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Assessment of lightweight concrete properties under cryogenic temperatures: influence on the modulus of elasticity

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Abstract

The current development of Liquid Natural Gas (LNG) storage site requires a thorough analysis of concrete behaviour under cryogenic temperatures. Indeed, this kind of infrastructure is based on a set of tanks that presents several layers. The first one is the cryogenic steel tank that directly contains the LNG. An outer concrete box represents the external layer and usually between these two layers there is a thermal insulating material. A leak from the steel tank can apply a tremendous thermal gradient to the concrete external layer. Thus, the study of concrete behaviour in this situation is important and few studies are available for concrete characterized by lightweight clay aggregate. In this experimental work, the variation of the modulus of elasticity of lightweight clay aggregate concrete, due to temperature gradients have been analyzed and discussed. A set of concrete cubes has been immersed in liquid nitrogen to reach -180°C, then they have been tested under compressive stress measuring both stress and strains. Correlations between elastic properties and temperatures are proposed.

Keywords: concrete, cryogenic, LNG, lighghtweigth.

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1. Introduction

The current development of LNG gas storage sites, see Zakaria et al. (2019), Krstulovic-Opara (2007), linked to the needs of alternative energy sources rises the need of reliable models for the mechanical behaviour of this kind of infrastructure. An LNG gas storage site is composed by a set of tanks that presents several layers. The first one is the cryogenic steel tank that directly contains the LNG. An outer concrete box represents the external layer and usually between these two layers there is another one realized with thermal insulating material.

In case of leak from the steel tank the LNG at very low temperature (-160 °C) can reach the concrete layer with a tremendous thermal gradient that push the concrete to extreme conditions.

Usually, cryogenic temperature range is defined from -150 °C to -273 °C and given that LNG temperature in the storage site is almost -160 °C we can consider materials exposed to LNG at cryogenic temperature. For this reason, the study of concrete behaviour in this situation is becoming more important.

The early works of Rostasy et al. (1980) and Lee et al. (1988) proved that concrete mechanical properties improves as temperature decreases, however the same authors pointed out that successive freezing cycles lead to a reduction of compressive and bond strength and of the Young's modulus. Indeed, the ice formation makes the concrete to expand upon cooling creating microcracking damages that will affect the material behaviour in the successive loading cycles. The evolution of fracture energy of saturated concrete at extremely low temperature has been studied by Maturana et al. (1990) that reports a strong increase in the fracture energy with decreasing temperature.

A review of concrete properties at cryogenic temperatures can be found in Kogbara et al. (2013).

Planas and Elices (2003) presented a phenomenological model for concrete during cooling down to very low temperatures. The thermomechanical deformation of the material considering damage modelling is well described by the model. Xie et al. (2014) presented an experimental study on the compressive performance of concrete at very low temperatures. Kogbara et al. (2014) presented an interesting study on the concrete damage evolution at cryogenic temperatures highlighting how limestone and trap rock present a better resistance than lightweight and sandstone mixtures.

The needs of more experimental analysis are patent, in particular few studies are available for concrete characterized by lightweight clay aggregate and as far as the authors know nobody has measured the longitudinal elastic modulus of this kind of concrete at cryogenic temperatures.

In this work, several concrete cubes have been tested at cryogenic temperatures with the aim of assessing the elastic properties variation due to temperatures gradient. After this brief introduction, Section 2 describes the experiments, while Section 3 presents the results followed by some conclusive remarks in Section 4.

2. Experimental Campaign

The considered lightweight concrete belongs to the LC30/33 class (UNI EN 206:2016) XC2 - S4 with maximum aggregate size equal to 16 mm and it is characterized by lightweight clay aggregate. The mix design is characterized by a water to cement ratio equal to 0.6. The mass density is between 1600 and 1800 kg/m^3. The average cubic compressive strength is over 30 MPa while its average elastic modulus at environmental temperature is 23000 MPa.

