TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
CIVIL ENGINEERING | BUDOWNICTWO

3-B/2015

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SELECTED ISSUES OF PRESTRESSED CONCRETE CONTAINMENT TANKS FOR THE STORAGE OF LIQUEFIED GASES DESIGN IN ACCORDANCE WITH EN 14620

WYBRANE ZAGADNIENIA PROJEKTOWANIA ZBIORNIKÓW Z BETONU SPRĘŻONEGO DO MAGAZYNOWANIA SKROPLONYCH GAZÓW W UJĘCIU EN 14620

Abstract

In 2014, a new tank for the storage of liquefied ammonia (capacity 22 000 m^3) was built for the chemical industry company ‘Grupa Azoty S.A.’. The LNG terminal in Świnoujście, where two large capacity containers (160 000 m^3 each) were built, is almost finished (2015). In both cases, prestressed concrete was used to build a secondary (outer) containment tank.This paper is devoted to general concepts and design considerations for secondary cylindrical, concrete containers for the storage of refrigerated, liquefied gases with temperatures between 0°C and –165°C, according to EN 14620.

Keywords: *prestressed concrete, cylindrical storage tanks, liquefied gases, low temperature*

Streszczenie

W 2014 roku przedsiębiorstwo przemysłu chemicznego Grupa Azoty S.A. oddało do użytku nowy zbiornik do magazynowania skroplonego amoniaku o pojemności 22 tys. m^3. Prace związane z budową terminala LNG w Świnoujściu, gdzie powstały dwa zbiorniki o dużej pojemności (160 tys. m^3 każdy), są niemal ukończone (2015). W obu wymienionych przypadkach konstrukcję zbiornika zewnętrznego wykonano z betonu sprężonego. Artykuł przedstawia ogólne koncepcje i zasady projektowania zewnętrznych walcowych zbiorników z betonu do magazynowania skroplonych gazów o temperaturach pomiędzy 0°C i –165°C, według normy EN 14620.

Słowa kluczowe: *beton sprężony, zbiorniki cylindryczne, skroplone gazy, niska temperatura*

DOI: 10.4467/2353737XCT.15.166.4341

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1. Introduction

The current version of standard EN 14620[1] specifies the recommendations for materials, design rules, construction details and installation principles for above ground containment tanks for the storage of liquefied, refrigerated gases.

Liquefied gas has to be stored at a temperature equal to its atmospheric boiling point (Table 1).The correct temperature level in combination with a small overpressure ($\leq$ 500 mbar) is necessary in order to achieve equilibrium between liquid and vapour phases inside the storage tank.

Table 1

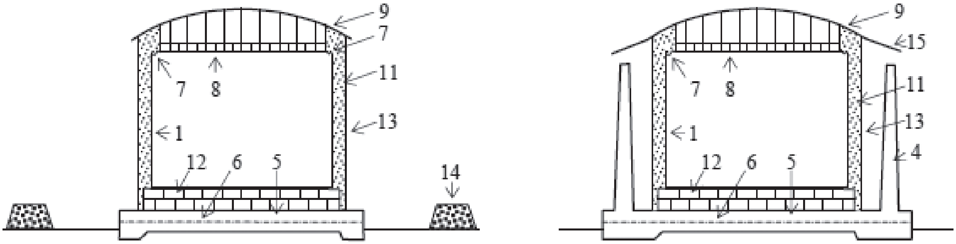
Physical properties of pure gases [1.1]

