that the contractor/executing party has all the detailed competencies necessary to ensure that specified quality is reached in the final concrete structure.
- In the USA, T.A.C is controlled at the concrete batch plant [7] and upon delivery of the truck on site [6]. Impact of a subsequent delivery, especially in the case of concrete pumping, should be taken into consideration during mix design in accordance with PCA and ACI recommendations [4,16].
- The Norwegian and Russian national standards [21,44,47] do not require to control T.A.C after transportation and use of delivery equipment, whereas Norwegian road authorities [24] and Canadian, Swedish and German national standards [17, 29,35] will have concrete checked immediately before placing.
- The frequency of the tests under production varies significantly. CSA [17] requires high reproducibility for concretes that are to be in saturated condition and exposed to de-icing agents, whereas other documents do not seem to have such a requirement.

<u>Air content. Verification tests</u>:

- Russian standards offer retention tests or test of the stability of technological parameters (air content, temperature, workability, fresh density, bleeding). However, there is no uniformity of the description for required properties retention found between GOST 7473 [41], GOST 30459 [47] and GOST 10181 [44], which entails a contradiction between producers and users. Even though GOST 7473 for fresh concrete is logically the first to check the requirements, a majority of the producers is prone to follow GOST 30459 for admixtures, since they are interested mainly in workability retention. However, GOST 10181 for test methods sets its own list of technological requirements to fresh concrete that should be retained in time.
- American ACI 304.2R [5] for concrete pumping and ASTM C172 [9] for fresh concrete suggest making a verification test before and after pumping to account for air loss and change in air-void structure in the mix design. At the same time, ACI 212 [2] suggests verification by using unit weight in addition to the air meter test.
- SVV [24,25] require reproducibility of T.A.C-value 3 times in a row with pressure meter with circa 25% allowable tolerance.
- The specifications do not stipulate verification tests for concrete containing SCM in terms of stability of air entrainment.

<u>W/C-ratio control</u> during production seems to be of interest only for the road authorities [24, 38]

Temperature control.

- The standards agree on the minimum allowable fresh concrete temperature of 5°C. It is the road authorities [15, 38] that are more concerned about maximum concrete temperature to avoid high (over 70°C) peaks in hardened concrete, which are likely to jeopardize concrete durability due to thermal crack formation, coarsened pore structure, delayed ettringite formation etc.
- Stability of the concrete temperature is very important because the variations in temperature entail deviations in T.A.C and air-void parameters [4, 72].

4. Placing and finishing

- ACI 302 [3] for slab and floor is the only document among all reviewed that offers finishing techniques and rules in order to prevent surface scaling under freezing from happening.
- ACI 304.2R [5] with a reference to [56] says that ordinary pumping has a minor effect on the spacing factor and, hence, frost resistance of the concrete. However, Jacobsen et al. 2012 [72] found that different researchers discovered a strong impact of pumping on an air-void system of concretes with low w/c-ratio, which is contrary to work presented in ACI standard.

5. Surface protection and curing

- There is a big difference between European and Russian codes for requirements for surface strength before first freezing (5MPa versus minimum 70% of design strength).
- Only AASHTO and CSA standards draw attention to curing precautions for concretes that are to be subjected to de-icing agents.
- AASHTO assigns a requirement for minimum strength level for concrete before exposure, while other documents from North America simply require a number of days and conditions for curing independent of concrete mix design.
- For offshore concrete structure NS-EN ISO 19903 [23] imposes the requirements to strength development (degree of hydration) and climatic conditions when curing (see a copy of the table from the standard below).

Reproduced from NS-EN ISO 19903 [23], table 7, page 66
Minimum values of a ratio for the strength of concrete at the end of curing to 28d strength

Climatic conditions when curing			**Strength proportion**		
			Submerged zone	Splash zone	Other zones
H	Humid	RH > 80%	0,5	0,6	0,5
M	Moderate	65% < RH ≤ 80%	0,6	0,7	0,6
D	Dry	45% < RH ≤ 65%	0,6	0,7	0,6
VD	Very dry	RH ≤ 45%	0,7	0,8	0,7

Note: Alternatively, curing duration can be estimated by calculating maturity based on appropriate function, suitable for selected binder combination. It is suggested that surface permeability or strength of concrete cover can also prove the equivalence of curing.

Table 5. Production and execution of concrete works. Requirements and recommendations

Country	Standard / Document	Execution parameters	Requirements / Recommendations
Europe	EN 206:2013 [20, p. 42]	Min temperature of fresh concrete	5 °C at the time of delivery
		Determination of curing time	Determination by a strength development curve at 20°C between 2 and 28 days or acc. to Table 16. Then curing class is determined by Table 4 in EN 13670 [21] with a subsequent duration determined in acc. with Annex F [21]
	EN 13670:2009 [21, p.27]	Curing regime	The concrete temperature should not fall below 0°C until the concrete surface compressive strength is min 5MPa
		Peak concrete temperature	Shall not exceed 70°C upon hydration, unless specified and proved otherwise
Norway	NS-EN 13670:2009/NA:2010 [21]	Total air content. Frequency of tests	Measured on starting and every 50 m^3 and at least every 3 hours
	NS-EN 14487-1+NA:2012 [22]	Total air content control	No requirements for control of air content for sprayed concrete
	Kværner AS [54] NCA Pub. 25 [26]	Protection against surface frost damage of young concrete during slipforming	Use insulation mats (with possible heating), covering young concrete under the form until it gained sufficient strength (ca 2-3 days old) to withstand F-T cycle, in addition to compulsory curing compound protection. Insulation should be evaluated for every case.
	NS-EN ISO 19903 [23]	Surface protection in freezing conditions	Concrete slabs and other parts that can become saturated shall be protected from the ingress of external water for at least 7 days after casting. Differential temperature across a section should not be allowed to exceed 10°C per 100mm to minimize early age cracking. Peak concrete temperature max 70°C. Concrete should always stay above 0°C until it reaches 5MPa
	SVV Prosesskode 2 [24]	Total air content and temperature (when cold or hot weather). Frequency of tests	Measured (just before placing, i.e. after pumping) every 50 m^3 or at least every 3 hours
		Stability of air content	Air content is stable if 3 consecutive measurements are within tolerance of ±1,5%
		Mass ratio	Tested for every 2000 m^3, produced by the plant (acc. to [25])
Sweden	SS 137003:2015 [29]	Total air content. Time of sampling	Immediately before placing
Germany	DIN 1045-2 [35] ZTV-ING [38]	Total air content. Time of sampling	In-situ just before placing
	ZTV-ING [38]	Maximum fresh concrete temperature	25 °C - for tunnel elements, 30 °C - for other structures
		Addition of water after mixing	Planned subsequent addition of water is permitted (after Client's consent) for concrete for pavements in-situ.
		W/c determination in fresh concrete	Within 1 hour after mixing. Microwave oven method [70] - 5.000±1g sample baked for at least 20min.

Country	Standard / Document	Execution parameters		Requirements / Recommendations
Russia	GOST 7473-2010 [41]	Maximum transportation time		Controlled by workability retention category[1]
	GOST 10181-2014 [44]	Retention of technological parameters: workability, fresh density, total air content, bleeding, fresh temperature		Two tests to be compared: within 15 min after production and within 20 min after delivery to site
	GOST 30459-2008 [47]	Total air content (when AEA[2] is used)		Immediately and 1 hour after mixing
		Properties retention - slump		Immediately and every 30 min after mixing
	SP 70.13330.2012 [71]	Curing regime	General	Protection against evaporation and meteorological precipitation until concrete reaches 70% of designed strength with subsequent maintenance of temperature-humidity conditions. In winter, it is curing during 5-7 days with concrete temperature 5-10^{o}C
			For concretes exposed to freeze-thaw in saturated conditions	The concrete temperature should not fall below 0^{o}C until the concrete reaches 80% of designed compressive strength
North America	ASTM C172/C172M [9] ACI 304.2R-00 [5]	Total air content and workability control		A correlation test is suggested by comparing concrete entering the hopper and that discharged at the end of the pipeline
	ASTM C94/C94M-16a [7]	Mixing time (without mixer performance test)		Not less than 1 min for mixers of 1yd^3 (0,76m^3). Increase by 15 seconds for each cubic meter (or cubic yard) of increased mixer capacity. It gives about 2 min of mixing time for 4m3 batch plant mixer
		Addition of water after mixing		A one-time addition of water is not prohibited, but it shall be completed within 15 min from the start of the first addition (ref. Clause 12.7 [7]). In that case, the drum of the mixer shall be turned min 30 additional revolutions.
		Maximum transportation time		Max within 1,5 hours after water is added into the mix (or cement introduced to the aggregates)
		Maximum fresh concrete temperature		32^{o}C (90^{o}F)
		Workability, temperature, density, total air content. Frequency of tests		At least every 115 m^3 (150yd^3). Sampling to be done after the discharge of not less than 0.25 m^3 of concrete.
Canada	CSA A23.1-09- A23.2-09 [17]	Curing regime. General (see Appendix 1, Table A1)		Additional curing (7d, +10^{o}C) – mainly for structurally reinforced concrete (except for elements submerged in manure) and saturated condition. Basic curing (3d, +10^{o}C) for other elements and unsaturated conditions.
		Total air content. For exposure classes: F-1, C-XL, C-1, C-2 (Table 2)	Time of sampling	Measured from the first portion of the concrete prior to placement, i.e. after the delivery.
			Frequency of tests	Every load or batch of concrete shall be tested until satisfactory control of the air content is established. Whenever a test falls outside the specified limits, the testing frequency shall revert to one test per load or batch until satisfactory control is re-established.
		Curing regime. For exposure classes: C-XL, C-1, C-2		Recommended for concrete to air-dry for at least a month after the end of the curing period, before exposure to de-icing chemicals

