Non-destructive assessment of concrete mixtures at cryogenic temperatures: Towards primary LNG containment

Reginald B. Kogbara[1], Srinath R. Iyengar[1], Zachary C. Grasley[2,3], Eyad A. Masad[1,2], Dan G. Zollinger[2]

[1]Mechanical Engineering Program, Texas A&M University at Qatar,
P.O. Box 23874, Education City, Doha, Qatar.

[2]Zachry Department of Civil Engineering, Texas A&M University,
College Station, TX 77843, USA.

[3]The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA.

Abstract

A number of non-destructive techniques were used in this study to assess the suitability of different concrete mixtures for primary containment of liquefied natural gas (LNG). Concrete mixtures were prepared using limestone, traprock, sandstone and lightweight coarse aggregates, with siliceous river sand and limestone sand as fine aggregates. The mixtures were cured under water for at least 28 days and then cooled from ambient (20°C) to cryogenic temperatures (-165°C). The coefficient of thermal expansion and damage evolution of the concrete mixtures were measured with strain gages and acoustic emission sensors during the cooling process. Changes in porosity and pore size distribution were measured using 1H nuclear magnetic resonance; while changes in microstructure were examined using scanning electron microscopy and x-ray computed tomography, before and after cryogenic freezing. Damage consisted of well-distributed microcracks rather than macrocracks. Limestone and traprock mixtures showed better damage resistance during cooling to cryogenic temperatures than sandstone and lightweight mixtures.

[1] Corresponding author email: regkogbara@cantab.net. Tel: +974 4423 0289.

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Introduction

- ➢ Traditional liquefied natural gas (LNG) storage tanks utilize 9% nickel steel for the primary containment tank as it has greater ductility at cryogenic temperatures (i.e. ≤ -165°C) compared to normal carbon steel. This is becoming increasingly expensive!
- ✓ However, literature review [1,2] shows that concrete properties generally improve at cryogenic temperatures. Utilizing concrete for LNG tanks would greatly reduce costs.
- ✓ The development of the American Concrete Institute (ACI 376-11) standard [3] on concrete structures for containment of refrigerated liquefied gases, may increase the impetus for tank designs utilizing concrete for primary LNG containment (see Fig. 1).
- ➢ Therefore, this research aims to design damage-resistant cryogenic concrete. Its objectives are to:
- ❑ Study the mechanism governing damage growth due to coefficient of thermal expansion (CTE) mismatch stresses of concrete components.
- ❑ Understand how changes in cryogenic concrete at the microstructural level affects its durability and behavior at the larger scale.

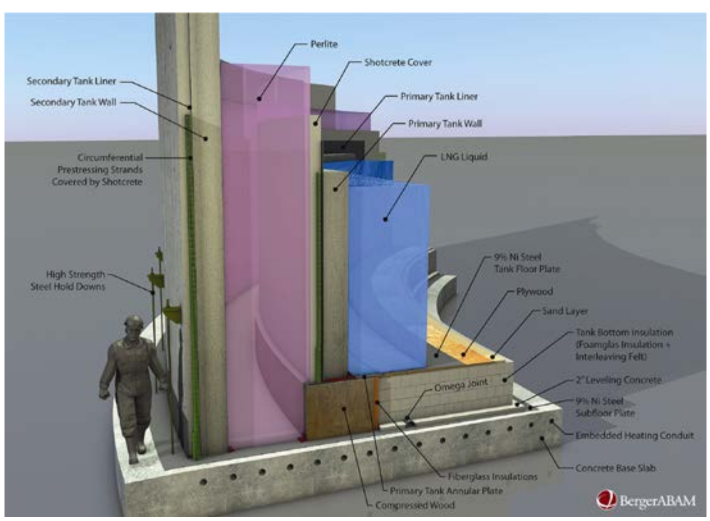

Fig. 1: Possible design of LNG tank with concrete as primary containment wall

(*Image courtesy of BergerABAM)*

Methodology

A series of experiments were conducted using concrete samples made from different coarse aggregates with a reasonably wide CTE range using river sand as fine aggregate (Table 1) [4]. The concrete samples were cooled from 20°C to -165°C (3°C/min) in an LN2-cooled chamber (Fig. 2).