In this experimental campaign, eight 15x15x15 cm cubic concrete specimens have been considered. The strains have been recorded by two central strain gauges located in the lateral sides of each specimen. A removable thermocouple has been used in order to record the temperature variation during the tests.

The compression load was applied by means a hydraulic press machine (manufactured by Controls Testing Equipments Ltd) with a capacity of 3000 KN and a digital force control. A National Instruments C-DAQ system was used for stress and strain acquisition. The secant elastic modulus has been obtained according to the UNI EN 12390-13:2013. The stress was applied in three different steps (11 MPa, 13 MPa, 15 MPa) and each step was kept constant for 14 sec. Strains were measured by means a couple of encapsulated constantan gauges, type Micro Measurements 20CLW120, gauge length 50,80 mm and strain range ± 3%.

After measuring the mechanical properties at environmental temperatures, the cubes were immersed in liquid nitrogen to reach the temperature till -180°C. Then they were extracted and compressed, measuring stress and strain in order to obtain the elastic modulus, see Fig. 1. The temperature was continuously controlled by a thermocouple. The loading cycles were repeated at several thermal steps until the temperatures reached -50°C. In this way, it was possible to measure the compressive behaviour at different temperatures for each specimen.

The authors are aware that the secant elastic modulus measured in a cube is different from the one measured in a cylinder or a prism. However, many studies provide linear relationship between these two values: Del Viso et al. (2008), Sinaie et al. (2015). The aim of this paper is focused on the variation of the elastic properties and not on the absolute value and for this reason hereinafter we refer to the secant elastic modulus measured on the mentioned cubes.

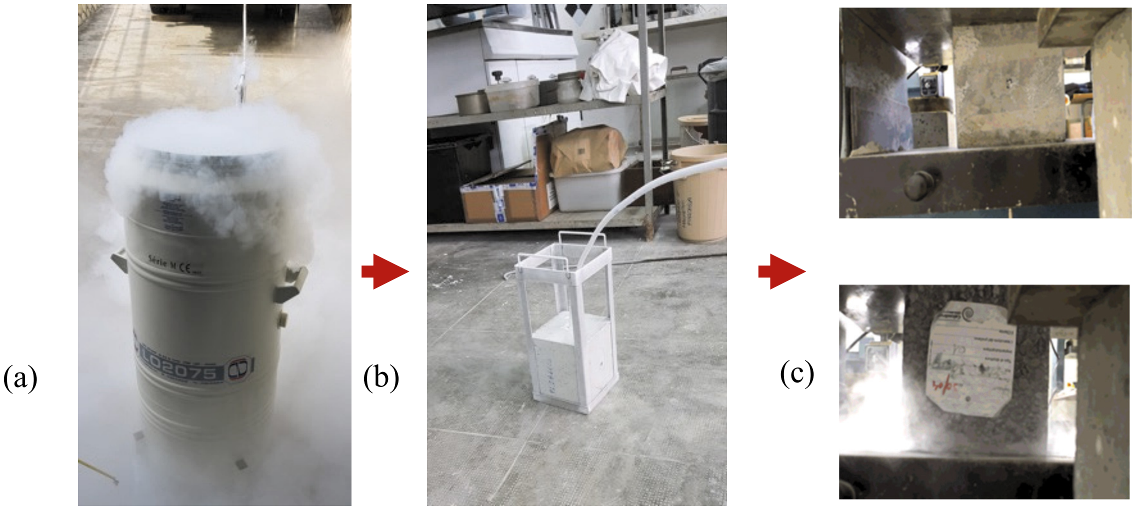

Fig. 1. Stages of the experimental tests: (a) submersion in nitrogen tank; (b) the twin cube with thermocouple; (c) the compression test.

3. Results

Inside the liquid nitrogen tank, the cubes experience a progressive temperature reduction and a compressive strain as it is shown by the two diagrams in the following: in Figure 2 a typical temperature time history is reported while Figure 3 presents a typical strain-temperature relationship, where a progressive contraction of concrete is recorded when temperature lowered.