Table 5 continued

Country	Standard / Document	Execution parameters	Requirements / Recommendations
USA	ACI 212.3R-2010 [2]	Total air content. Verification	Air content readings should be verified on site by unit weight (density) test, ASTM C138/C138M
	ACI 302.1R-96 [3]	Finishing rules (to avoid scaling)	Air-entrained concrete should not receive a troweled finish. Magnesium floats should be used. Any finishing operation performed while there is excess moisture or bleed water on the surface is strictly forbidden
	ACI 304R-00 [4]	Maximum transportation time (for trucks with and without an agitator)	30-45 min (with possible corrections on weather conditions)
	ACI 318-14 [6]	Total air content. Time of sampling	As the concrete is discharged from a mixer to the conveying equipment, transferring concrete to the forms.
	AASHTO LRFD Bridge construction specification [15]	Mixing time for concrete Exposure to saltwater	More than 2 min, but less than 5 min (without concretizing the volume of the mix)
		Maximum fresh concrete temperature. Bridge decks. Exposure to saltwater	80°F (ca 26,5C°) at time of placement
		Maximum time for placement and consolidation	Prior to initial set and in no case more than 1.5 h after the cement was added to the mix
		Curing regime	Maintain the temperature of concrete above 45F (ca 7,2 C°) at least 6 days, when up to 25% of cement is replaced by pozzolana or up to 50% by slag – at least 10 days until concrete reaches 70% of designed strength
		The time required before exposure to salt water	Prevent salt water from coming in direct contact with the concrete for a period of not less than 30 days after placement
	PCA. Volume 19/1 [16]	Air loss when pumping concrete	Suggests to account for the reduction in air content from 2 to 3%

Table 5 continued

[1] Producers for simplification classify workability retention in 3 classes C1 – < 20 min, C2 – 20…60 min, C3 - > 60 min, which are connected to binder properties, temperature, etc.

[2] AEA – air entraining agent

5 Overview of test methods for freeze-thaw resistance. Requirements to frost durable concrete

An overview of freeze/thaw test methods is given. Testing is mainly done to understand what material characteristics that matter the most in the performance testing for frost resistance and to compare mixes with acceptance criteria.

Requirements and tests should ideally focus on documenting that with due curing conditions composition (especially mass-ratio) and material quality come out as specified in the finished concrete structure. This includes the entrained air voids that must survive the entire concrete production cycle to give the right air void system in the hardened structure. However, not all the reviewed documents follow this logic.

Table 6a shows material characterization and performance criteria, which we can relate to frost resistant concrete. The main material parameter measured is air void content.
Main observations:

- (Ultra) High-performance concretes in accordance with practice for offshore concrete structures [62] require only results from ASTM C666, procedure A to judge about frost durability of the structure. Whereas road authorities require in the first place a salt-scaling test to be done, even though the exposure can be as severe as for offshore structures.
- Russian freeze-thaw classes F for concrete use a compressive strength as a material characterization. The other standards that set requirements for the lowest strength for concrete surface before it is exposed to first freezing (see **Table 5**), could supposedly consider strength as a performance criterion, but at an early stage.
- Most of the specifications that do not require analysis of hardened air-void structure, offer other methods to assess potential to frost resistance like pore protection factor or protective pore ratio (known as PF) [24,25], and permeability [45].

Table 6b provides an overview of test methods for freeze-thaw resistance, which is one of the most controversial topics of production and documentation of frost durable concrete.
Even though a great deal of work has been done with clear separation between the two main deterioration forms, surface scaling and internal cracking, the discussion about the relation to real exposure and acceptance criteria are found to often cause disagreement and difficulties. This is partly due to effects of preparation, curing and aging of specimens, to what extent both scaling and cracking occur in the tests, and, last but not least, the relation between the tests and the field performance/service life. Well-known examples and uncertainties are:

1. Improved salt scaling durability by accelerated carbonation in OPC concrete while for slag concrete it can worsen the performance in lab tests. Unclear how carbonation will contribute to field performance and to the service life of the structure from frost resistance perspective.
2. Concrete that will be deemed durable in a severe deicer salt scaling test CEN TS 12390-9 may not pass a severe internal cracking test such as ASTM C666, procedure A.
3. The uncertainty of how long an air void system will be protective when frozen and thawed with liquid at the surface, i.e. what happens if/when air voids get water-filled.
4. How low w/b-ratio is needed for different binders and frost tests to obtain frost durability without entrained air voids of a specific spacing factor under varying curing- and exposure conditions (see 4th bullet point on page 18 on Russian old requirements for highest w/b-ratio of 0.41 for concrete without air entrainment).

The lack of understanding of how test methods work in such cases is a part of the challenge to find reliable specifications for concrete based on frost testing.

"Calibration" of frost test methods versus behavior of small specimens in field exposure stations has been done for many years, pointing to a probable reasonable connection between the European CEN/TS 12390-9 [67] salt-frost slab test and field exposure along heavily deicer exposed roads. However, there are some ageing-/microstructure issues and problems with excessive internal cracking compared to reinforced structures. Fast solutions to practical recommendations for a wide range of new binder types and exposed structures based on calibrated frost testing have therefore not been found yet. The time-consuming practice of field exposure stations and the transfer of experience from these to realistic acceptance criteria still needs updating for new binders.

D. Hooton [58] embraces salt-scaling standards in North America, concluding that:

- ASTM C 672 does not correlate well with field performance and appears to show fly ash and slag concrete at a disadvantage.
- Air-entrained concrete with up to 30% fly ash or 35% slag should be resistant to deicer salt scaling, provided that sufficient maturity is gained.
- The standard MTO LS-413 (almost the same as ASTM C672 but with mass loss measurements) is overly severe to SCM concretes unless additional maturity beyond the standard 14-day cure is attained prior to the test. However, in practice, there is no time to wait for concrete to mature for proving frost durability of a given structural element. Hence, SCMs are usually deemed unacceptable.

<u>Some additional observations</u>:

- ASTM C672 as a qualitative test requires an expert opinion on what the rate of scaling is. Table C1 (Appendix C1) shows a suggestion for more precise evaluation [58].
- Only Russian test standard [42] among all the other tests reviewed here comply with severe exposure, such as exposure to arctic and seawater, low-temperature frost cycles and exposed to chlorides surface. It is understood that GOST 10060 also allows user to choose between standard and accelerated freeze-thaw tests (see Appendix C2, Table C2.2).
- Russian tests do not offer any of the qualitative nor quantitative methods for evaluation of surface damage during freeze-thaw experiments, even though they put emphasis on following up surface scaling and cracking and that the test is to be interrupted when the surface is damaged enough.

VTT Technical Research Centre of Finland issued a comprehensive literature review of freeze-thaw testing in 2012 [80], where they also gave description of the test methods that had been withdrawn from use, for example, standard test method ASTM C671-94 for determining dilation caused by freezing-thawing cycles. However, conservative clients such as Exxon Mobil that build marine concrete structures still require using withdrawn ASTM C671 along with ASTMC666, procedure A [62].

Observation for laboratory works:

Studying mixing procedures for laboratories in Norway (SVV Method 411 in R210), it was discovered that ASTM C192/C192M (par. 8.1.2) suggests a completely different sequence of addition of part materials and a procedure for preparation of mixing equipment: "8.1.2. Prior to starting rotation of the mixer add the coarse aggregate, some of the mixing water, and the solution of admixture when required…. When feasible, disperse the admixture in the mixing water before addition. Start the mixer, then add the fine aggregate, cement, and water with the mixer running." While in Norway, it starts with misting of the mixer and its parts, followed by sequential addition of sand, coarse aggregate, cementitious material; mixing water and admixtures in a given sequence of addition is added 60 seconds after the dry mixing.

Variability in the lab routines leads to additional complications in correlating the results between countries, and different sequences of admixture dosage (AEA then SP, SP then AEA, AEA and SP together) can largely affect the resulting air void system [75].

Table 7 shows a selection of requirements to frost durable concrete both from standards, recommendations, and from some major projects. It also gives understanding of how complete the reviewed documents are when it comes to the all-round requirements for concrete in a given exposure.

Examples of requirements from project specifications with brief descriptions for Øresund Bridge (Danmark/Sweden), Hebron and White Rose gravity base structures (Canada, Newfoundland) are presented in Appendix E.

