Review paper

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Special requirements for freeze-thaw resistance of concrete in PWR nuclear civil works

Dodatkowe wymagania dotyczące mrozoodporności betonu przy budowie elektrowni jądrowych typu PWR

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Abstract. The authors describe the additional requirements to ensure freeze-thaw resistance of concrete resulting from the French Rules for Design and Construction of PWR nuclear civil works RCC-CW. Since these requirements are based both on European standards and the French experience they are not fully compatible with the conditions and requirements in other countries, including Poland. The article seeks therefore to be an introduction to the discussion on adapting the guidelines for the freeze-thaw resistance of concrete from RCC-CW to Polish conditions.
Keywords: freeze-thaw resistance of concrete, requirements, nuclear power plant.

Streszczenie. Autorzy artykułu przedstawili dodatkowe wymagania dla zapewnienia mrozoodporności betonu wynikające z francuskich wytycznych do projektowania obudowy reaktora elektrowni jądrowej RCC-CW. Ponieważ wymagania te bazują zarówno na normach europejskich, jak i doświadczeniu francuskim, to nie są one całkowicie kompatybilne z warunkami i wymaganiami obowiązującymi w innych krajach, w tym w Polsce. Artykuł może być zatem wstępem do dyskusji na temat dostosowania wytycznych dotyczących mrozoodporności betonu RCC-CW do warunków polskich.
Słowa kluczowe: mrozoodporność betonu, wymagania, elektrownia jądrowa.

Freeze-thaw attack is the main corrosion process of concrete in Poland. It is a progressive phenomenon increasing with the number of frost cycles. Moreover, in connection with de-icing salt, the frost attack is much stronger. Only 50 years of durability of concrete is assured by PN-EN 206:2014, but the PWR nuclear structures life is extended to 80 and even 100 years. Therefore the RCC-CW *Design and construction rules for civil works in PWR nuclear islands* [17] is more restricted. It is based on French experience and technical measures that are defined for different frost exposure classes (requirements for concrete composition and performance). In many countries, including Poland, the conditions and experience (especially the test methods and qualification procedures) are different [6] so it is worthy to present these regulations.

Freeze-thaw durability according to PN-EN 206:2014

In PN-EN 206: 2014 if concrete is exposed to significant attack by freeze-thaw cycles whilst wet, the environmental action is classified as XF1 to XF4 exposure classes for risk of freeze-thaw attack:

- **XF1 Moderate water saturation, without de-icing agent**, e.g. vertical concrete surfaces exposed to rain and freezing;
- **XF2 Moderate water saturation, with de-icing agent**, e.g. vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents;
- **XF3 High water saturation, without de-icing agent**, e.g. horizontal concrete surfaces exposed to rain and freezing;
- **XF4 High water saturation, with de-icing agent or sea water**, e.g. road and bridge decks exposed to de-icing agents; concrete surfaces exposed to direct spray containing de-icing agents and freezing; splash zones of marine structures exposed to freezing.

Due to this classification the recommended limiting values for composition and properties of concrete are specified in Annex F. In RCC-CW these values are more restricted:

- for XF2: w/c ratio decreased from 0,55 to 0,50 and minimum strength class increased from C25/30 to C30/37;
- for XF4: minimum strength class increased from C30/37 to C35/45.

Additional requirements are given in PN-EN 206:2014 as well:

- **for all XF classes:** an **aggregate** should be in accordance with PN-EN 12620+A1:2010 with sufficient freeze/thaw resistance;
- **for XF2, XF3 and XF4:** minimum air content is limited to 4,0% and where the concrete is not air entrained, the performance of concrete should be tested according to an appropriate test method in comparison with a concrete for which freeze-thaw resistance for the relevant exposure class is proven.

In the bibliography of PN-EN 206:2014 there are two standards given for this purpose.

In PKN-CEN/TS 12390-9:2007 [15] it is recommended the use of „slab test" (based on the Swedish standard SS 13 72 44 [18], so-called Borås method) as a reference. The other two methods: one taken from RILEM-CF/CDF and the other „cube test" – based on original cube German method, are also contemplated for use as alternatives.

In CEN/TR 15177:2006 [2] there are presented three methods of testing internal frost resistance of concrete, i.e. test beam, slab test and CIF.

