BEHAVIOR OF SELF-CONSOLIDATING CONCRETE AT CRYOGENIC TEMPERATURES

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INTRODUCTION

Self-consolidating concrete (SCC) was recommended in an effort to speed up placement during the construction of a liquefied natural gas (LNG) containment tank in Freeport, Texas. Liquefying gases to cryogenic temperatures is widely used to reduce their volume, and therefore making their transportation over long distances more economical. The behavior of ordinary concrete exposed to very low temperature is somewhat documented, but because the composition of a self-consolidating concrete (SCC) slightly differs from that of an ordinary concrete, the design/engineering group wanted some assurance that an SCC mix would present similar properties than those found for ordinary concrete.

In this project, the concrete, like in the majority of cases, is used as secondary containment, in which case the concrete tank wall will come in contact with the cryogenic liquid only if the primary tank has failed (fig. 1). The lack of recent study on the performance of concrete at cryogenic temperatures is the primary reason why concrete is not more often used as primary containment. The available data indicate that concrete properties generally improve when exposed to cryogenic temperatures and that the level of improvement depends on the amount of freezable water, and the moisture content. The mechanism governing this is the formation of load bearing ice in the pores (1). Generally, a *w/c* less than 0.45 will not exhibit expansion in the thermal range between -20 to -60 °C. Thermal shock loading will not cause appreciable loss in strength if the concrete is not saturated, or if it has a low *w/c*. A comprehensive literature review (1) was published on the behavior of concrete when exposed to these conditions and is not the subject of this paper. The intent is to verify that SCC will exhibit similar properties then those found for ordinary concrete.

Compressive strength (ASTM C39) loss after one cycle of cryogenic exposure (EN 1473 annexe C, C.1.1), coefficient of Thermal dilation between -196 °C and 50°C (ASTM E 228), compressive strength loss after 20 cycles of freezing and thawing between -25 °C and 5 °C (ASTM C-666), dynamic modulus (ASTM C-215) and water content (ASTM C-642) before and after exposure were evaluated. Tensile strength, modulus of elasticity (ASTM C-469) and chloride ion permeability (ASTM C1202) were also performed according to the specification requests for the concrete mix.