Table 6a. Tests for frost durability – material characterization

Country	Standard	Material characterization	Performance testing
Norway	NS-EN 206:2013+NA:2014	Total air-content, compressive strength, w/c_{eff}	Salt scaling – Slab test acc. to NS-CEN/TS 12390-9:2006: Lab or pre-testing: $M_{56} < 0{,}2$ kg/m^3 or $M_{56} < 0{,}5$kg/m^3 and $M_{56}/M_{28} < 2$.
	SVV Prosesskode 2	Total air-content, compressive strength, w/c_{eff} Pore protection factor - PF method, method 426 [25] Water-to-cement ratio – microwave	Salt scaling – Slab test acc. to NS-CEN/TS 12390-9:2006 Lab or pre-testing: $M_{56} < 0{,}2$ kg/m^3 or $M_{56} < 0{,}5$kg/m^3 and $M_{56}/M_{28} < 2$.
	NS-EN ISO 19903:2006	Total air-content, compressive strength, w/c_{eff} Air-void system in acc. with NS-EN 480-11:2005	Internal cracking, ASTM C666, procedure A
Sweden	SS 137003:2015	Total air-content, compressive strength, w/c_{eff} Air content / air-void system ASTM C457/C457M	Frost resistance: XF2, XF4 – SS137244, method A XF3 – SS137244, method B
Denmark	HETEK committee, Danish Road Directorate	Pore protection factor (only exp. class 1)[1] Req. - Min. 25%	Salt scaling – "Borås method", SS 147244: Lab or pretesting: $M_{56} < 0{,}2$ kg/m^3 or $M_{56} < 0{,}5$kg/m^3 and $M_{56}/M_{28} < 2$. In situ: $M_{56} < 1{,}0$ kg/m^3 Internal cracking, ASTM C666-A (only exp. class 1) Lab.: $expansion_{300} < 0{,}05$ % (0,1% - in-situ)
	DS 2426	Total air-content, compressive strength Air content / air-void system in acc. with ASTM C457/C457M	Internal cracking by ASTM C666 – Good
Finland	B4, Liite 3, SFS-EN 206-1	w/c (XF1, XF3), P - (XF1, XF3) and F(XF2, XF4) – values Protective pore ratio (similar to PF-method [25]): SFS 4475 (1980)	Salt scaling – Slab test acc. to CEN/TR 15177: Transit time ≥75% or relative flex. or splitting tensile strength ≥67% [80]
Germany	DIN 1045:2:2008-08	Total air-content, compressive strength, w/c_{eff} Water-to-cement ratio – microwave	Frost resistance and durability by DIN CEN/TS 12390-9:2006-08
	ZTV-ING		Frost resistance and durability by CDF test (BAW Code of practice [39])
Russia	SP 35.13330	Air content, compressive strength Concrete impermeability, GOST 12730.5-84	Frost resistance by GOST 10060 + Compressive strength
Canada	CSA A23.1-09-A23.2-09	Air content: The pressure method CSA A23.2-4C The volumetric method CSA A23.2-7C Compressive strength Air content / air-void system: ASTM C457/C457M (magnification 100…125) – cylindrical forms	Salt scaling (owner selects a method) - recommendations: ASTM C672/C672M BNQ NQ 2621-900 MTO LS-412
USA	ACI 201.2R-01, ACI 212.3R-10	Air content: The pressure method ASTM C231 The volumetric method – ASTM C173/C173M The gravimetric method (or the Unit weight test) – ASTM C138/138M Air content / air-void system ASTM C457/C457M	De-icer salt scaling ASTM C672
China	GB/T 50476	w/c, total air-content, compressive strength Air-void system (Spacing factor)	Frost resistance in acc. with GB/T 50082-2009

[1] Vuorinnen J., Om skyddsporförhållandet hos betong [About pore protection factor in concrete]. DBT publication nr. 22, Nordisk Workshop Beton & Frost, Køge, 1984

Table 6b. Tests for frost durability – freeze-thaw tests

Country	Type of frost resistance experiment		Procedure name	Samples			Freezing/thawing cycles		Test setup			Expression of test results				Exceptions / Limitations / Notes
	Scaling test	Internal cracking test		L x W x D, mm (Min surface area, m²)	Min. # of speci-mens per series	Curing plan	Duration of 1 cycle	Temp. range, C° (Where measured)	Test liquid / Setup	Freezing	Thawing	Parameter	Number of F/T cycles	Unit	Passing criteria	
Sweden, Europe	SS 137244 [30], CEN/TS 12390-9 [67]		Slab test or Borås method	150 x 150 x 50	4	1d - 20°C, 95%RH 6d - water, 20°C 21d - 20°C, 65%RH 3 d - 3mm deionized water on a test surface	24 h (16h/8h)	-18...-22 / +16...+24 (in the middle of test liquid above a specimen)	Method A [30] - 3%NaCl 3mm of FM on TS, one-sided Method B [30] – fresh water	Chamber controlled		Scaled material (gathered by brushing of loose material from TS)	56 (112 - with SF)	kg/m²	M_{56}<1 kg/m² M_{56}/ M_{28}<2	14±1 weeks in 65%RH, 20C deg for concrete with Slag content ≥ 35%
		SIS-CEN/TR 15177 [31]	Beam test	400 x 100 x 100	3	1d - 20°C, 95%RH 6d - sealed, 20°C 21d - water, 20°C	12 h (8h/4h)	-18...-22 / +22...+4 (center of a specimen)	Deionized water		in water +5...+21°C	Rel. Dyn.E-Modul	56	%		Visual assessment (cracks, scaling from aggregate particles, leakage of freezing medium) before the start and after the specified number of cycles should be reported
			Slab test	150 x 150 x 50	4	1d - 20°C, 95%RH 6d - water, 20°C 21d - 20°C, 65%RH 3 d - 3mm deionized water on a test surface	24 h (16h/8h)	-18...-22 / +16...+24	De-ionised water or 3%NaCl / 3mm of FM on TS	Chamber controlled		Length change Rel. Dyn.E-Modul	56	% %		
			CIF-test	150 x 150 x 70	5	1d - 20°C, 95%RH 6d - water, 20°C 21d - 20°C, 65%RH 7 d - test surface is dipped into 3%NaCl	12 h (7h/5h)	-19,5...-20,5 / +19...+21	3%NaCl / Inverted positioning with TS immersed in FM. 5 mm FM under TS			Length change Water uptake Rel. Dyn.E-Modul	56	%		
Germany, Europe	Bunke [68], CEN/TS 12390-9		Cube-Test	100 x 100 x 100	4	1d - 20°C, 95%RH 6d - water, 20°C 20d - 20°C, 65%RH 1d - submerged in the test liquid	24 h (16h/8h)	-13...-17 / +18...+22 (in the middle of reference specimen)	Submerged cubes in 3%NaCl, all sides	Chamber. Rapid thawing in 3 h from -15 to +20, then constant +20 for 5h		Scaled material (gathered by brushing of loose material from TS)	56 (100 - Bunke, DIN 1048)	%	M_{56} / M_0 < 3%	
	RILEM TC 117-FDC/CDF [69], CEN/TS 12390-9		CF-/CDF-Test	150 x 140 x 50 (0,08)	5	1d - 20°C, 95%RH 6d - water, 20°C 21d - 20°C, 65%RH 7d - capillary suction of 5mm test liquid	12 h (7h/5h)	-19,5...-20,5 / +19...+21 (liquid-cooling under the container and test liquid)	One-sided, capillary suction of 5mm CF - deionized water CDF - 3% NaCl	Chamber controlled		Scaled material (gathered by ultrasonic bath)	14 (CDF) 28(CF)	kg/m2	M_{56}<1,5 kg/m² M_{56}/ M_{28}<3	

Country	Type of frost resistance experiment		Proce-dure name	Samples			Freezing/thawing cycles		Test setup			Expression of test results				Exceptions / Limitations / Notes
	Scaling test	Internal cracking test		L x W x D, mm (Min surface area, m²)	Min. # of speci-mens per series	Curing plan	Duration of 1 cycle	Temp. range, C° (Where measured)	Test liquid / Setup	Freezing	Thawing	Parameter	Number of F/T cycles	Unit	Passing criteria	
North America	ASTM C672 [13]			A x B x 75 (0,045)	2	1d - 23±2oC 13d - moist storage, 23±2oC, 95%RH 14d - 23±2oC, 45-55%RH	22-26 h (16-18h / 6-8h)	-15...-21 / +21...+25 (in the chamber)	ca 3,87%CaCl2 (4g of CaCl2(H2O)x for 100ml of solution) / 6mm of liquid on TS	air +21…+25oC, 45-55%RH		Rating of scaling, photo documentation	50	0-5 (no - severe scaling)		No thermal elements suggested. No prevention against evaporation. No side insulation. No conditioning before F-T experiments. Water is added instead to maintain 6 mm FM.
North America		ASTM C666 [61]	Proc. A	275…405 x 75…125 x 75…125	3	1d - 23±2oC 14d - water, 23±2oC From structure: 2d - saturated lime water, 23±2oC	2-5 h (50% / 50%)	-16…-20 / +2…+6 (center of the specimen)	Immediately after curing bring spec in temp -1…+2oC, make measurements and start cycling in water	water	water	Rel. Dyn.E-Modul and durability factor Length change Mass loss	300	%		
			Proc. B							air	water					
Canada, Ontario	MTO LS-412 [19]			300 x 300 x 75	2	1d - 23±2oC, 95%RH 13d - 23±2oC, 95%RH 14d - 23±2oC, 45-55%RH	22-26 h (16-18h / 6-8h)	-19,5...-20,7 / +19...+21	3%NaCl / 6mm of liquid on TS		air 23±2oC, 45-55%RH	Scaled material	50	kg/m2	<0,8 kg/m²	Wooden supports for air circulation and temperature distribution.
Canada, Quebec	BNQ NQ 2621-900 [18]					1d - 23±2°C 13d - moist storage, 23±2°C, 95%RH 14d - 23±2°C, 45-55%RH 7d – resaturation of TS with 3%NaCl	24 h (16±1h/8±1h)	-15...-21 / +5...+28 (at the interface of FM and TS)	3%NaCl		chamber controlled	Scaled material	56	kg/m2	<0,5 kg/m²	Recommended test by ICON/CANMET, Canada for concretes with SCM
China		GB/T 50082—2009	Slow FT	100 x 100 x 100	3	24d - climate room 4d - water storage	> 8 h (1,5-2…4h/4h)	-18...-20 / 18...20 (water temp)		In air	Water, temp more than 10C for first 30 min, then 18-20 C	Mass loss Compressive strength loss	min 25	%	not more than 5% not more than 25%	
China			Fast FT	100 x 100 x 400	3	24d - climate room 4d - water storage	2...4h (1...2h/1h...2h) Lowest temp. is held for max 10 min	-16...-20 / 3...7 (temp in the center of the sample)		In water	Water	Weight change Rel. Dyn. E-Modulus Basic frequency, ʃ	min 25	%	<5% E reduced less than to 60%	The box for FT - 500 x 115 x 115 F/T cycles cannot be stopped for longer than the duration of 2 cycles when samples are not kept frozen, and not more than 2 times, whether samples are frozen or not