Requirements for aggregates in Poland

Actual requirements for freeze-thaw resistance of aggregates in Poland are

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formulated in PN-EN 12620+A1:2010. In Annex F it is stated that the aggregates can be considered resistant to freeze-thaw attack when the water absorption of the aggregates determined in accordance with PN-EN 1097-6:2013 is not greater than 1%. However, many satisfactory aggregates have higher absorption values. In such cases, resistance to freezing of aggregates shall be declared in accordance with the relevant category based on either a freeze-thaw value determined in accordance with PN-EN 1367-1:2007 or a magnesium sulfate value determined in accordance with PN-EN 1367-2:2010. The magnesium sulfate test is considered most appropriate for situations where the aggregates may be exposed to seawater or de-icing salts. Following an informative Annex F, freeze-thaw severity related to climate and end use are specified in categories which can be used to set the required level of categories freeze-thaw resistance or magnesium sulfate soundness (Table 1).

Table 1. Categories for aggregate freeze-thaw resistance and the requirements for freeze-thaw severity category related to end use in continental climate according to PN-EN 12620+A1:2010

Tabela 1. Kategorie mrozoodporności kruszywa i wymagania dla poszczególnych kategorii nasilenia zamrażania-rozmrażania w zależności od końcowego zastosowania w klimacie kontynentalnym zgodnie z PN-EN 12620+A1:2010

PN-EN 1367-1:2007		PN-EN 1367-2:2010		PN-EN 12620+A1:2010	
Freeze-thaw	Category	Magnesium sulfate value	Category	Environmental conditions	Climate
% loss of mass	F	% loss of mass	MS	(XF acc. to PN-EN 206:2014)	Continental
≤ 1	F_1	≤ 18	MS_{18}	Frost free or dry situation	Not required
≤ 2	F_2	≤ 25	MS_{25}	Partial saturation, no salt (XF1)	F_2 or MS_{25}
≤ 4	F_3	≤ 35	MS_{35}	Saturated, no salt (XF3)	F_1 or MS_{18}
> 4	$F_{Declared}$	> 35	$MS_{Declared}$	Salt – seawater or road surfaces (XF2, XF4)	F_1 or MS_{18}
No requirement	F_{NR}	No requirement	MS_{NR}	Airfield surfacings (XF4)	F_1 or MS_{18}

Requirements given in RCC-CW

In RCC-CW the basic requirements for concrete resulting from XF exposure classes that are expressed in limiting values for composition and properties of concrete are increased [16]. Additional requirements related to freeze-thaw attack are formulated both for aggregates as a component and concrete as a final product as well.

Aggregates for concrete subject to exposure classes XF3 and XF4 should not be liable to frost damage according to NF P 18-545 [11]. In addition, the water absorption of both fine and coarse aggregates shall comply with the requirements of code A aggregated described in NF P 18-545:2004 [11] – it means that WA_{24} ≤ 2,5% measured according to PN-EN 1097-6:2013. In qualification stage of aggregate freeze-thaw susceptibility can be measured according to PN-EN 1367-1:2007 (F) or PN-EN 1367-2:2010 (MS) or PN-EN 1097-2:2010 (LA), or PN-EN 1097-6:2013 (WA_{24}). In suitability test and conformity control these tests are not required.

The use of fly ash, either as an addition or as a constituent of the cement, is acceptable on condition that the loss on ignition of the fly ash respects Category A of PN-EN 450-1:2012 (loss of ignition, L ≤ 5% measured according to PN-EN 196-2:2013). In RCC-CW qualification stage for nominal concrete mix it is repeated after PN-EN 206:2014 that concrete subject to exposure classes XF2, XF3 or XF4 shall have a minimum air content of 4% measured according to PN-EN 12350-7:2011. In addition for concrete subject to exposure classes XF3 or XF4 and formulated with an air-entraining admixture, the qualification test shall include (for the one of the nominal concrete mix) a measurement of the spacing factor $\bar{L}$ according to PN-EN 480-11:2008 with the following criteria:

- $\bar{L}$≤ 250 μm for concrete subject to exposure class XF3;
- $\bar{L}$≤ 200 μm for concrete subject to exposure class XF4.

This requirement could be replaced by the performance tests based on French experience using freezing map and de-icing map of France (Figure 1). They present freezing zones divided onto:

- mild freezing conditions – less than 3 days with temperature < -5°C;
- moderate freezing conditions – other cases than mild or severe;
- severe freezing conditions – more than 10 days with temperature < -10°C;

and de-icing zones based on number of days with de-icing:

- not frequent: n < 10;
- frequent: 10 ≤ n < 30;
- very frequent: n ≥ 30.

In Poland, the appropriate map could be prepared by IMGW based on years of observations, eg. for the Suwałki station in the period 1971-2010 the average number of very cold days withT_{max} <-10°C was 5, but 7 times in a 40 year period, the number of very cold days was more than 10 and 13 times was >-5 (Figure 2). However, if we consider as the criterion days T_{min}<-10°C in Warsaw these days in winter average is 18 [7].