Name	Chemical formula	Mol. mass [g/mol]	Boiling point [°C]	Latent heat of vapour at boiling point [kJ/kg]	Liquid density at boiling point [kg/m^3]	Gas density at boiling point [kg/m$^3\cdot10^{-8}$]	Vol. of gas liberated by 1 m^3 of liquid (exp. to 15 [°C] at 1 [bar]) [m^3]
N-Butan	C_4H_{10}	58 123	–0.5	385	601	270	239
Izo-Butan	C_4H_{10}	58 123	–11.7	366	593	282	236
Amoniak	NH_3	17 030	–33.3	1367	682	905	910
Butadien	C_4H_6	54 091	–4.5	417	650	255	279
Propan	C_3H_8	44 096	–42.0	425	582	242	311
Propylen	C_3H_6	42 080	–47.7	437	613	236	388
Etan	C_2H_6	30 069	–88.6	487	546	205	432
Etylen	C_2H_4	28 054	–103.7	482	567	208	482
Metan	CH_4	16 043	–161.5	509	422	181	630
Note 1: Commercial butane is a mixture in N-Butane and isobutane with a small content of propane and pentane. Note 2: Commercial propane is propane with a small content of ethane and butane.							

2. Concepts of the tank construction

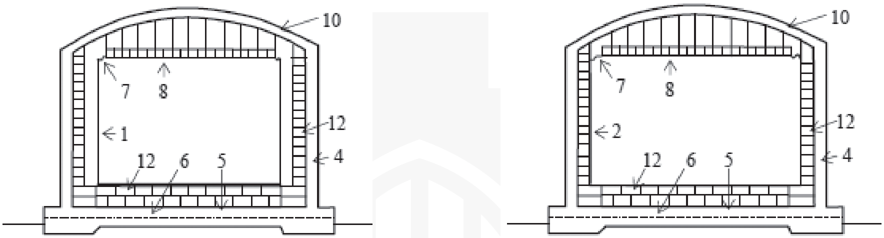
Cylindrical tanks for the storage of liquefied gases are designed on the grounds of four general concepts. Taking into account risk assessment, a certain type of tank construction should be selected:

– **Single containment tank** (Fig. 1a) – in this solution, there is only one (*primary*) self-supporting, steel cylindrical tank to store the liquid product. This primary containment tank may be surrounded by an outer steel tank designed as a vapour barrier or as protection for thermal insulation. Due to the risk of leakage, a single containment tank should be surrounded by a bund wall.



a) Single containment

b) Double containment



c) Full containment

d) Membrane containment

Key:
1. Primary container (steel)
2. Primary container (membrane)
3. Secondary container (steel)
4. Secondary container (prestressed concrete)
5. Foundation
6. Foundation heating system
7. Flexible insulating seal
8. Suspended roof (insulated)
9. Steel roof
10. Concrete roof
11. Loose fill insulation
12. External insulation
13. Outer shell (not capable of containing liquid)
14. Bund wall
15. Cover (rain shield)

Fig. 1. Examples of containment tanks: a) single, b) double, c) full, d) membrane [1.1]

- **Double containment tank** (Fig. 1b) – consists of an inner, primary container (liquid and product vapour barrier) and an outer, secondary containment tank (only liquid barrier in case of leakage from a primary tank). This outer (steel or prestressed concrete) tank should ensure the containment of the whole volume of liquid stored inside the primary tank. The annular space, between both containers, should not be greater than 6.0 m and needs to be protected by a steel shield against rain, snow, dirt etc.
- **Full containment tank** (Fig. 1c) – the primary (inner) and the secondary (outer) container form one integrated tank. Contrary to the 'double containment tank' the secondary containment (steel or prestressed concrete) tank should be equipped with a dome roof. Both containers are designed to contain liquid. In cases where the primary tank is open at the top, the product vapours are contained in the outer tank. The annular space between the primary and the secondary containers should not exceed 2.0 m.