Table 6b continued

Country	Type of frost resistance experiment: Scaling test	Type of frost resistance experiment: Internal cracking test	Procedure name	Samples: L x W x D, mm (Min surface area, m²)	Samples: Min. # of speci-mens per series	Samples: Curing plan	Freezing/thawing cycles: Duration of 1 cycle	Freezing/thawing cycles: Temp. range, C° (Where measured)	Test setup: Test liquid / Setup	Test setup: Freezing	Test setup: Thawing	Expression of test results: Parameter	Expression of test results: Number of F/T cycles	Expression of test results: Unit	Expression of test results: Passing criteria	Exceptions / Limitations / Notes
China	GB/T 50082—2009		One-sided FT	150 x 110 x (70±2)	5	1d - 20±2ºC 6d - water, 20±2oC (cutting) 21d - 20±2ºC, 65±5%RH 7 d - resaturation in 3%NaCl (10±1 mm column), TS down	12 h (4h + 3h constant / 4h+1h constant)	-19…-21 / 20 cooling rate - 10 C /h (in the air)	3%NaCl / Inverted positioning with TS immersed in FM. 5 mm FM under TS	In a freezing medium, surrounding test dish with specimens. Chamber controlled		Water adsorption Scaled mass Rel. Dyn.E-Modulus, transition time	min 4		<1,5 kg/m² E reduced less than to 80%	CIF-cycle and type of test. Butyl tape is used for insulation of cube facets other than test surface. Sealing - 2-4 days before the end of conditioning Ultrasound test lasts 3 min for each measurement
Russia	GOST 10060-2012		First method F_1	100 x 100 x 100	12 (for FT) + 6 (reference)	1d - 20±2oC 27d - moist storage, 20±2ºC, 95%RH 4d - gradual saturation in water	> 4 h (> 2,5h / >1,5…2,5h)	-16…-20 / +18…22 (air/water temperature)		In air	Water	Mean compressive strength loss Mass loss Visual check Rel. Dyn.E-Modulus, Transition time (UPV) Deformation	15…800	%	ca < 10% (< 15% for LWA) strength loss < 2% mass loss No cracks, chips, spalling of ribs < 25% loss of E-Modul < 15% reduction of transition time < 0,1% average deformation	All concretes, except for concretes used for road and airfield pavement in the presence of mineralized water
				150 x 150 x 150			> 6 h (> 3,5h / >2,5…3,5h)									
			Second method F_2	100 x 100 x 100		1d - 20±2oC 27d - moist storage, 20±2oC, 95%RH 4d - gradual saturation in 5%NaCl	> 4 h (> 2,5h / >1,5…2,5h)	-16…-20 / +18…22 (air / solution temperature)			In 5%NaCl, 18…20C		50…800			Concretes used for road and airfield pavement in the presence of mineralized water
				150 x 150 x 150			> 6 h (> 3,5h / >2,5…3,5h)									
			Second rapid	100 x 100 x 100			> 4 h (> 2,5h / >1,5…2,5h)						20…300			All concretes, except for concretes used for road and airfield pavement in the presence of mineralized water and light-weight concretes lighter than 1500 kg/m3
				150 x 150 x 150			> 6 h (> 3,5h / >2,5…3,5h)									
			Third rapid	100 x 100 x 100	6 (for FT) + 6 (reference)	1d - 20±2oC 27d - moist storage, 20±2oC, 95%RH 4d - gradual saturation in 5%NaCl	> 8,5…10,5 h (2,5…3h + 2,5…3h constant / 1…2h in chamber down to -10C, in solution - min 2,5h)	-48…-52 / 18…22 (air / solution temperature)		5%NaCl			2…35 (Structure type 1) 5…205 (Structure type 2)			Structure types: 1. All concretes, except for concretes used for road and airfield pavement in the presence of mineralized water and light-weight concretes not heavier than 1500 kg/m3; 2. Concretes used for road and airfield pavement in the presence of mineralized water
				150 x 150 x 150			> 9,5…11,5 h (2,5…3h + 2,5…3h constant / 1…2h in chamber down to -10C, in solution - min 3,5h)									

Table 6b continued

Table 7. Overview of requirements for frost durable concrete

Country / Organization, Project	Exposure class, area, decisive parameter		Material requirements											Laboratory tests		Execution
			Max w/c (effective w/c)	Min cement (binder) content, kg/m^3	Max (Min) SF content, %	Max FA content (Max Fa/C-ratio), % or kg/m^3	Min air content in fresh / *hardened*** concrete (for aggregate D_{max}, mm), %	Max electric conductivity, Coulombs	Frost resistance, cycles (frost res. class or min. durability factor,%)	Quality of macro-porosity in hardened concrete: Min specific surface, mm^2/mm^3	Quality of macro-porosity in hardened concrete: Max spacing factor (single results) L, mm	Min concrete comp. strength (strength for cement), MPa or class	Water impermeability class (Durability class)	Porosity, air content, parameters of air voids (other requirements)	Frost resistance and other tests	Placing, Pumping, Curing
General Europe EN 206:2013	XF1		0,55	(300)*	11	(33)						C30/37				
	XF2		0,55	(300)*	11	(33)	4					C25/30				
	XF3		0,50	(320)*	11	(33)	4					C30/37				
	XF4		0,45	(340)*	11	(33)	4					C30/37				
Norway NS-EN 206:2013 +NA:2014	XF1		0,60	(250)*		(35)							M60			
			0,45	(300)*		(35)							M45			
			0,40	(330)*	(6)	(35)							M40			
		XF2 XF3	0,45	(300)*		(35)	4						MF45			
		XF4	0,40	(330)*	(6)	(35)	4						MF40			
Norway NS-EN ISO 19903:2006	Very severe, splash zone		0,40	400	10	35	4,0 (40) 5,0 (20)		$M_{s,56}\leq$ 0,50kg/m^2	25	0,25	40				Max vertical drop – 2,0m Protection from the ingress of external water for min 7 days after casting
Norway Road Authorities Prosesskode 2	SV-Standard concrete		0,40	(350$_{eff}$)	3…5 class 1	30 – class A	3…6% for B45 2…5% for over B45[1]				0,2	(42,5… 52,5)	(MF40 or M40)		NS-CEN/TS 12390-9 – F/T, slab test EN 480-11	

Country / Organization, Project	Exposure class, area, decisive parameter	Material requirements											Laboratory tests		Execution
		Max w/c (effective w/c)	Min cement (binder) content, kg/m^3	Max (Min) SF content, %	Max FA content (Max Fa/C-ratio), % or kg/m^3	Min air content in fresh / *hardened*** concrete (for aggregate D_{max}, mm), %	Max electric conductivity, Coulombs	Frost resistance, cycles (frost res. class or min. durability factor,%)	Quality of macro-porosity in hardened concrete: Min specific surface, mm^2/mm^3	Quality of macro-porosity in hardened concrete: Max spacing factor (single results) L, mm	Min concrete comp. strength (strength for cement), MPa or class	Water impermeability class (Durability class)	Porosity, air content, parameters of air voids (other requirements)	Frost resistance and other tests	Placing, Pumping, Curing
Sweden SS137003: 2015	XF1	0,60	(200)*	10	(35)						(42,5)				
	XF2	0,45	(200)*	10	(35)	4,0 (>16) 4,5 (>8; ≤16)					(42,5)			SS 137244, method A – with 3%NaCl	
	XF3	0,46	(200)*	5	(35)	5,0 (≤8)					(42,5)			SS 137244, method B – with fresh water	
	XF4	0,45	(200)*	5	(20)						(42,5)			SS 137244, method A – with 3%NaCl	
Denmark/ Sweden ASO Group, Skanska, Øresund Bridge [77,79]	Splash zone -3.0 to +6.0 m	0,42	270 (340)	6 (2)	20	4			25		45		(max Cl content 0,1% of powder content. Na_2O_{eq}≤3.0kg/m^3 with a mortar content of 60 vol.% Cores for air content drilled every 5000 m^3)	SS 137244, method A – with 3%NaCl Dilation method. Water saturated concrete should withstand 1 cycle – no cracks allowed	Avoid exposure to chlorides before concrete is 1 year old
Denmark DS 2426	XF1 (M - moderate)	0,55	150	11	35 (33)	4,5					(42,5) C25/30				
	XF2 (A - aggressive)	0,45	150 (375)	11	20 (33)	4,5/3,5**				0,2	(42,5) C35/45		Air void analysis DS/EN 480-11 2 samples 100x150mm2 with min age of 7 days		
	XF3 (A - aggressive)	0,45	150 (375)	11	20 (33)	4,5/3,5**				0,2	(42,5) C35/45			SS 137244, method A – with 3%NaCl	
	XF4 (E - extra aggressive)	0,40	150 (375)	11	20 (33)	4,5/3,5**				0,2	(42,5) C40/50				