Following RCC-CW [17] for concrete in XF3 and XF4 in place of the measurement of the factor $\bar{L}$ or in case

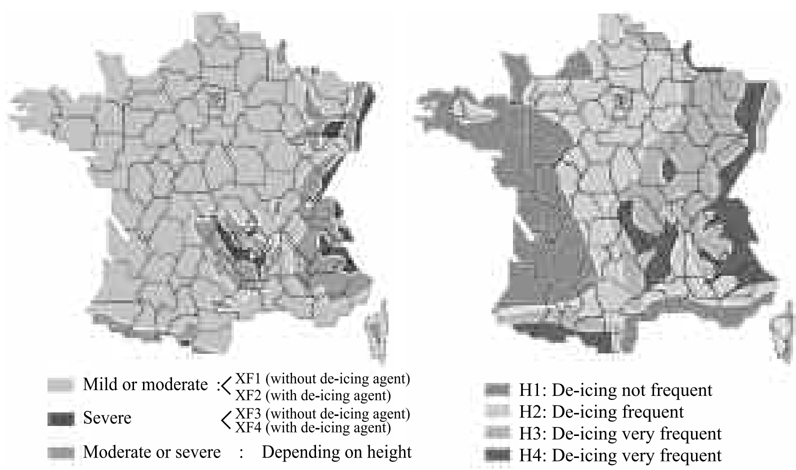

Fig. 1. Freezing map and de-icing map of France according to NF EN 206/CN [12]

Rys. 2. Mapa nasilenia zamrażania-rozmrażania oraz odladzania we Francji zgodnie z NF EN 206/CN [12]

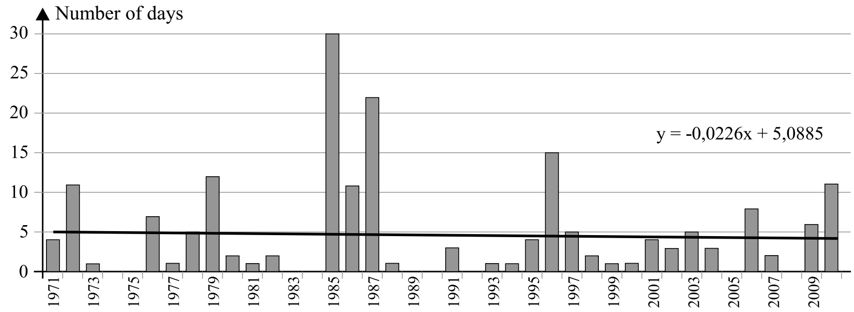

Fig. 2. Long-term variability of occurrence days with T_{max} ≤-10°C at the Suwałki station in the period of 1971-2010 [4]
Rys. 2. Wieloletnia zmienność występowania dni z T_{max} ≤-10°C na stacji Suwałki w okresie 1971 – 2010 [4]

Table 2. Exposure class description and performance test selection for specific conditions in France
Tabela 2. Dobór klasy ekspozycji i wybór badania mrozoodporności dla wybranych warunków we Francji

Exposure class	PN-EN 206:2014		NF EN 206/CN [12]		Performance test according to RCC-CW [17]
	Saturation	De-icing	Freezing zone	De-icing zone	
XF1	**Moderate**	No	Mild/Moderate	No-deicing/Not frequent	–
XF2	**Moderate**	Yes	Mild/**Moderate**	Frequent/Very frequent	NF P 18-425 [22]*
XF3	**High**	No	**Severe**	No-deicing/Not frequent	**NF P 18-424 [21]**
XF4	**High**	Yes	**Severe**	Frequent/Very frequent	**NF P 18-424 [21]**

* only for HPC

the specified maximum value of $\bar{L}$ is not respected, the concrete shall be subject to a performance test as follows (Table 2):

● NF P 18-424 [9] (freezing in water and thawing in water), for concrete subject to **severe freeze-thaw attacks** with a **high degree of water saturation** defined by PN-EN 206:2014– it means XF3 and XF4 – the limit value is Δl/l < 400 μm/m;

● NF P 18-425 [10] (freezing in air and thawing in water), for concrete subject to **moderate freeze-thaw attacks**, irrespective of the degree of water saturation of the concrete (in NF EN 206/CN there is no such case with high water saturation), or for concrete subject to **severe freeze-thaw conditions** with a **moderate degree of water saturation** defined by PN-EN 206:2014 (such case is not possible according to NF EN 206/CN) – the limit value is $(Fn^2/Fo^2)x100 \geq 75$. For high performance concrete subject to exposure classes XF2, XF3 or XF4, which are formulated with little or no air entraining admixture and do not contain the minimum air content the measurement of $\bar{L}$ is not relevant, so the qualification test shall include a performance test as well. HPC is differentiated from ordinary concrete by a compressive strength class of a High Strength Concrete (HSC – concrete with a higher strength than C50/60) and by one or more desired properties such as a higher level of compactness (for example for porosity or permeability requirements).