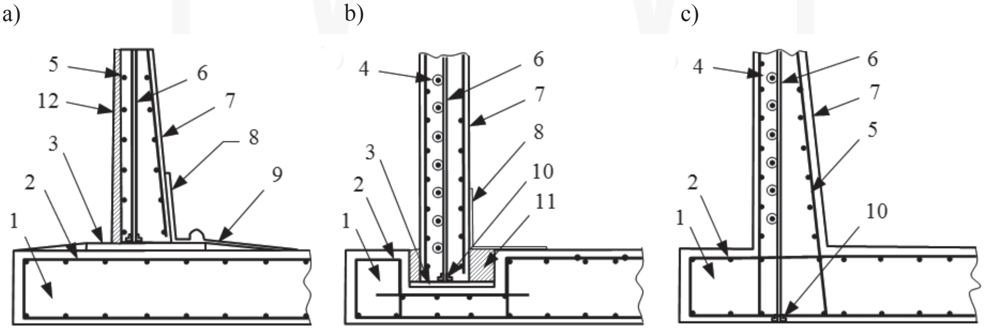
- **Membrane tank** (Fig. 1d) – consists of a thin steel membrane and load-bearing thermal insulation working together with a concrete container equipped with a dome roof. In the case of membrane leakage, the secondary concrete tank should be able to hold liquid and the product vapours.

3. Liquid tightness

The prestressed concrete secondary tank should ensure liquid and/or vapour tightness. Liquid leakage through concrete can be prevented in two ways [1.3]:

- Liners (steel plates) or reinforced/unreinforced polymer coatings may be used as a liquid (or vapour) barrier applied on the internal surface of the concrete. If concrete cracking occurs, the liner/coating should prove to be capable of 'bridging'a gap equal to 120% of the calculated crack width.
- A minimum compression zone in the concrete cross-section: x_{min} = 100 mm.

The selection of the type of wall to base connection is an important aspect of liquid tightness. It could be designed as: a sliding joint, pinned joint and fixed joint (Fig. 2). The last connection type is preferred for liquid tightness, but in the case of LNG tanks, it has to be thermally protected due to the risk of cracking in the case of leakage from the primary tank.



Key:
1) tank base
2) base reinforcement
3) bearing plate
4) circumferential prestress
5) wall reinforcement
6) vertical prestress
7) prestressed wall
8) stainless/nickel stell seal
9) radial strap
10) prestressing anchorage
11) grout
12) wire wound circumferential prestress with shotcrete layer

Fig. 2. Typical connections between the presteressed tank wall and the base: a) sliding joint, b) pinned joint, c) fixed joint [1.3]

4. Load cases

Typical load cases for the prestressed concrete outer tank in all phases of its operational life according to BS 7777-3 [5] are presented in Table 2. In the case of the design values of actions, the effects of actions, material properties, geometric data and design resistance, the reference should be made to EN 1992-1-1 [3]. Recommended values of partial factors for accidental actionsare shown in table 3. There is lack of reference to EN 1991-4 [6] in the range of load combinations or the values of partial load factors.

Table 2

Design situations for prestressed concrete secondary containment [5]

Loading conditions	Normal loads										Emergency loads							
	Construction		Test		Cool down		Operation		Maintenance		Leakage		Blast		Earthquake		Fire	
	W	B	W	B	W	B	W	B	W	B	W	B	W	B	W	B	W	B
Dead weight of concrete	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Dead weight of steel tank		+		+		+		+		+		+		+		+		+
Live load	(+)	+					+	+		+								
Pressure				+		+		+		+	+	+	+	+	+	+	+	+
Wind load	+		+		+		+		+		+		(+)		(+)		+	
Prestressing	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)	+	(+)
Shrinkage	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Creep	+	+	+	+	+	+	+	+	+	+								
Temperature					(+)	+	(+)	+			+	+		+		+	+	+
Leakage											+	+						
Blast													+	(+)				
Earthquake															+	+		
Fire																	+	
+ applicable, (+) not always applicable, W – tank wall, B – tank base																		

Table 3

Partial load factors for accidental actions [1.3]

Load combinations	Load factors					
	Dead		Imposed		Abnormal	Wind
	Adverse	Beneficial	Adverse	Beneficial	–	–
Normal actions + one accidental action	1.05	1.0	1.05	0	1.0	0.3
Accidental actions: earthquake (SSE), blast overpressure, external impact, fire or leakage from inner tank*						

* In the case of leakage from the primary container it shall be assumed that the secondary container is filled gradually and can contain the whole liquid from the inner tank.