Table 7 continued

Country / Organization, Project	**Exposure class, area, decisive parameter**	**Material requirements**											**Laboratory tests**		**Execution**
		Max w/c (effective w/c)	Min cement (binder) content, kg/m³	Max (Min) SF content, %	Max FA content (Max Fa/C-ratio), % or kg/m³	Min air content in fresh / *hardened*** concrete (for aggregate D_{max}, mm), %	Max electric conductivity, Coulombs	Frost resistance, cycles (frost res. class or min. durability factor,%)	Quality of macro-porosity in hardened concrete: Min specific surface, mm²/mm³	Quality of macro-porosity in hardened concrete: Max spacing factor (single results) L, mm	Min concrete comp. strength (strength for cement), MPa or class	Water impermeability class (Durability class)	Porosity, air content, parameters of air voids (other requirements)	Frost resistance and other tests	Placing, Pumping, Curing
Finland SFS-EN 206-1, liite 3	XF1	0,60	270	11	(30)			(F = 1,0)							
	XF2			7	(30)			(P = 25)							
	XF3	0,50	300	11	(30)			(F = 1,5)							
	XF4			7	(30)			(P = 40)							
Germany ZTV-ING	XF2, tunnel walls (airborne De-icer)	0,50	(300)	10	80 kg/m³	4,0…6,0(16)[3]					C30/37				
	XF4, horizontal surfaces (snow, De-icer)	0,50			[4]			$M_{s,28} \leq 1{,}50$ kg/m²			$C25/30_{28}$			BAW Code of practice	
Germany DIN 1045-2:2008-08	XF1	0,60	280 (270)								C25/30				
	XF2	0,55[5] / 0,50[5]	300 / 320[5] (270[5])								C25/30 or C35/45[6]			RILEM TC 117-FDC/CDF	
	XF3	0,55 / 0,50	300 / 320[5] (270)								C25/30 or C35/45[6]				
	XF4	0,50	320 (270[5])								C30/37			RILEM TC 117-FDC/CDF	
Canada KKC, Hebron GBS Project	Splash zone	0,36	(400)	8	15	5,0…8,0 (22)	1000	500 (90%)		0,25 (0,30)	B55 after 56 days		ASTM C457	NS 3473 – comp. strength ASTM C1202 – El. Conductivity NT Build 443 – Chloride diffusion ASTM C666, proc. A – rapid F/T	Max vertical drop – 1,5m Min 7d of moist curing to gain min. 70% strength Max cooling rate for concrete surface – 20°C per 24h.

Table 7 continued

Country / Organization, Project	Exposure class, area, decisive parameter	Material requirements											Laboratory tests		Execution
		Max w/c (effective w/c)	Min cement (binder) content, kg/m^3	Max (Min) SF content, %	Max FA content (Max Fa/C-ratio), % or kg/m^3	Min air content in fresh / *hardened*** concrete (for aggregate D_{max}, mm), %	Max electric conductivity, Coulombs	Frost resistance, cycles (frost res. class or min. durability factor,%)	Quality of macro-porosity in hardened concrete: Min specific surface, mm^2/mm^3	Quality of macro-porosity in hardened concrete: Max spacing factor (single results) L, mm	Min concrete comp. strength (strength for cement), MPa or class	Water impermeability class (Durability class)	Porosity, air content, parameters of air voids (other requirements)	Frost resistance and other tests	Placing, Pumping, Curing
Canada Confederation bridge [78]	Class A concrete Main piers and T-beams	0,34	416	7,5	-	6	300_{28d}				82_{28d}				Target slump – 200mm
	Class C concrete Massive foundations	0,37	285	7,5	32	7	420_{28d}				50_{28d} 76_{91d}				Target slump – 185 mm
USA Portland Cement Association	De-icer exposed HPC for bridges, severe exposure	0,45	(335)	10	25	6,0 (16-22)[2]	1500	(90) Visual rating 1, scaling	24	0,2			ASTM C457	ASTM C666, proc.A ASTM C672 ASTM C1202	Curing begins within 15 min after finishing Wet curing for 7 days and until comp. strength of 22 MPa is reached
USA ACI 201.2 ACI 212.3R ASTM C457	Severe exposure	0,45				4,5…7,5 (25,4)			24	0,2					
USA ACI 318-14	F3, De-icing salt, saturation, reinforced concrete	0,4		10	35	4,5…7,5 (25,4)					34,5				
Russia GOST 26633-2015	Road surface layer, bridges	0,45				5,0…7,0		($F_2$200) GOST 10060			B30	W8			
Russia GOST 31384-2017	XF1	0,55	300								B20				
	XF2	0,55	300			4					B35				
	XF3	0,50	320			4					B25				
	XF4	0,45	340			4					B35				

Table 7 continued

Country / Organization, Project	Exposure class, area, decisive parameter	Material requirements												Laboratory tests		Execution
		Max w/c (effective w/c)	Min cement (binder) content, kg/m³	Max (Min) SF content, %	Max FA content (Max Fa/C-ratio), % or kg/m³	Min air content in fresh / *hardened*** concrete (for aggregate D_{max}, mm), %	Max electric conductivity, Coulombs	Frost resistance, cycles (frost res. class or min. durability factor,%)	Quality of macro-porosity in hardened concrete		Min concrete comp. strength (strength for cement), MPa or class	Water impermeability class (Durability class)	Porosity, air content, parameters of air voids (other requirements)	Frost resistance and other tests	Placing, Pumping, Curing
									Min specific surface, mm²/mm³	Max spacing factor (single results) L, mm					
Russia Kværner, Sakhalin I GBS Project	Shaft concrete / splash zone	0,4	360	8	-	5,0...8,0 (20)	1000	($F_2$500) GOST 10060	25	0,25	C70/85 (52,5N)	W12	EN 12350-7 – air content NS-EN 480-11 – Air quality of hardened concrete	EN 206-1 – comp. strength GOST 12730.5 - Permeability GOST 10060 – rapid freeze-thaw tests ASTM C666, proc. A – rapid F/T	Max vertical drop – 1,5m. Min 3d of moist curing. Max cooling rate for concrete surface – 20°C per 24h. Exposure to F/T when min 80% of strength is attained

Table 7 continued

Note: **(**+**)** means that a given standard uses a material requirement, written in **(**parentheses**)** in the table heading, f. ex. SS 137003:2015 specifies requirements for effective w/c, while ACI – for max acceptable w/c.

[1] It serves as a requirement for frost resistance, it the last is not documented by any other means

[2] Based on criteria of required 9% air in the mortar phase of concrete

[3] Air content varies from stiff (4,5±0,5%) to flowable (5,5±0,5%) consistency within one aggregate size

[4] FA use in XF4 concrete is not permitted unless agreed separately with the customer

[5] Additions, excluding fly ash, may not be taken into account for the calculation of water-cement ratio and min. cement content

[6] For slow hardening concretes

[7] 0,55 for binders with min 80% PC-clinker

* Effective binder - Ceff =C+∑ki×pi, where Pi - puzzolana (FA, SF, GBFS)