It is also acceptable to waive the requirement for the minimum air content for concrete exposed to frequent or very frequent attack from de-icing agents (XF2 or XF4) – in such case the scaling test according to XP P 18-420 [19] that is the same as „slab test" in PKN-CEN/TS 12390-9:2007 [15] should be performed. This procedure is also similar to the one expressed in PN-EN 1388:2005 except for number of cycles (increase from 28 to 56). The requirement is the mass of the scaling particles after 56 freeze-thaw cycles is M ≤ 600 g/m². This value is different than the conformity criteria for concretes according to Borås method in Swedish Standard SS 13 72 44 [18] that are based on mass of scaling at 28 days (m_{28}), 56 days (m_{56}) and at 112 days (m_{112}) and are expressed as:

■ very good: m_{56} average < 100 g/m²;

■ good m_{56} average < 200 g/m² or m_{56} average < 500 g/m² and m_{56}/m_{28}< 2 or m_{112} average < 500 g/m²;

■ acceptable: m_{56} average < 1000 g/m² and m_{56}/m_{28} < 2 or m_{112} average < 1000 g/m²;

■ unacceptable: the above not complied with.

Requirements for structural concrete in bridge construction in Poland

Additional requirements for freeze--thaw resistance of structural concrete in road infrastructure in Poland can be found in OST M-13.01.00 Structural concrete [14]. There is recommended that freeze-thaw resistance degree of structural concrete should be specified according to PN-B-06250:1998 and should be not less than: F100 for exposure class XF1; F150 for exposure class XF2 and XF3; F200 for exposure class XF4.

The required freeze-thaw resistance degree of concrete is achieved, if after the required number of cycles freezing on water saturated samples at -18 ± 2°C and thawing at +18 ± 2°C, the following conditions are met:

■ the sample is not broken;

■ total weight loss of concrete sample does not exceed 5%;

■ reduction of the compressive strength is not more than 20% relative tothe strength of the reference samples.

Also an additional requirement for coarse aggregate is presented. There are given two limits for resistance to freezing and thawing in the presence of salt (NaCl) according to PN-EN 1367-6:2008 (F_{NaCl} = 6 and 2%) and resistance to fragmentation according to PN-EN 1097-2:2010 (LA_{25} and LA_{40}).

Requirements for pavement concrete in Poland

Concrete designed for concrete pavements in Poland despite the requirement for aggregate should meet the requirements of OST D-05.03.04 Concrete pavements [13] (Table 3) and corresponding to the exposure class chosen as follow:

● XF3 in the absence of the use of chemical winter maintenance of roads/de-icing salts,

● XF4 for the use of chemical winter maintenance of roads.

Other requirements

In Lithuania where there are similar climate conditions to Poland and where Visaginas Nuclear Power Plant is a planned to be constructed, there is another sense of freeze-thaw resistan-

Table 3. Requirements for freeze-thaw resistance in accordance with OST D-05.03.04 Concrete pavements [13]
Tabela 3. Wymagania dla mrozoodporności betonu zgodnie z OST D-05.03.04 Nawierzchnia z betonu cementowego [13]

Exposure Class	Factor $\bar{L}$ PN-EN 480-11:2008	Category PN-EN 13877-2:2013	PKN-CEN/TS 12390-9:2007 Mass lost after 28 cycles (m_{28})	56 cycles (m_{56})	m_{56}/m_{28}
		FT0	–	–	–
XF3	≤ 0,250 mm	FT1	m_{28} average ≤ 1,0 kg/m², while no single result > 1,5 kg/m²	–	–
XF4	≤ 0,200 mm	FT2	m_{28} average ≤ 0,5 kg/m²	m_{56} average ≤ 1,0 kg/m², while no single result > 1,5 kg/m²	≤ 2

ce presented in LST 1974:2012 [8]. It is limited to 5% and defined as:

$$\Delta f_c = (f_{c28} - f_c^{Ncycle})/f_{c28}$$

where
f_c^{Ncycle} – compressive strength after N cycles of freezing-thawing (for XF4 it is recommended Ncycle = 300);
f_{c28} – 28 days compressive strength.