Table 4

Hydrostatic tests [1.5]

Contents	Single containment	Double containment	Full containment	Membrane tank
Ammonia, butane, propane, propylene	Tank (type I–II steels) FH	Inner tank (type I–II steels): FH	Inner tank (type I–IIsteels): FH	–
		Outer tank (type I–IIsteels): FH	Outer tank (type I–IIsteels): FH	–
		Outer tank (prestressed concrete): notest	Outer tank (prestressed concrete): no test	Outer tank (prestressed concrete): PH
Ethane, ethylene, LNG	Tank (type IV steel) PH	Inner tank (type IV steel): PH	Inner tank (type IV steel): PH	–
		Outer tank (type IV steel): PH	Outer tank (type IV steel): PH	–
		Outer tank (prestressed concrete): no test	Outer tank (prestressed concrete): no test	Outer tank (prestressed concrete): PH
FH1) – Full height hydrostatic test; PH2) – Partial height hydrostatic test				

1) Full height (FH) hydrostatic test – the inner tank should be filled to the maximum design liquid level.
2) Partial height (PH) hydrostatic test – the inner tank should be filled to a level equalling 1.25 times the height of the maximum design liquid level multiplied by the density of the specified product to be stored.

In both cases, the same quantity of water should be used for the testing of the outer tank.

5. Hydrostatic tests

Hydrostatic tests should be carried out to prove that the tank is well designed and constructed to contain the product with no leakage and that its foundation is able to support the tank contents. In the case of the prestressed concrete outer tank, this type of testing is not required (Table 4) – one exception is the membrane tank, which should be hydrostatically tested before the insulation membrane is installed.

6. Material properties under cryogenic conditions

Concrete is well suited for the storage of cryogenic liquids because the majority of its properties improve substantially as temperature is lowered into the cryogenic range (Table 5). In the case of the prestressed concrete tanks, concrete of at least the class C40/50 should be used.

Table 5

Ranges of 'normal' and 'low'temperatures for concrete and steel

Standard	Concrete		Prestressed steel		Normal steel	
	Normal	Low	Normal	Low	Normal	Low
MC2010 [7,8]	$0°C \le T \le +80°C$	$T < 0°C$	$-40°C \le T \le +40°C$	$T < -40°C$	$-40°C \le T \le +40°C$	$T < -40°C$
PN-EN 1992-1-1 [3]	$0°C \le T \le +80°C$	$T < 0°C$	$-40°C \le T \le +100°C$	$T < -40°C$	$-40°C \le T \le +100°C$	$T < -40°C$
PN-EN 1992-3 [4]	$-25°C \le T \le +20°C$	$T < -25°C$	$-40°C \le T \le +100°C$	$T < -40°C$	$-40°C \le T \le +100°C$	$T < -40°C$
PN-EN 14620-3 [1]	$T \ge -20°C$	$T < -20°C$	$\ge -50°C$	$T < -50°C$	$T \ge -20°C$	$T < -20°C$

6.1. Concrete compressive strength

The compressive strength of the concrete increases with cryogenic temperatures [7]. The influence of the low temperature and moisture content on the concrete compressive strength gain Δf_{cm} (Fig. 3) can be estimated fromformula (1):

MC2010
$$\Delta f_{cm}\left(T, mc\right) = 12mc\left[1-\left(\frac{T+170}{170}\right)^2\right] \text{ if } 0°\text{C} \ge T \ge -170°\text{C} \tag{1}$$

where:

T – the temperature [°C];

mc – the percentage of moisture content by mass.