6 Conclusive remarks and future work

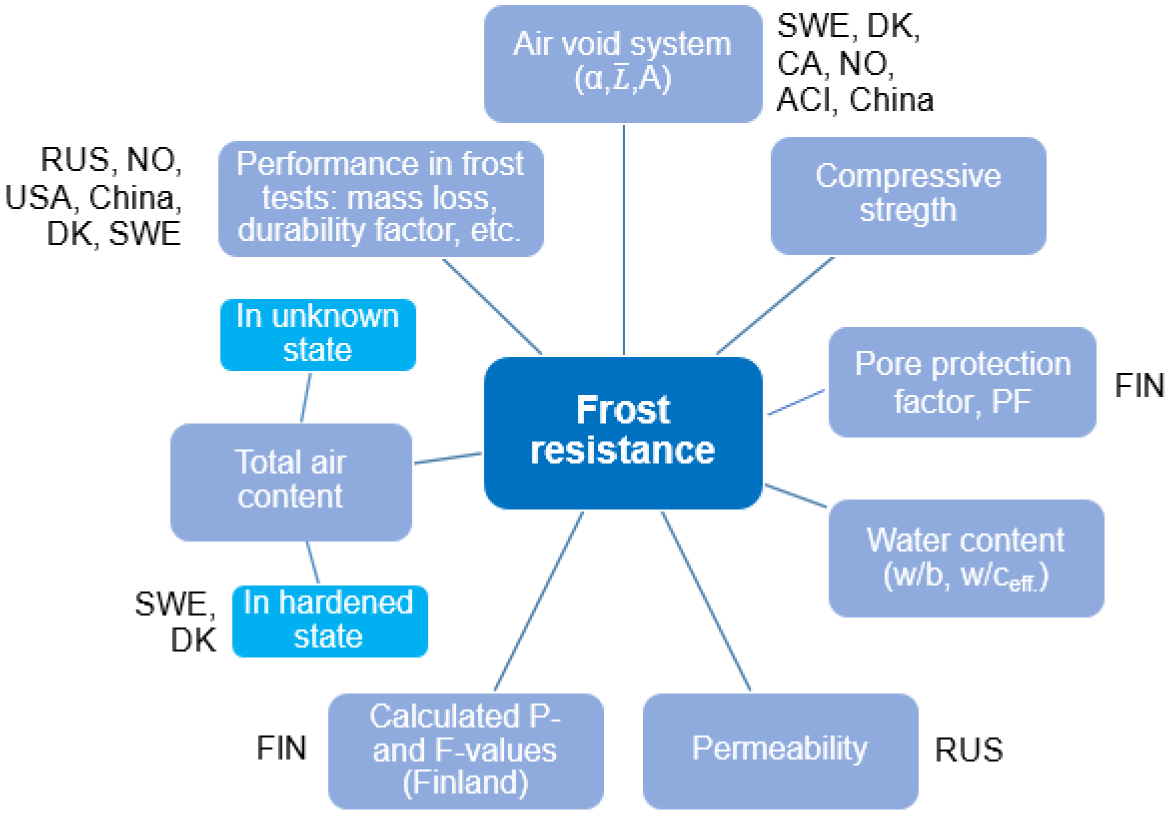

Figure 2. The meaning of frost resistance in different countries

If one should list down the requirements for concrete in a certain exposure from material requirements and testing to execution, quality assurance and handover, the results in different countries will vary in parameters, numbers and level of detailing.

Concerning material requirements, Figure 2 shows how variable the definition of frost resistant concrete can be, depending on which country one is going to design and build the structure in. As for execution requirements, it starts out with uncertainties about mixing procedures, especially when concrete contains SCM. Then there come requirements to transportation and delivery, which we found no description about in European documents. Another question is how to ensure that concrete put into the structure is of right quality, where to measure air and when, what is the requirement to concrete temperature (Dodson[3] stressed that air content is very dependant on fresh concrete temperature).

Practicalities that affect the quality of end product like placing, finishing and curing surprisingly are rarely described. For example, in the USA level of detailing in the regulatory documents allows people at supervisor level to understand how a task before him/her should be tackled.
In Norway, the system of standards and regulations is mainly oriented for a managerial level, providing only general information used as a tool to control processes. The system holds the management responsible by requiring a "Central approval" that is given based on proof of competence (see also the Norwegian hierarchy of acts and standards [76] in Appendix D). The Contractor is approved by the

[3] Dodson, Vance H. "Concrete admixtures", Chapter 6: "Air entraining admixtures", Van Nostrand Reinhold, New York, ISBN 0-442-00149-5 (1990)

Control Council for Concrete [kontrollbetong.no], The Directorate of Building Quality [dibk.no] or some other deputy or nominee for the particular field of work.
This difference between the end users of requirements can be an obstacle for international teams and projects.

Kukko and Kuosa [74] in 1999 reviewed the standards that define the requirements for frost resistant concrete in North America (Canada, USA) and Europe (Finland, Denmark, Norway, Sweden, Germany) with a slight focus on freezing and thawing without de-icing salts. At that time, they concluded that variations in exposure classification and frost resistance requirements were considerable. Today, 20 years after that review, we could stand by every word of their conclusion. However, there has been a positive change towards unifying environment classification in Europe, and that one day will make European (and maybe Russian) contractors speak “the same language”.

As per today’s knowledge, frost salt-scaling resistance of concrete has a direct relationship with its air-void system, the formation of which an air-entraining agent is responsible for. Contractors should always perform a certain number of trial batches and also use mockups to verify that the ingredients and procedures used would result in satisfactory and reproducible air-void system in the concrete as placed [57]. It turns out there is a lack of information on how to combine chemical admixtures in a given binder system [75]. Therefore, concerning frost resistance, the standard requirements for chemical admixtures and practice of combining them in the industry requires a thorough revision.

The present report is published in Open Access as a DaCS project report.

The document will also serve as a contribution in a rather major future literature review by newly (October 2018) established RILEM Technical Committee FTC[4]: Durability and service life of concrete under the influence of freeze-thaw cycles combined with chloride penetration; Cluster B.

[4] Chair: Prof. Dr. Dr.-Ing h.c. Folker H. Wittmann. Deputy chair: Dr. Peng Zhang

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Appendices

Appendix A. Canadian standard requirements for concrete in freeze-thaw exposure conditions

Table A1. Requirements for concrete, exposed to F/T, given by CSA A23.1-04 – Concrete Materials and Methods of Concrete Construction, Canadian Standards Association International

Reference	Exposure classes	A-1	A-2	A-3	F-1	F-2	C-2	C-1	C-XL
Table 1, s.121		Manure and/or silage gases exposure with/without F/T conditions			F/T exposure without chlorides		Exposure to chlorides with/without F/T conditions		
4.1.1.3, Tables 2 and 4	**Description** **Concrete requirements**	Structurally reinforced concrete exposed to severe manure and/or silage gases, with or without freeze-thaw exposure. Concrete exposed to the vapour above municipal sewage or industrial effluent, where hydrogen sulphide gas might be generated. Examples: reinforced beams, slabs, and columns over manure pits and silos, canals, and pig slats; and access holes, enclosed chambers, and pipes that are partially filled with effluents.	Structurally reinforced concrete exposed to moderate to severe manure and/or silage gases and liquids, with or without freeze-thaw exposure. Examples: reinforced walls in exterior manure tanks, silos and feed bunkers, and exterior slabs.	Structurally reinforced concrete exposed to moderate to severe manure and/or silage gases and liquids, with or without freeze-thaw exposure in a continuously submerged condition. Concrete continuously submerged in municipal or industrial effluents. Examples: interior gutter walls, beams, slabs, and columns; sewage pipes that are continuously full (e.g., forcemains); and submerged portions of sewage treatment structures.	Concrete exposed to freezing and thawing in a saturated condition, but not to chlorides. Examples: pool decks, patios, tennis courts, freshwater pools, and freshwater control structures.	Concrete in an unsaturated condition exposed to freezing and thawing, but not to chlorides. Examples: exterior walls and columns.	Non-structurally reinforced (i.e., plain) concrete exposed to chlorides and freezing and thawing. Examples: garage floors, porches, steps, pavements, sidewalks, curbs, and gutters.	Structurally reinforced concrete exposed to chlorides with or without freezing and thawing conditions. Examples: bridge decks, parking decks and ramps, portions of marine structures located within the tidal and splash zones, concrete exposed to seawater spray, and salt water pools.	Structurally reinforced concrete exposed to chlorides or other severe environments with or without freezing and thawing conditions, with higher durability performance expectations than the C-1, A-1, or S-1 classes.
Table 2, p.122	Max w/c-ratio[1]	0,4	0,45	0,5	0,5	0,55	0,45	0,4[3]	0,37
Table 2, p.122	Min strength[2], Mpa / age, d	35/28	32/28	30/28	30/28	25/28	32/28	35/28	50/56
	Air content category	1	1	2	1	2	1	1	1
Table 4, p.124	Air content, max agg size 22mm (14-20)	5-8%	5-8%	4-7%	5-8%	4-7%	5-8%	5-8%	5-8%

Table A1 continued

Reference	Concrete requirements	A-1	A-2	A-3	F-1	F-2	C-2	C-1	C-XL
Table 2, p.122	Curing type, normal concrete	2	2	1	2	1	1	2	3
Table 20, p. 134	Description of curing procedure	Additional curing. 7d at +10C	Additional curing. 7d at +10C	Basic curing. 3d at +10C	Additional curing. 7d at +10C	Basic curing. 3d at +10C	Basic curing. 3d at +10C	Additional curing. 7d at +10C	Extended wet curing 7d at +10C
4.3.3.3, a	Average air-void spacing factor / max value, µm	230/260	230/260	230/260	230/260	230/260	230/260	230/260	230/260
4.3.3.3, b	Average air-void spacing factor / max value for w/c lower than 0,36, µm	250/300	250/300	250/300	250/300	250/300	250/300	250/300	250/300
4.3.3.3, note 2	Target max spacing factor, considering large variations in ASTM C457/C457M, µm	170	170	170	170	170	170	170	170

[1] Clause 8.7.3. The maximum water-to-cementing materials ratio of the HVSCM-1 concrete, exposed to freezing and thawing, shall be reduced by 0.05 in all exposure classes.

[2] Clause 8.7.3. Minimum strength requirement for HVSCM-1 concrete (min 40%FA) should be given for 56 days

[3] Clause 8.7.3. For HVSCM-1 concrete max w/c should be 0,35.