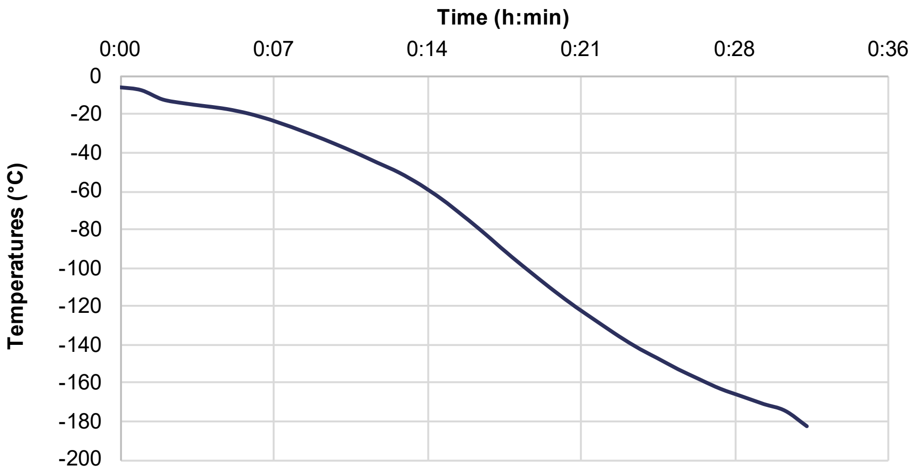

Fig. 2. Time-history of concrete temperature inside the liquid nitrogen tank.

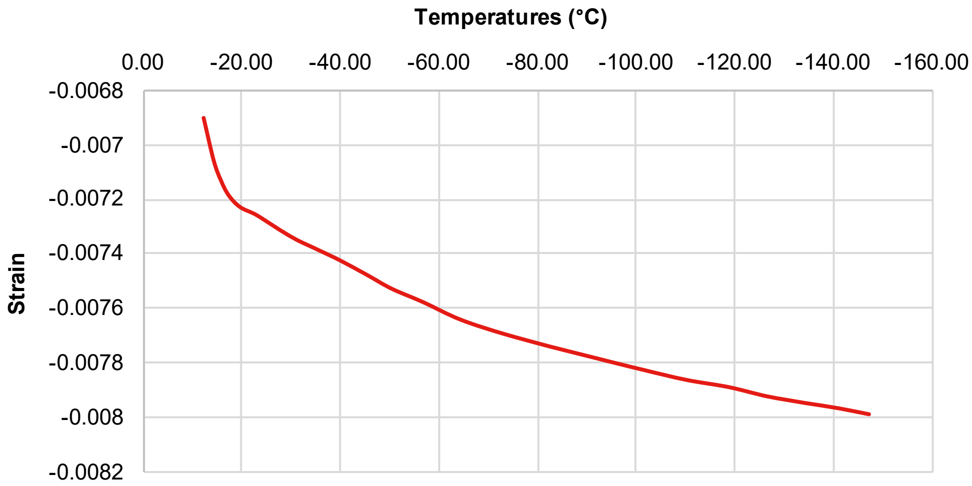

Fig. 3. Concrete axial strain Vs temperature on the cube inside the liquid nitrogen tank.

After emerging from liquid nitrogen, the concrete temperature tends to rise. A general temperature time trend has been detected considering all the cubes in all conditions. Figure 4 presents this trend and also the cubic polynomial expression that fits the data set. This information is relevant to understand how the successive loading cycles modify the concrete cubes temperature.