Table 1. Composition and mixture proportions of the concrete mixtures

Constituent	Limestone mixture	Sandstone mixture	Trap rock mixture	Lightweight mixture
Cement (kg/m^3)	512	512	512	512
Coarse aggregate (kg/m^3)	868	889	1056	661
Fine aggregate (kg/m^3)	694	687	670	550
Water (kg/m^3)	215	215	215	215

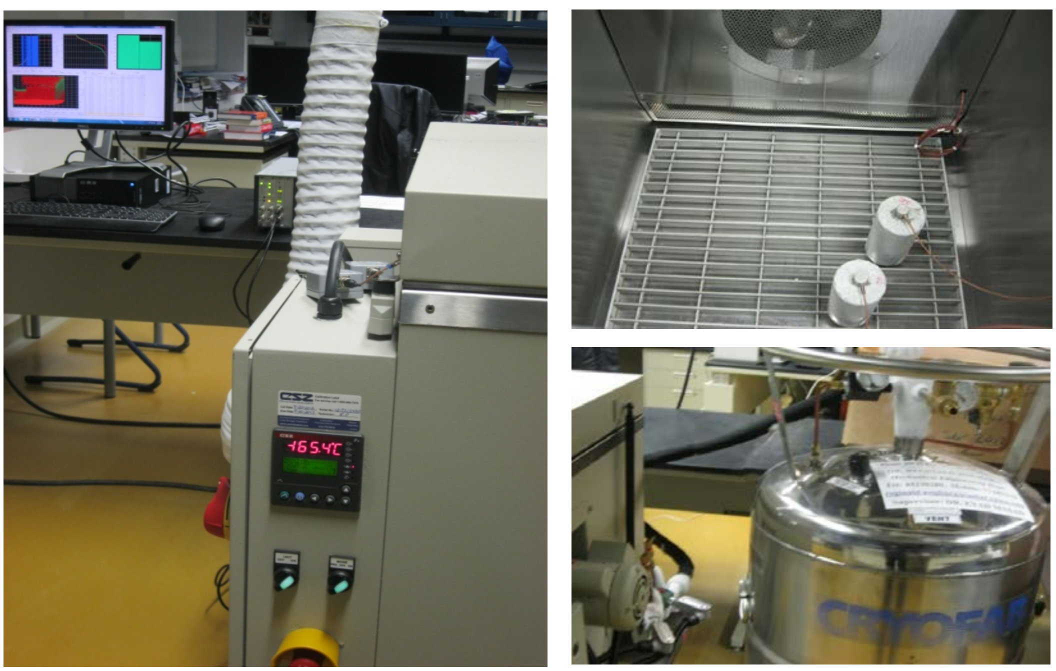

Fig. 2: Temperature chamber showing AE sensors on concrete

During cooling to cryogenic temperatures:

- The CTE of the concrete mixtures was measured using coupled strain gages.
- While damage evolution was monitored using acoustic emission sensors (Fig. 2).

Before and after cryogenic cooling, the following techniques were used to monitor changes in concrete behavior such as:

- 1H Nuclear magnetic resonance (NMR) transverse relaxation time (T2) for *porosity and pore size distribution*.
- X-ray computed tomography (XRCT) and scanning electron microscopy (SEM) imaging for *microstructure*.
- Water permeability test for *validation of observed damage*.

Results and discussion

Selected results for acoustic emission and permeability of the 4 concrete mixes, made with a water/cement ratio of 0.42, are shown in Figures 3 and 4.