Appendix B1. Chinese requirements for frost durable concrete

- Air-void characteristics

Table B1.1. Chinese standard requirements to air-void parameters

Air content / Conditions / Maximum aggregate (mm)	High water content	Moderate water content	With salt/De-icer
10	6.5	5.5	6.5
15	6.5	5.0	6.5
25	6.0	4.5	6.0
40	5.5	4.0	5.5
Spacing factor (pac	250	300	200

- Water / cement ratio, strength and other parameters

Table B1.2. Chinese standard design requirements for concrete

Service life / Environment			100 years			50 years			30 years		
			Comp. strength grade	Max. w/c	Min. cover	Comp. strength grade	Max. w/c	Min. cover	Comp. strength grade	Max. w/c	Min. cover
Slab, wall, other surface structural elements	II-C, no salt		C45	0.40	35	C45	0.40	30	C40	0.45	30
			≥C50	0.36	30	≥C50	0.36	25	≥C45	0.40	25
			Ca35	0.50	35	Ca35	0.55	30	Ca30	0.55	25
	II-D	No salt	Ca40	0.45	35	Ca35	0.50	35	Ca35	0.50	30
		Salt									
	II-E, salt		Ca45	0.40		Ca40	0.45		Ca40	0.45	
Beam, column, other strip structural elements	II-C, no salt		C45	0.40	40	C45	0.40	35	C40	0.45	35
			≥C50	0.36	35	≥C50	0.36	30	≥C45	0.40	30
			Ca35	0.50	35	Ca35	0.55	35	Ca30	0.55	30
	II-D	No salt	Ca40	0.45	40	Ca35	0.50	40	Ca35	0.50	35
		Salt									
	II-E, salt		Ca45	0.40		Ca40	0.45		Ca40	0.45	

Requirements for concrete cover in the presence of De-icing salts belong to a separate durability / exposure class IV.

Appendix B2. Finnish standard. Definition of F- and P-values

$$\boldsymbol{F} = \frac{1}{-4{,}0 + 7{,}2 \times \frac{(\frac{w}{c})^{0{,}45}}{(a-1)^{0{,}14}}} \quad (1)$$

$$\boldsymbol{P} = \frac{46 \times \boldsymbol{k_{jh}} \times \boldsymbol{k_s}}{\frac{10 \times (\boldsymbol{WAS_{RED}})^{1{,}20}}{\sqrt{a}} - 1} \quad (2)$$

where

$\boldsymbol{k_{jh}}$	curing factor
$\boldsymbol{k_s}$	binder factor
$\boldsymbol{WAS_{RED}}$	reduced water-air-binder ratio
a	total air content, %

$$\boldsymbol{k_{jh}} = 0{,}85 + 0{,}17 \times \log_{10}(t_{jh}) \quad (3)$$

where

t_{jh}	curing time, days

$$\boldsymbol{k_s} = 1 - (\frac{Q_{vesi}}{\boldsymbol{Q_{sid}}})^{1{,}5} \times (0{,}05 \times sil + 0{,}02 \times kuona + 0{,}01 \times lt) \quad (4)$$

where

Q_{vesi}	effective water content, kg/m³
$\boldsymbol{Q_{sid}}$	effective binder content, kg/m³
$sil, kuona, lt$	silica fume (SF/b), slag (BFS/b), fly ash (FA/b) contents in binder respectively, %

$$\boldsymbol{Q_{sid}} = Q_{sem} + 2{,}0 \times Q_{sil} + 0{,}8 \times Q_{kuona} + 0{,}4 \times Q_{lt} \quad (5)$$

where

$Q_{sem}, Q_{sil}, Q_{kuona}, Q_{lt}$	cement, silica fume, slag and fly ash contents respectively, kg/m³

$$\boldsymbol{WAS_{RED}} = \frac{Q_{vesi} + 10 \times (a-2)}{\boldsymbol{Q_{sid}}} \quad (6)$$

Appendix C1. Tests of frost durability. Interpretation of scaling rating in Canada

Equivalency Chart Relating Visual Scaling to Mass Loss			
	CSA Scaling Rating	Mass Loss Range g/m2	Visual Characteristics of the scaling surface
Equivalency Rating	0	0 - 50	No significant scaling observed
	1	51 - 210	Very slight scaling 3mm (1/8") depth, max, no coarse aggregate visible and no popouts present
	2A	211 - 500	Slight to moderate scaling and/or presence of a few popouts
	2B	211-500	Slight to moderate scaling and/or presence of many popouts
	3	501 - 1300	Moderate scaling of mortar with some exposed coarse aggregate
	4	1301 - 2100	Moderate to severe scaling: the coarse aggregate is clearly exposed and there is significant scaling of the surface mortar
	5	>2100	Severe scaling: coarse aggregates are visible over the entire surface

Table C1. Recommendation for transition from qualitative rating of scaling to quantitative mass loss. [Reprinted from 58, page 44]

Figure above shows an attempt of how to interpret CSA's scaling rating in physical mass loss, g/m^2. It, however, remains unclear how rating #1 with 51-210 g/m^2 was translated to 3mm scaling depth in CSA A23.2-22C Scaling Test Visual Ratings, because, following a simple calculation of concrete with density of 2400 kg/m^3, we get 7.2 kg/m^2 of mass loss corresponding to 3mm.

Appendix C2. Requirements and tests of frost durability. The relationship between different frost tests in Russia

Table C2.1. Requirements for frost resistance of concrete structures, working in alternating temperatures (Translated and reproduced from GOST 31384-2017, Table E.1, page 36)

Exposure	Calculated ambient winter temperature[2], °C	Frost resistance class requirement[1]
XF2	Below -40	F_1300
Moderate water saturation, atmospheric action	-20 … -40	F_1200
	-5 … -20	F_1150
	Above -5	F_1100
XF3	Below -40	F_1400
High water saturation in fresh water	-20 … -40	F_1300
	-5 … -20	F_1200
	Above -5	F_1150
XF4	Below -40	F_2450
High water saturation in presence of seawater, de-icing agent, mineralized or subpermafrost water	-20 … -40	F_2300
	-5 … -20	F_2200
	Above -5	F_2100

[1] F_1 and F_2 – minimum frost resistance class by first and second respectively basic method (see Table C2.2 below)

[2] Calculated on the basis of average ambient temperature of the coldest five-day stretch (with max variability 8%)

Notes (selected):

2. For structures with variable degree of saturation for different parts, for example foundations for ETL, columns, etc., frost resistance class is based on the most severely exposed element.
3. Frost resistance classes for structures of water supply systems, bridges and pipes, airfields, roadways and hydraulic structures should be stipulated by country codes and standards of the receiving party. In Russia it is:
   - SP 31.13330.2012 SNiP 2.04.02-84* «Water supply. Outdoor systems and structures»,
   - SP 35.13330.2011 SNiP 2.05.03-84 «Bridges and pipelines»,
   - SP 121.13330.2012 SNiP 32-03-96 «Airfields»,
   - SP 34.13330.2012 SNiP 2.05.02-85* «Automobile roads»,
   - SP 41.13330.2012 SNiP 2.06.08-84 «Concrete and reinforced concrete hydraulic structures».

Table C2.2. The relationship between a number of test cycles and a grade for frost resistance of concrete
(Translated and reproduced from GOST 10060-2012, Table 4, page 5)

Methods		Types of concrete	Grades for frost resistance of concrete **F_1** or **F_2** and a number of cycles when intermediate tests are performed (abobe the line) and a number of cycles corresponding to a grade for frost resistance of concrete (under the line)												
Basic	**First**	All concretes, except for concretes used for road and airfield pavement in the presence of mineralized water[1]	$F_1$25	$F_1$35	$F_1$50	$F_1$75	$F_1$100	$F_1$150	$F_1$200	$F_1$300	$F_1$400	$F_1$500	$F_1$600	$F_1$800	$F_1$1000
			15 / 25	25 / 35	35 / 50	50 / 75	75 / 100	100 / 150	150 / 200	200 / 300	300 / 400	400 / 500	500 / 600	600 / 800	800 / 1000
	Second	Concretes used for road and airfield pavement in the presence of mineralized water[1]	-	-	-	$F_2$75	$F_2$100	$F_2$150	$F_2$200	$F_2$300	$F_2$400	$F_2$500	$F_2$600	$F_2$800	$F_2$1000
			-	-	-	50 / 75	75 / 100	100 / 150	150 / 200	200 / 300	300 / 400	400 / 500	500 / 600	600 / 800	800 / 1000
Accelerated	**Second**	All concretes, except for concretes used for road and airfield pavement in the presence of mineralized water[1] and light-weight concretes lighter than 1500 kg/m^3	-	-	$F_1$50	$F_1$75	$F_1$100	$F_1$150	$F_1$200	$F_1$300	$F_1$400	$F_1$500	$F_1$600	$F_1$800	$F_1$1000
			-	-	-	— / 8	— / 13	— / 20	20 / 30	30 / 45	45 / 75	75 / 110	110 / 150	200 / 300	300 / 450
	Third	All concretes, except for concretes used for road and airfield pavement in the presence of mineralized water[1] and light-weight concretes not heavier than 1500 kg/m^3	-	-	-	$F_1$75	$F_1$100	$F_1$150	$F_1$200	$F_1$300	$F_1$400	$F_1$500	$F_1$600	$F_1$800	$F_1$1000
			-	-	-	2	3	4	5	8	12	15	19	27	35
		Concretes used for road and airfield pavement in the presence of mineralized water[1]	-	-	-	-	$F_2$100	$F_2$150	$F_2$200	$F_2$300	$F_2$400	$F_2$500	$F_2$600	$F_2$800	$F_2$1000
			-	-	-	-	5	10	20	37	55	80	105	155	205