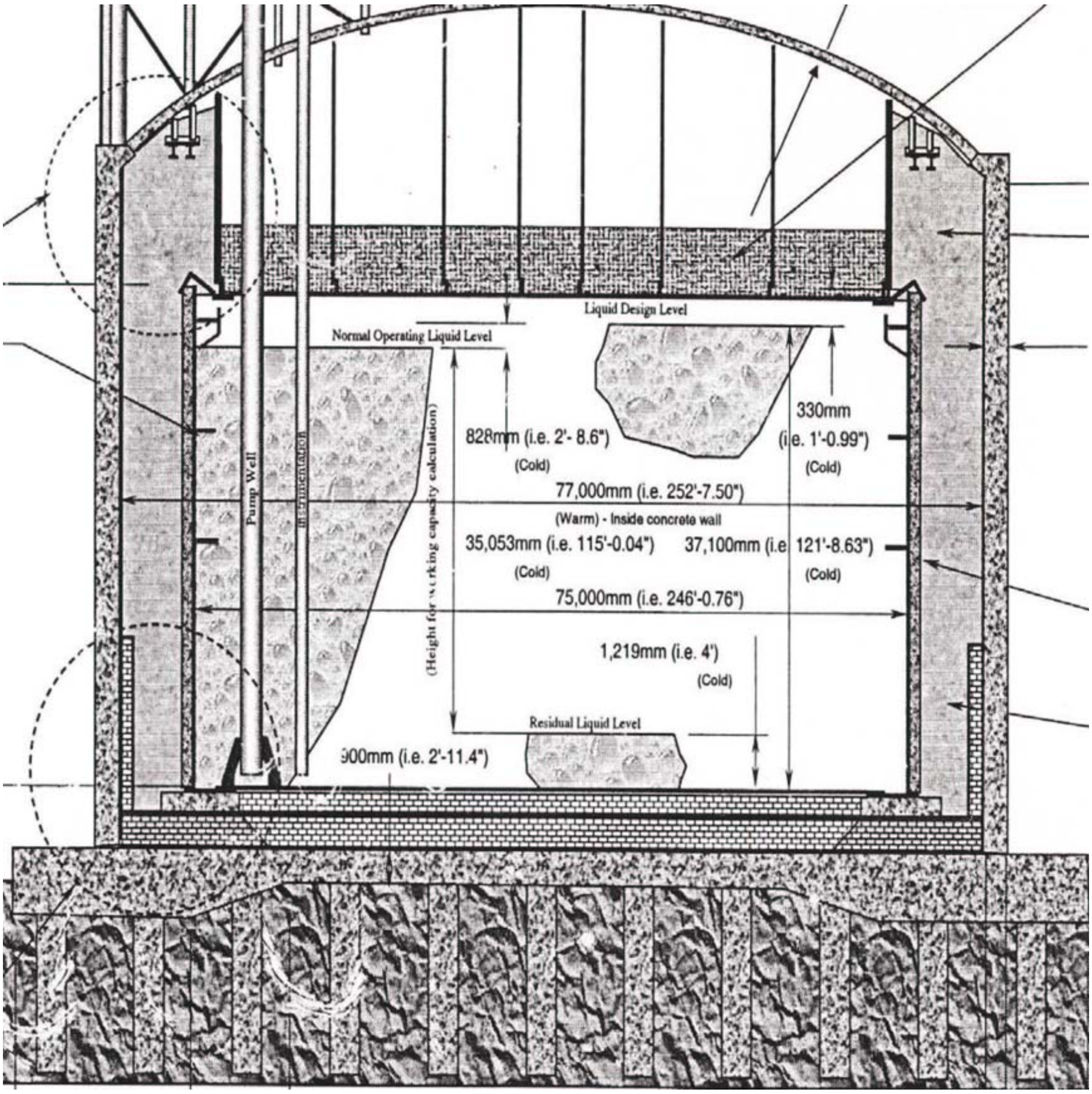

Fig.1: Schematic representation of containment tank

PARTIES INVOLVED

The following team members collaborated to achieve success on this project.

Freeport LNG, L.P.: Owner
Technip-Zachry-Saipem LNG, L.P.:Engineering/Contractor
The Euclid Chemical Company- Admixture Supplier;
Dorsett Brothers- Concrete Supplier;
Stork Southwestern Laboratories– Laboratory/Quality Control

MATERIALS

All materials used had to be tested by the testing laboratory prior to the pour and approved per the established specification from the design/engineering firm. Table 1 and 2 present the Coarse Aggregate (#67 maximum size) and Sand gradation respectively (river sand and gravel). The moisture content of the aggregates had to be tested twice daily during the pour. Table 3 presents the mix designs used during the construction. Note that 3 different mixes were used for the Roof, Slab and Walls. Only the Walls used SCC, and only the SCC was tested for cryogenic exposure. The cement used was a Type I/II manufactured by the local Holcim cement plant, and the fly ash was a Type F with 0.66% LOI and a specific gravity of 2.46 as manufactured by Boral Material Technoloies.

Table 1 – Coarse Aggregate (ASTM C33)

U.S. sieve size	% Passing	Specification
1.5 ”	100.0 %	100%
1”	95.0 %	95-100%
½	39.7 %	25-60%
#4	5.0 %	0-10%
#8	1.0 %	0-5%

Table 2 – Fine Aggregate (ASTM C33)

U.S. sieve size	% Passing	Specification
3/8”	100.00 %	100%
#4	96.11 %	95-100%
#8	84.43%	80-100%
#16	76.10 %	50-85%
#30	56.00 %	25-60%
#50	12.09 %	5-30%
#100	0.70 %	0-10%

Table 3 –Mix Designs and Slump requirement

	Roof kg/m^3 (lb/yd^3)	Slab kg/m^3 (lb/yd^3)	Walls/SCC mix laboratory kg/m^3 (lb/yd^3)	Walls/SCC mix field kg/m^3 (lb/yd^3)
W/C	0.33	0.33	0.38	0.38
Water	150 (250)	150 (250)	170 (285)	170 (285)
Type I Cement	170 (285)	170 (285)	415 (700)	335 (565)
Flyash	335 (565)	335 (565)	30 (50)	110 (185)
Coarse Aggregate	1038 (1750)	1038 (1750)	830 (1398)	830 (1398)
Sand	650 (1094)	650 (1094)	805(1357)	805(1357)
Eucon LR Type A WR mL/100 kg (oz/cwt)	260 (4)	260 (4)	-	-
Plastol 5000 HRWR mL/100 kg (oz/cwt)	-	585 (9)	915 (14)	915 (14)
Visctrol VMA ml/m^3 (oz/yd^3)	-	-	155 (4)	155 (4)
Eucon Air 40 Air entraining mL/100 kg (oz/cwt)	60 (1.5)	60 (1.5)	60 (1.5)	60 (1.5)
Slump or **Flow mm (in)**	50-100 (2-4)	150-200 (6-8)	750-775 (30-31)	650 ($\geq$26)
Compressive Strength specified psi (Mpa)	5800 (40)	5800 (40)	5800 (40)	5800 (40)