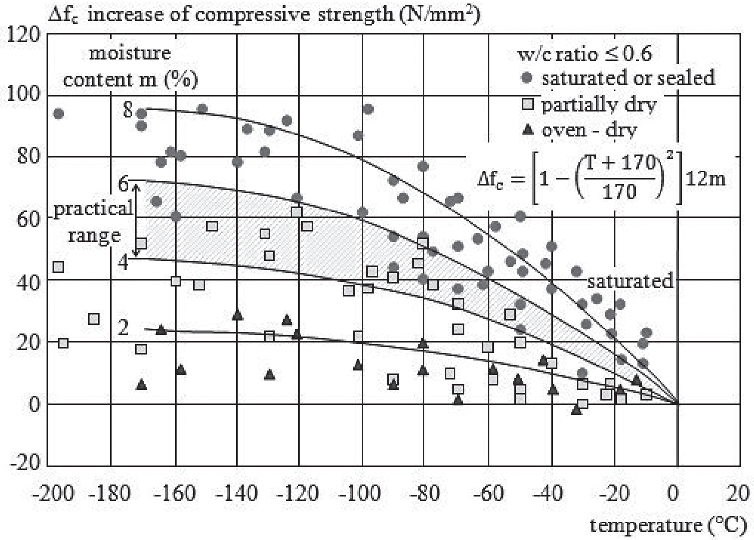


Fig. 3. Increase of compressive strength Δf_{cm} as a function of temperature and moisture content (Van der Veen, 1987) [9]

In practice, the following values of m may be assumed:

- 2% (general indoor);
- 4% (general outdoor);
- 6% (exposed to rain).

6.2. Compressive stress – strain relation for concrete

The influence of temperature on the stress-strain relationship (Fig. 4) can be expressed by equation (2):

MC2010
$$\sigma_c(t) = f_c(T, mc) \cdot \left[1 - \left(1 - \frac{\varepsilon_c(T)}{\varepsilon_{f_c}(T)} \right)^n \right] \tag{2}$$

where:

$\sigma_c(t)$ and $\varepsilon_c(T)$ – are stress and strain at a given point of the stress – strain curve,
$\varepsilon_{fc}(T)$ – is the strain at ultimate strain,
n – exponent n:

$$n = \begin{cases} 2 & \text{for} \quad T = 0°\text{C} \\ 1 + \dfrac{T + 170}{170} & \text{for} \quad -17°\text{C} < T < 0°\text{C} \\ 1 & \text{for} \quad T = -170°\text{C} \end{cases} \tag{3}$$

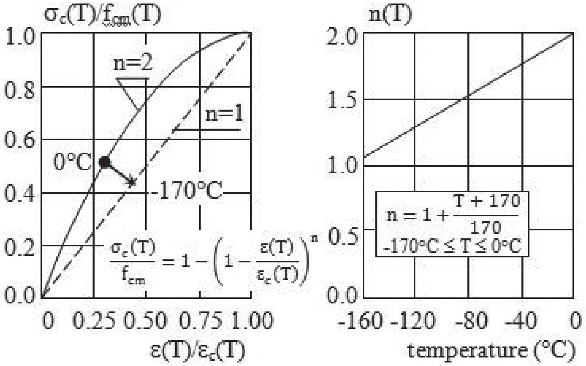


Fig. 4. Relative stress – strain relationship for concrete [9]

The ultimate strain $\varepsilon_{fc}(T)$ may be estimated as:

$$\varepsilon_{f_c}\left(T\right) = \varepsilon_{f_c}\left(T = 20°\mathrm{C}\right) + \kappa \cdot \Delta\varepsilon_{f_c}^{\max}\left(T = -60°\mathrm{C}\right) \tag{4}$$

where:

- concrete strain at 'normal'temperature: $\varepsilon_{fc}(T = 20°\mathrm{C}) = 0.2\%$
- coefficient κ:

$$\kappa = \begin{cases} 1 - \left(\dfrac{T+60}{60}\right) & \text{if} \quad T > -60°\mathrm{C} \\ \dfrac{T+170}{110} & \text{if} \quad -170°\mathrm{C} < T \le -60°\mathrm{C} \end{cases} \tag{5}$$

- maximum increase in strain experienced at –60°C:

$$\Delta\varepsilon_{f_c}^{\max} = \begin{cases} 0.1\% & \text{for Portland cement-based concretes} \\ 0.15\% & \text{for blast furnace cement-based concretes} \end{cases}$$

6.3. Concrete splitting tensile strength

The splitting tensile strength $f_{c,spli}$ can be calculated according to the expression:

MC 2010 $$f_{c,spli}\left(T, mc\right) = C \cdot f_c\left(T, mc\right)^{0.67} \tag{6}$$

The value of coefficient Cvaries between 0.3 (air-dry concrete) and 0.56 (water saturated concrete).