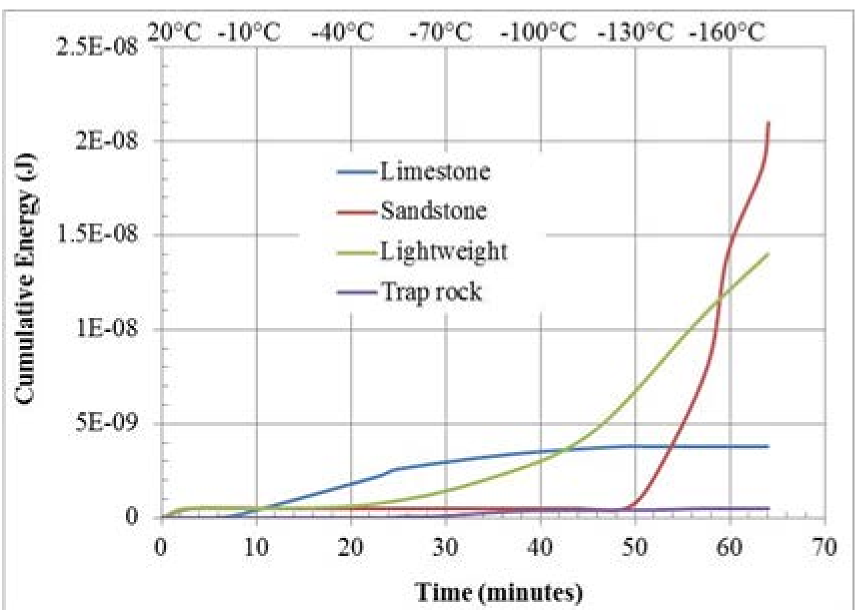

Fig. 3: Acoustic emission

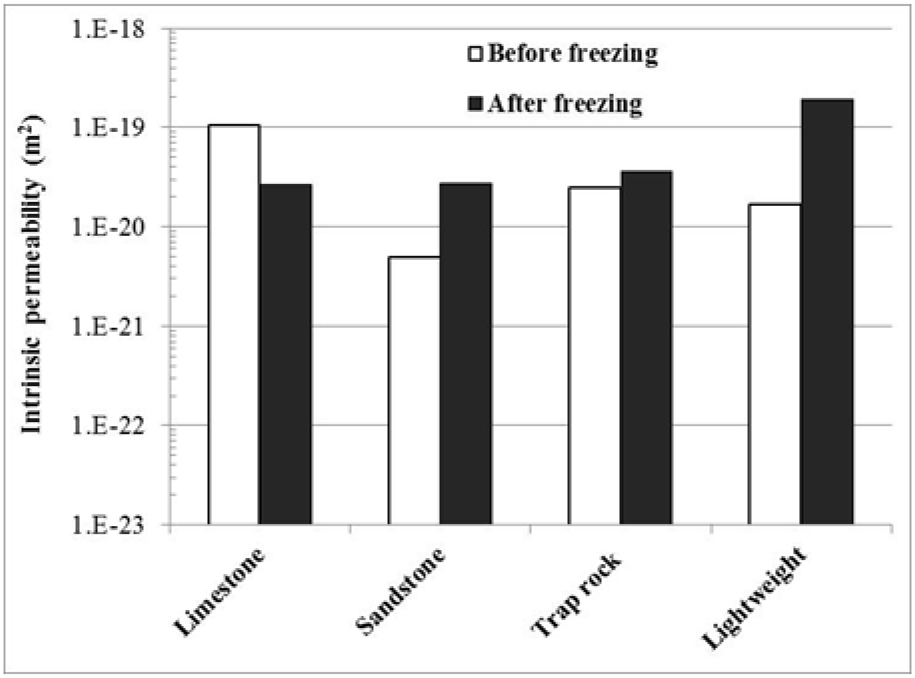

Fig. 4: Water permeability

Note: The 28-day compressive strength (ASTM C39) [5] *of all 4 mixes was > 35 MPa.*
Permeability tests using depth of penetration method (BS EN 12390-8) [6] *were done on thawed cubes as opposed to use of flexible wall permeameters as in some previous studies* [7-9] *due to the low permeabilities involved .*

- Concrete with sandstone and lightweight aggregates showed higher cumulative energy levels associated with the propagation of microcracks, compared to the limestone and trap rock aggregates (Fig. 3). This is corroborated by the water permeability results (Fig. 4).
- The XRCT scans (FOV = 23 mm, voxel dimensions = 22 x 22 x 50 µm) of the limestone, sandstone and trap rock mixtures did not show any visible damage due to cryogenic cooling but the lightweight mixture did (e.g. Fig. 5). Hence, damage mostly consisted of well distributed microcracks below the resolution of the CT, rather than macrocracks.
- NMR results show that there was very little or no change in porosity in the limestone and trap rock mixes after cooling (Fig. 6). However, the sandstone and lightweight mixes had 1% and 3% porosity increases, respectively.