The Type A water reducer used was a lignin base, the superplasticizer (HRWR) was a polycarboxylate type and the viscosity enhancing admixture (VMA) was a polysaccharide base. In order to reduce the Chloride ion permeability below the specified value of 2000 coulombs, the mix used ultimately during the project incorporated more fly ash than the laboratory mix initially tested.

TEST METHOD FOR QUALIFICATION OF THE MIX FOR EXPOSURE TO CRYOGENIC TEMPERATURES

Three batches of the proposed mix and three samples (6x12 cylinders) from each batch had to be exposed to one cycle at -196 °C. The compressive strength of the cycled samples was compared to that of a reference non cycled specimen. The samples were cured in a plastic bag and placed in a chambers for 28 days and maintained at 20°C and at a 95% minimum RH. When the samples were ready for the cycling process, they were removed from the bag and placed in the liquid nitrogen for 1 hour. The samples were then removed from the liquid nitrogen and replaced in the plastic bag for 48 hours. After that, they were removed from the bag and tested for compressive strength along with the reference samples. The results are reported as a percent of the compressive strength of the reference samples in Table 5.

For the 20 freeze-thaw cycle samples, the same curing and compressive strength comparison was used. The samples had to be instrumented with a thermocouple. The dynamic modulus had to be determined prior to breaking the samples for compressive strength. Samples for water content were taken from the reference and cycled cylinders for comparison. All the results are presented in Table 4 and 5.

Table 4 – Laboratory Plastic Properties (Averages)

Plastic Properties	
Slump Flow, mm (in.)	775 (31)
Air content, %	3.2
Unit Weight, kg/m^3 (lb/yd^3)	2298 (3876)

Table 5 – Laboratory Hardened Properties (Averages)

	SCC low Fly Ash Content	SCC 25% FA Content	20 cycles Freeze-thaw Low Fly Ash Content	Cryogenic exposure Low Fly ash Content
Compressive strength 28 days psi (MPa)	8338 (58)	6102 (42)	98%	96%
Tensile strength 28 days psi (MPa)	699 (4.8)	-		
Dynamic modulus (Pa)	49380 x 10^6	-	100%	84%
Water Content %	4.43	5.4	4.7	5.4
Modulus of Elasticity psi (MPa)	6.05 x 10^6 (41724)	-	-	-
Thermal dilation % Cryogenic temperature	0.23	-	-	-
28 day Chloride ion Permeability, Coulombs (56 days)	4200 (-)	1935 (1028)*	-	-

*sample sent from the field trial of the same mix, tested at 2329 Coulombs at 28 days and 1221 at 56 days.

The field results on slump flow ranged from 26-30 inches (650-750 mm) and the strengths at 28 days were higher then 6000 psi (41 MPa) throughout the project.

COMPARISON WITH RESULTS IN LITERATURE FOR NORMAL CONCRETE

Krstulovic-Opara reported in his recent article (1) that the thermal deformation for hardened cement paste is in the range of 0.2-0.25 % in the cryogenic temperature range. This is similar to what was obtained in this evaluation of SCC. The loss of compressive strength was minimal as typically observed for ordinary concrete and was well above the minimum requirement of 80%.

CONCLUSION

SCC was used successfully on this approximately 25000 yd^3 on self consolidating concrete. All parties were satisfied with the performance of the mix increasing the ease of placement and providing better, more uniform appearances for exposed concrete.

Fig. 2: Completed Liquid Nitrogen Gas Tank

REFERENCE

(1) Krstulovic-Opara, N., “Liquified Natural Gas Storage: Material Behavior of Concrete at Cryogenic Temperatures” ACI Materials Journal, May-June 2007, pp297-306.