A similar equation for tensile strength f_{ctx} is recommended in PN-EN 1992-3 [4]:

EC2-3 $$f_{ctx} = \alpha \cdot f_{ckT}^{2/3} \tag{7}$$

The values of coefficient α are shown in Table 6.

Table 6

The coefficient α [4]

Tensile strength	Water saturated concrete	Dry concrete
f_{ctm}	0.47	0.30
$f_{ctk\,0.05}$	0.27	0.21
$f_{ctk\,0.95}$	0.95	0.39

6.4. Concrete modulus of elasticity

The modulus of elasticity E_c increases with decreasing temperature.According to EC2-3 [4], the influence of the moisture content on the modulus of elasticity gain ΔE_c can be estimated as:

EC2-3 $$\Delta E_c\left(T = -25°\text{C}\right) \approx \begin{cases} +2\ \text{GPa} & \text{for dry concrete} \\ +8\ \text{GPa} & \text{for water saturated concrete} \end{cases}$$

For concrete exposed to temperature $T = -165°\text{C}$, the modulus of elasticity increases significantly [8]:

MC 2010 $$E_c\left(T = -165°\text{C}\right) \approx \begin{cases} 1.15 \times E_c\left(T = 20°\text{C}\right) & \text{for dry concrete} \\ 1.5 \times E_c\left(T = 20°\text{C}\right) & \text{for sealed concrete} \\ 1.8 \times E_c\left(T = 20°\text{C}\right) & \text{for water saturated concrete} \end{cases}$$

6.5. Coefficient of thermal expansion

The coefficient of thermal expansion α_T decreases with reductions in temperature. The value of coefficient α_T strongly depends on the content of free moisture in concrete (Fig. 5). In the case of water saturated concrete, expansion behaviour (negative value of coefficient α_T) should be expected. For dry concrete, the coefficient of thermal expansion decreases by approximately 10% [8].