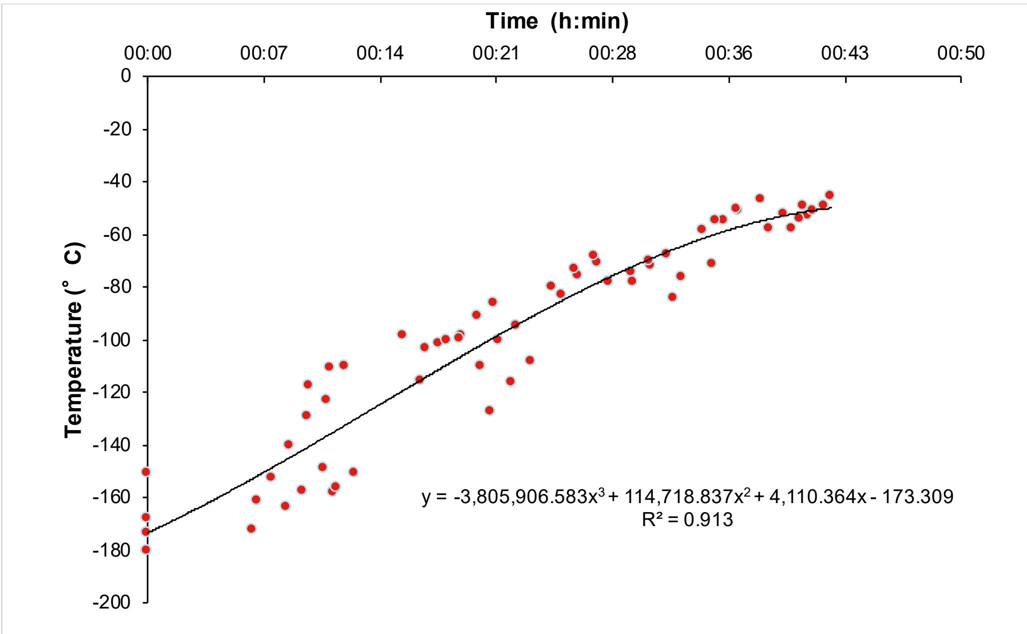

Fig. 4. Concrete temperature time history after the emersion from the liquid nitrogen tank.

The secant elastic modulus has been calculated as the slope of the least squares linear regression of the axial stress-strain diagram. Figure 5 presents a typical stress-strain diagram used to evaluate the secant elastic modulus.

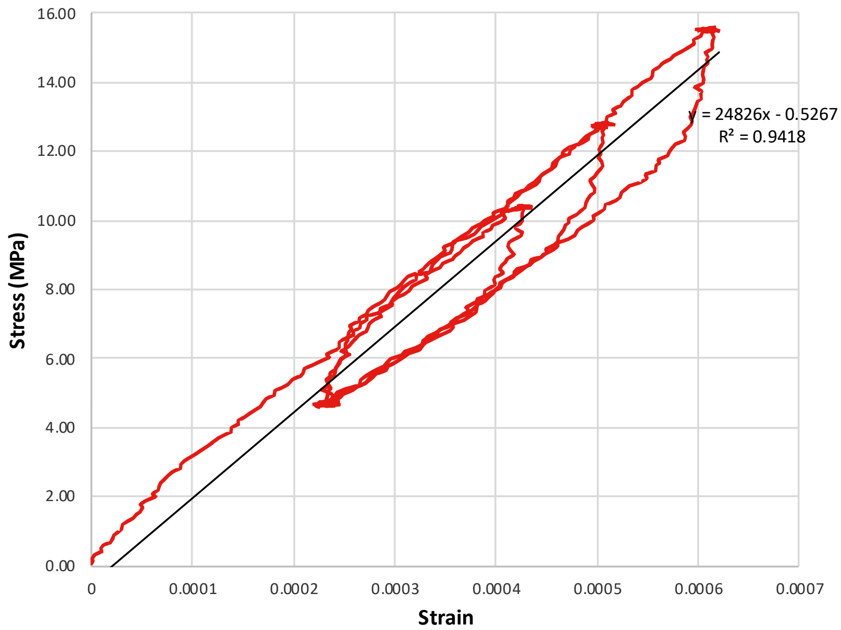

Fig. 5. Concrete elastic modulus evaluation.