[1] Seawater is one of the types of mineralized water

Appendix D. Standards hierarchy in Norway

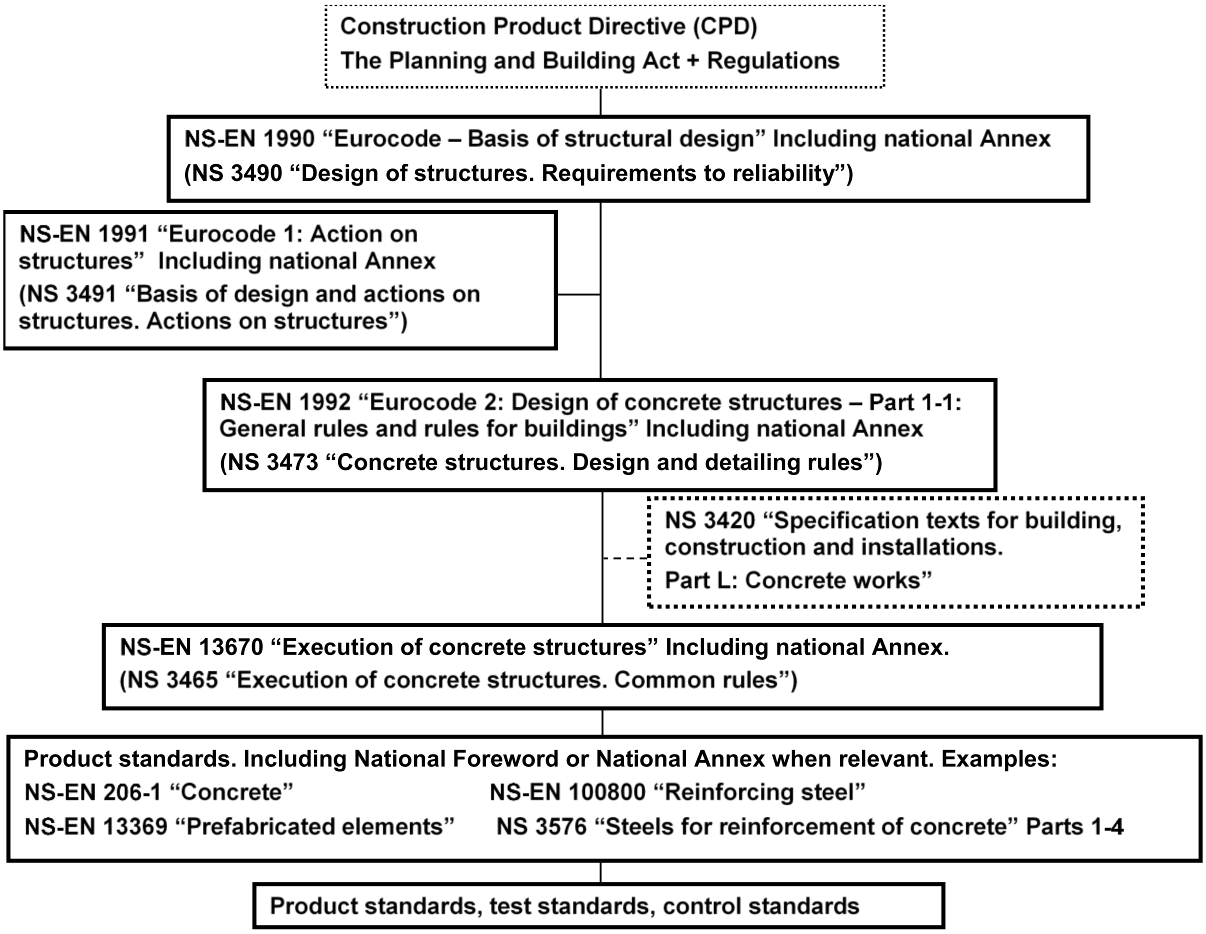

Figure D1. Hierarchy of acts and standards in Norway as it is autumn 2010.
(Reprinted from [76], figure 2.1, page 2-4)

Appendix E. Examples of requirements for frost durable concrete

E1. Requirements to concrete of Confederation Bridge

Figure E1. Confederation Bridge (retrieved from https://www.vinci-construction-projets.com/en/realisations/confederation-bridge/)

12.9 km long Confederation Bridge upon completion in 1997 connected Prince Edward Island with the main land of Canada, across the Northumberland Strait. It consists of 44 main spans of 250 m length each, massive main pier shaft and foundation elements fabricated on land.

Class A concrete (see Table E1) required a minimum of 55 MPa compressive strength and a maximum of 1000 coulombs chloride permeability (ASTM C 1202 test) at 28 days. Piers with an abrasion resistant ice shield required 80 MPa concrete. Class C concrete was used for pier foundations and some mass-concrete sections. It contained ca 32% fly ash as a cement replacement material. The requirements for Class C concrete were 30 MPa and 40 MPa minimum compressive strength at 28 and 90 days, respectively. All concrete also contained 7.5% silica fume by mass of the total binder content.

Table E1. Mix design and requirements for concrete of Confederation Bridge

Mix Proportions, kg/m^3	Class A Concrete for Main Piers and T-beams	Class C Concrete for Massive Foundations	Abrasion-resistant Ice Shield Concrete
Portland cement	416	285	478
Silica fume	34	22	42
Fly ash, Class F	-	133	60
Fine aggregate	737	744	650
Coarse aggregate	1030	1054	980
Water	153	159	142
Superplasticizer	3	2	6
W/cm	0.34	0.37	0.25
Properties			
Entrained air, %	6.1	7.0	-
Slump, mm	200	185	-
Compressive Strength, MPa			
1-day	35	9.7	-
3 days	52	27.4	-
28 days	82	50.0	100
91 days	-	76.0	-
Rapid chloride permeability, Coulombs (AASHTO T277)			
28 days	300	420	-
90 days	-	-	-

E2. Requirements to concrete of Hebron and White Rose gravity base structures

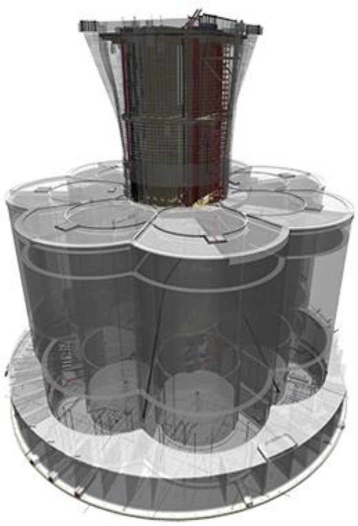
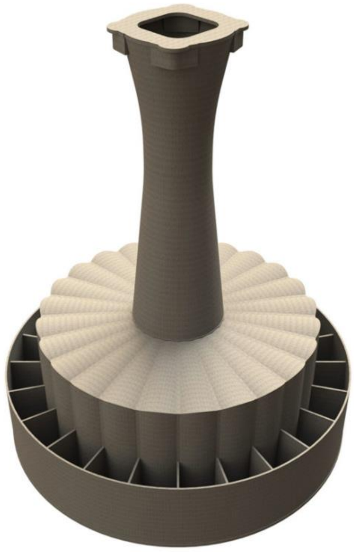

Figure E2. Offshore gravity base concrete structures:
- to the left - Hebron GBS (retrieved from https://www.kvaerner.com/Products/Concrete-structures-for-offshore-platforms/Hebron-GBS-Project/)
- to the right - West White Rose GBS (retrieved from http://westwhiteroseproject.ca/)

Table E2.1. Key parameters for the gravity base structures

Key parameters	Hebron GBS	White Rose GBS
Water depth (mean sea level)	93 m	120
Height of GBS	120 m	145 m
Diameter of GBS base	130 m	122 m
Concrete volume	130 000 m3	76 000 m3
Rebar	40 000 t (325kg/m3)	
Post tensioning steel	3 400 t	
Mechanical outfitting	5 500 t	
Completion	2016	2022

Note: Sources of information: https://www.kvaerner.com/, http://westwhiteroseproject.ca/, http://wwrp.huskyenergy.com/

Table E2.2. Requirements for concrete and prequalification tests

Parameters	**Hebron GBS**	**White Rose GBS**
Concrete grade	B65, NS3473	60MPa (28d shaft), EN1992
Exposure class	-	Class C-1 (Shaft), Class C-3 (subm.), CAN/CSA A23.1
Chloride diffusion coefficient	$<4.0 \cdot 10^{-12} m^2/s$	
Electric conductivity	< 1500 Coloumbs (submerged) < 1000 Coloumbs (splash), ASTM C1202	< 1500 Coloumbs (splash)
Freezing and thawing	500 cycles, ASTM C666 (Splash)	CAN/CSA A23.2-24A
Air-void system	Spacing factor < 0.25mm ASTM C457	Spacing factor < 0.23mm (splash) Specific surface > 25 mm^{-1}
W/c-ratio	< 0.40	< 0.40 shaft, < 0.45 submerged
Max chloride content	0.10%	0.10%
Cement content per m^3	Min 400 kg (shaft), min 340 kg (submerged)	400-475 kg (shaft) 360-450 kg (submerged)
Abrasion resistance	-	< 10mm loss
Air content, splash zone	5-8%	5-8%
Dmax aggregate	20mm	
Cementitious materials	Cement: C_3A 5-10% Fly ash: type F (low carbon) – max 30% replacement Silica fume: max 8%, SS 15-30 m^2/g, SiO_2 > 85%	Cement: C_3A 5-10% Fly ash: type F (low carbon) – max 35% replacement Silica fume: 5-10% (only shaft) CAN/CSA A23.1
Concrete temperature	Max peak - 70 °C Thermal gradient over 300mm – 20°C Cooling rate - 20°C per 24h	Max peak - 75 °C Thermal gradient over cross section – 20°C Cooling rate - 20°C per 24h

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