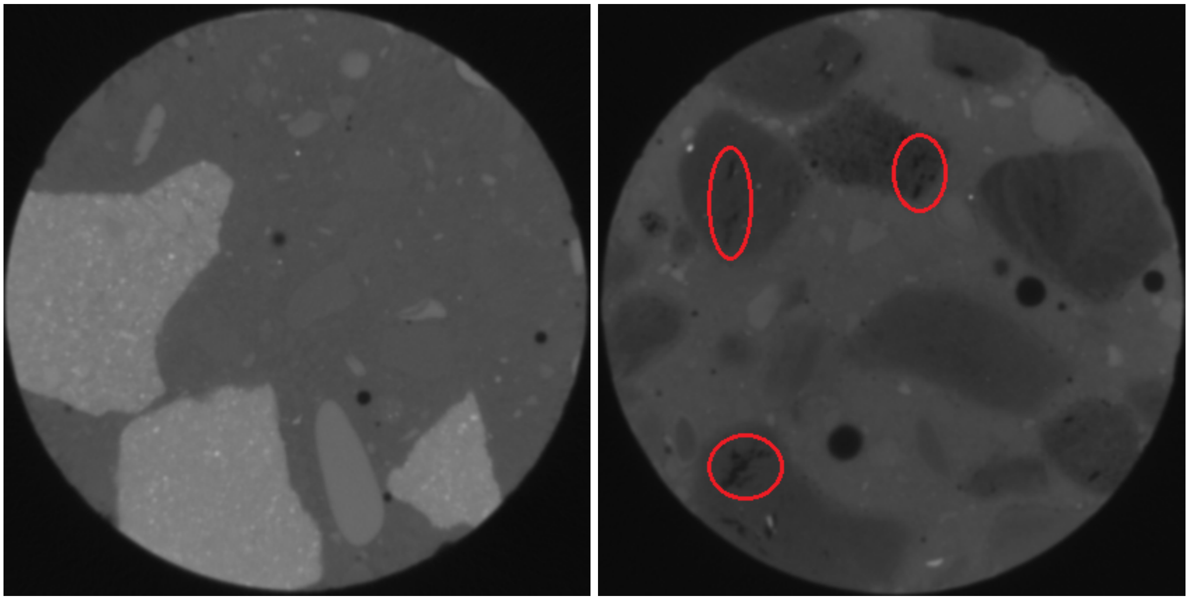

Fig. 5: XRCT cross-sections of frozen concrete from (a) trap rock and (b) light weight aggregate

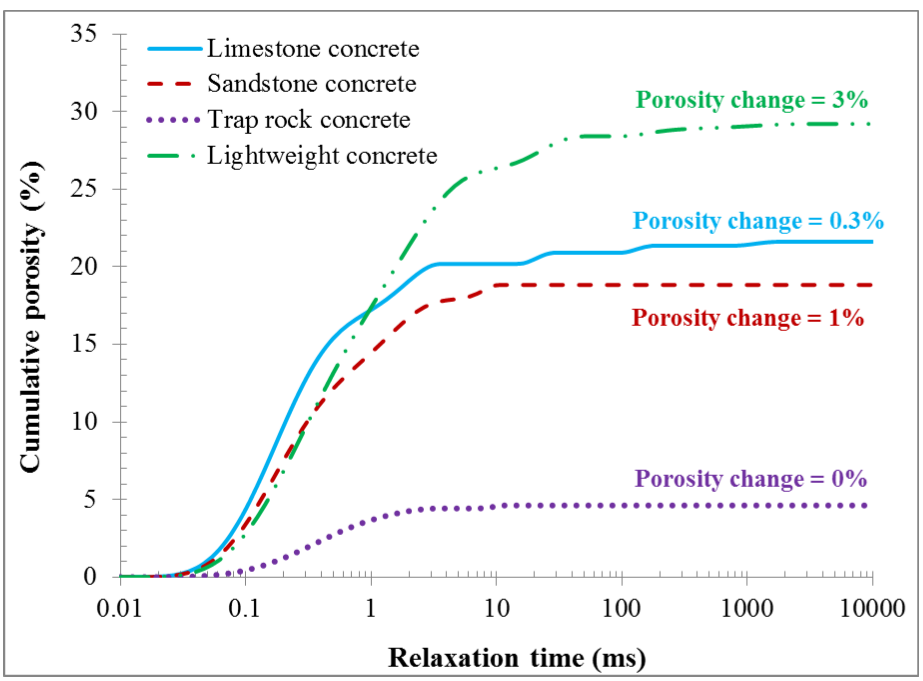

Fig. 6: NMR T2 data of frozen concrete mixes

Preliminary Conclusion

- ❖ The trap rock and limestone mixtures show better damage resistance than the sandstone and lightweight mixtures during cryogenic cooling. More design methodologies are been investigated in the search for damage-resistant concrete.

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