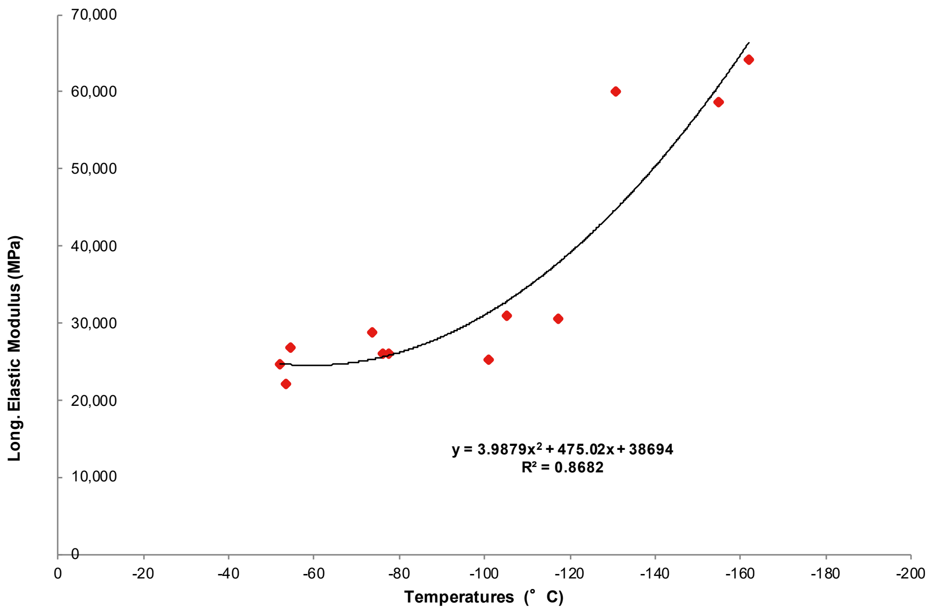

Fig. 6. Concrete elastic modulus Vs temperature.

The same procedure has been adopted for each cube at different temperature, obtaining a set of twelve secant elastic modulus values. Indeed, only the tests in which the temperatures were accurately measured have been considered for this analysis. The aim of this work is to relate these values to the corresponding temperatures in order to find a global trend. Figure 6 presents the relationship between the obtained elastic modulus and the temperatures. As expected, when the temperatures decrease the elastic modulus increases. This effect can be clearly observed below -80 °C and can be explained with the physical modification of the concrete. The latter can be described with two competitive mechanisms: the strengthening due to solid phase formation and the strength degradation due to microcracking induced by water expansion in freezing, see Maturana et al. (1990). In this specific case the final result yield to an improvement of the elastic modulus.

The polynomial regression proposed in equation (1) provides the best fit for experimental data; its coefficient of determination R^2 is equal to 0.8682:

$$E_c(T) = 3.9879T^2 + 475.02T + 38694 \quad (1)$$

4. Conclusions

In this preliminary work an experimental analysis on the elastic properties of lightweight clay aggregate concrete exposed to extremely low temperatures has been presented.

A relationship between secant elastic modulus and temperatures has been found and presented in equation (1). The lightweight concrete secant elastic modulus tends to improve as the temperature of concrete becomes lower and lower confirming the known behaviour described in literature also for this kind of concrete.

Further developments of this research are expected considering also the variation of compressive and tensile strength of concrete. In addition, a set of non-destructive tests, see Stochino et al. (2017), are scheduled in order to assess concrete mechanical properties under this extreme condition. The main aim of this study is to obtain a proposal for a constitutive model for lightweight clay aggregate concrete under cryogenic temperatures.

Finally, special attention will be devoted to concrete realized with recycled aggregate that has not been yet tested at cryogenic temperatures: Francesconi et al. (2016) and Stochino et al. (2017).

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