In BS 8500-1:2006 [1] there is Table A.8 that gives concrete properties and limiting values to resistthe XF exposure classes. These recommended concrete qualities are suitable for an intended working life of both „at least 50 years" and „at least 100 years". There are other limits minimum cement content for lower and higher strength concrete in specific exposure classes and they depends on aggregate size. Requirement for minimum air content is also applicable to lower strength concrete is specific exposure classes (Table 4).

Similar concept is in German DIN 1045-2:2008 [3] but due to more severe climate the requirements are more restricted as the limit value of air content depending on the aggregate size is: up to 8 mm ≥ 5,5%; up to 16 mm ≥ 4,5%; up to 32 mm ≥ 4,0%; up to 64 mm ≥ 3,5%. Probably in the nearest future the same idea will be implemented in new version of PN-B-06265:2004.

Summary

NPP construction in Poland has to be based on standards or some technical guidelines. The only guide that covers almost all aspects of construction phases is RCC-CW published by AFCEN. The problem is that it is based on French experience and European Norms (EN) but also partially on French National Standards, that are not always compatible polish conditions. Resistance to freeze-thaw cycles is, next to ASR [5], one of the example where there is a need for to adapt these requirements.

Table 4. Limiting values for composition and properties of concrete to resist freezing and thawing according to BS 8500-1:2006 [1]
Tabela 4. Wartości graniczne dla składu i właściwości betonu z uwagi na mrozoodporność zgodnie z BS 8500-1:2006 [1]

Exposure class	Min. strength class	Max w/c ratio	Min. air content and min. cement or combination content (kg/m³) for max. aggregate size: 32/40 mm	20 mm	14 mm	10 mm
XF1	C20/25	0,60	3,0 260	3,5 280	4,5 300	5,5 320
	C28/35	0,60	– 260	– 280	– 300	– 320
XF2	C25/30	0,60	3,0 260	3,5 280	4,5 300	5,5 320
	C32/40	0,55	– 280	– 300	– 320	– 340
XF3	C25/30	0,60	3,0 260	3,5 280	4,5 300	5,5 320
	C40/50	0,45	– 320	– 340	– 360	– 360
XF4	C28/35	0,55	3,0 280	3,5 300	4,5 320	5,5 340
	C40/50	0,45	– 320	– 340	– 360	– 360

Reference

[1] BS 8500-1:2006 Concrete – Complementary British Standard to BS EN 206-1 – Part 1: Method of specifying and guidance for the specifier.

[2] CEN/TR 15177 Testing the freeze-thaw resistance of concrete – Internal structural damage.

[3] DIN 1045-2:2008 Concrete, reinforced and prestressed concrete structures – Part 2: Concrete – Specification, properties, production and conformity – Application rules for DIN EN 206-1 (in German).

[4] http://klimada.mos.gov.pl/.

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[7] Kossowska-Cezak U. 2014. „Zmiany wieloletnie liczby termicznych dni charakterystycznych w Warszawie (1951–2010)". *Prace Geograficzne* 136: 9 ÷ 30. Kraków. Instytut Geografii i Gospodarki Przestrzennej UJ. DOI: 10.4467/20833113PG.14.001.1639.

[8] LST 1974:2012 Rules for the Application of LST EN 206-1 and Additional National Requirements (in Lithuanian).

[9] NF P 18-424:2008 Bétons – Essai de gel sur béton durci – Gel dans l'eau – Dégel dans l'eau (in French).

[10] NF P 18-425:2008 Bétons – Essai de gel sur béton durci – Gel dans l'air – Dégel dans l'eau (in French).

[11] NF P 18-545:2011 Granulats – Éléments de définition, conformité et codification (in French).

[12] NF EN 206/CN:2014 Béton – Spécification, performance, production et conformité – Complément national à la norme NF EN 206 (in French).

[13] OST D-05.03.04. 2011. Concrete pavements (in Polish). GDKiA.

[14] OST M-13.01.00. 2011. Structural concrete in bridge construction, GDKiA (in Polish).

[15] PKN-CEN/TS 12390-9: 2007 Testing hardened concrete – Part 9: Freeze-thaw resistance – Scaling.

[16] Piotrowski Tomasz. 2016. „Wymagania RCC-CW dotyczące betonu przy budowie elektrowni jądrowych PWR w świetle PN-EN 206:2014". *Materiały Budowlane* 529 (9): 89 ÷ 91; DOI: 10.15199/33.2016.09.35.

[17] RCC-CW. 2015. Rules for Design and Construction of PWR nuclear civil works. AFCEN.

[18] SS 13 72 44:1995 Concrete testing; Hardened concrete; Scaling at freezing (in Swedish).

[19] XP P 18-420:2012 Béton – Essai d'écaillage des surfaces de béton durci exposées au gel en présence d'une solution saline (in French).

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