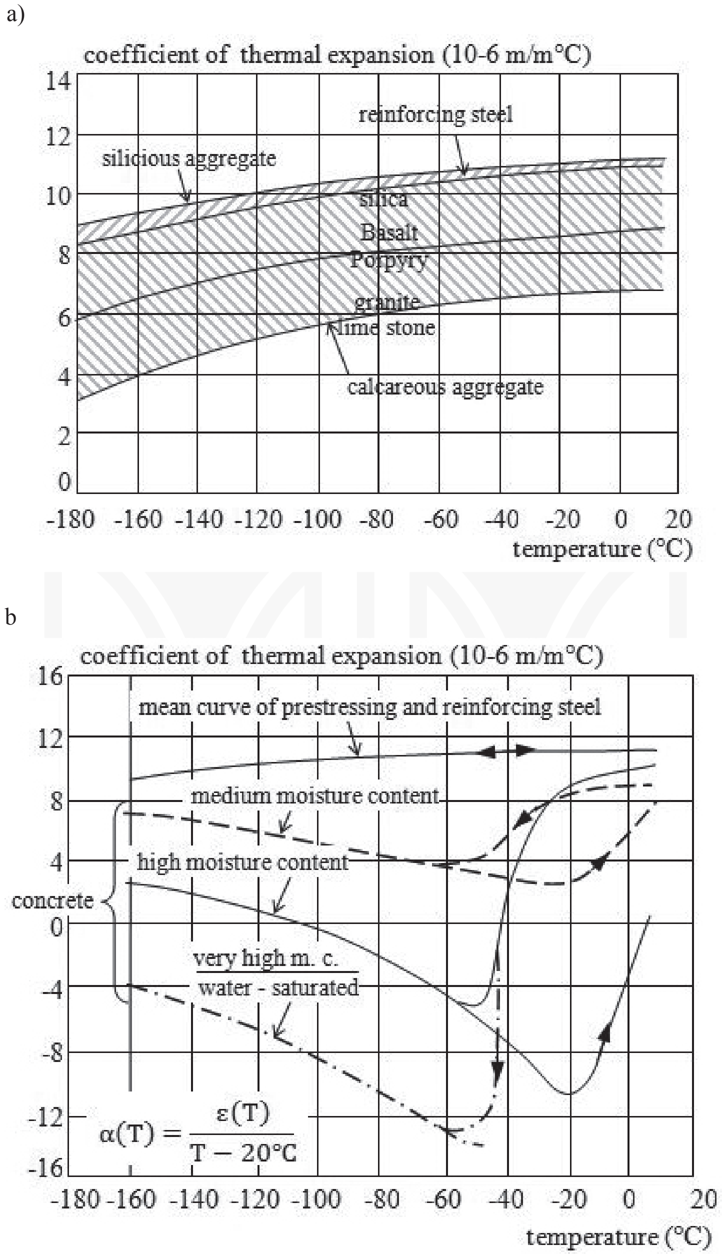


Fig. 5. Effect of a) type of aggregates, and b) moisture content, on the value of the coefficient of thermal expansion α_T [9]

6.6. Behaviour of normal and prestressed steel under cryogenic conditions

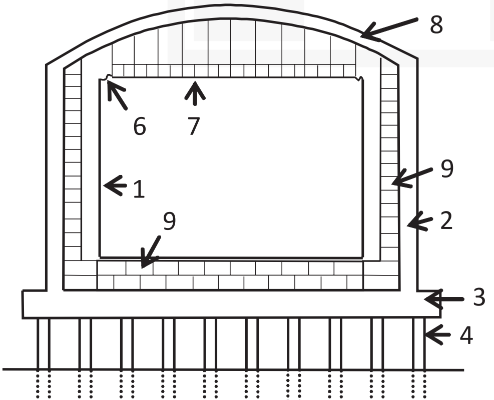
Generally, in the case of normal steel, the values of tensile strength, yield strength and the modulus of elasticity increase if the temperature decreases. The total elongation [in %] at maximum force increases initially but below –150°C, it decreases rapidly [10]. Tests on prestressing steel wires and strands showed that 0.1% proof stress and ultimate strength was higher than at room temperature and an elongation at maximum load was over 2% at temperature $T = -196°C$ [11]. In both cases, normal and prestressing steel stress-strain diagrams are suitable for behaviour assessment at cryogenic temperature [8]. If the designed temperature is lower than –50°C, then the prestressing system (strands and anchorages) should be tested in assumed cryogenic conditions. A tensile test on notched and un-notched reinforcing steel bars should be conducted if the designed temperature is lower than –20°C [1.3].

7. Tank foundation design

Two types of foundation may be designed to prevent the ground freezing:

- shallow foundation (concrete slab on ground);
- pile foundation (elevated concrete foundation, Fig. 6).

The temperature of the concrete slab foundation should not drop below 0°C at any point. In the case of shallow foundation, a concrete slab heating system must be designed. An effective way to avoid the ground freezing is the existence of an air gap under the foundation. In this solution, the base slab is heated by natural air convection and an additional heating system for the tank foundation is not necessary.



Key:
1. Primary container (steel)
2. Secondary container (prestressed concrete)
3. Elevated foundation – upper concrete slab
4. Concrete column
5. Shallow foundation concrete slab
6. Flexible insulating seal
7. Suspended roof (insulated)
8. Concrete roof
9. Thermal insulation

Fig. 6. Geometry of the cryogenic tank with pile foundation (according to EN 1473[12])

8. Summary

This paper presented some general concepts of prestressed concrete containment tank constructions, load cases or combinations and material properties under cryogenic conditions according to EN 14620 and fib Model Code 2010. It concentrated on the main differences in the design aspects of concrete tanks in the case of ‘normal’ and ‘low’ temperature.

References

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