Construction and Building Materials 72 (2014) 380–388

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental study on the axial-compression performance of concrete at cryogenic temperatures

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HIGHLIGHTS

- The effectiveness of cooling and cold insulation method in the test was proved.
- Experimental procedures on axial compression performance of concrete at cryogenic temperatures are presented.
- Effects of temperature and stirrup characteristic value on concrete compression performance were studied.
- Stress–strain curves for plain and confined concrete were established.
- Concrete ductility can be improved by increasing stirrup ratio in ultra-low environment.

ARTICLE INFO

Article history:
Received 10 August 2014
Received in revised form 20 September 2014
Accepted 21 September 2014
Available online 10 October 2014

Keywords:
Concrete
Cryogenic temperature
Axial compression
Stirrup confined
Stress–strain curve

ABSTRACT

This study on the axial-compression performance of concrete at cryogenic temperatures provides experimental basis and data support to analyze and design reinforced-concrete structures, particularly for axial-compression members in cryogenic environment. By examining 18 plain-concrete specimens and 18 reinforced-concrete specimens under axial-compression loading, the stress–strain curves were developed, and the characteristic points were analyzed. The test variables included temperatures of 20 °C, 0 °C, −40 °C, −80 °C, −120 °C and −160 °C and stirrup characteristic values of 0, 0.086, 0.131 and 0.172. Based on the plain-concrete tests, the concrete strength-increase coefficient and peak-strain-reduction factor were introduced to conduct a dimensionless analysis of the temperature parameters of confined concrete. Then, the compressive stress–strain curve equations of confined concrete at different temperatures with different stirrup characteristic values were established. The conclusions are summarized as follows: when the temperature decreases, the strength and elastic modulus of the concrete increase, but the peak strain decreases, which increases the brittleness. This phenomenon brings adverse effect on the ductility of structures. The concrete ductility can be improved by increasing the stirrup ratio in an ultra-low environment.

1. Introduction

Recently, the LNG industry has been developed, cold storage has achieved lower internal temperature, the western development strategy and the northeast old-industrial-base revitalization plan in China has been implemented, the construction of floating docks is developing, and the idea to build a concrete space base on the moon is introduced by the United States [1–3]; thus, civil engineering construction in cryogenic environment is on the rise. Concrete is the most widely used construction material worldwide. Concrete's properties at room temperature, ambient temperature and elevated temperature are well-documented, but they are not well-documented at cryogenic temperatures [4,5]. The effects of low temperatures on the mechanical properties of concrete have been investigated by researchers in several developed countries, such as America and Japan [4–8], but most studies on the cryogenic behavior of concrete was conducted in the 1950s to 1970s with notably few additional investigations since then until recent years. The performance of reinforced-concrete materials at cryogenic temperatures should be of great concern to engineers and designers. The axial-compression stress–strain curve reflects the basic mechanical properties of concrete, which is the basis to study the strength and deformation of reinforced-concrete structures, the

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http://dx.doi.org/10.1016/j.conbuildmat.2014.09.033
0950-0618/© 2014 Published by Elsevier Ltd.

ultimate bearing capacity of the components and the constitutive model of the inelastic whole-process analysis. The author's team has made a series of studies on the mechanical properties of concrete and the bonding performance between steel bar and concrete at ultra-low temperatures [9–13]. Upon exposure to low temperature, concrete experiences changes in its chemical composition, physical structure and water content. These changes are reflected by a reduction in ductility of the concrete. Studies have showed that when concrete was restrained using stirrups (hereinafter referred to as confined concrete), the core concrete was in a multi-axial compressive state, and the strength and ductility of the concrete significantly improved [14,15]. Therefore, this study will be of great theoretical and practical significance on the safety of concrete structures and the application of special structures in cryogenic environment.

2. Test of temperatures

The key procedure and difficulty of the test was the cooling and cold insulation of the specimens. Cooling and cold insulation were achieved by regularly spraying liquid nitrogen into the polyurethane box. With the temperature test, the cooling and cold insulation process was simulated during the test, and temperature rebounds with and without cold insulation were observed and compared. The representative curves are demonstrated in Figs. 1 and 2 (Note: the specimen temperature was the reading of a platinum temperature sensor, which was embedded at the center of the specimen; the environment temperature was the temperature in the polyurethane box).

As shown in Fig. 1, without cold insulation, the specimen temperatures have a large rebound. When the design specimen temperature is −160 °C, the temperature increases by 20–30 °C (the entire test process is approximately 20 min). The smaller specimens exhibit faster temperature rebound. It is difficult to ensure the accuracy of the test temperature requirements. As shown in Fig. 2, when the environmental temperature is controlled within 10 °C, the temperature of the specimen center fluctuates within 2 °C. The accuracy of the test temperature can be satisfied using this procedure.

3. Test design

3.1. Specimen design

The "standard for test method of mechanical properties on ordinary concrete" (GB/T50081-2002) is referred to for this test. In total, 36 concrete specimens were cast and tested in this

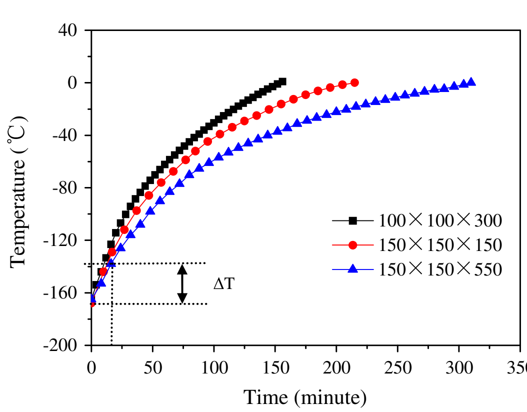

Fig. 1. Temperature rebound without cold insulation at the center of the specimens with different sizes (the legend is for the specimen size/mm × mm × mm).

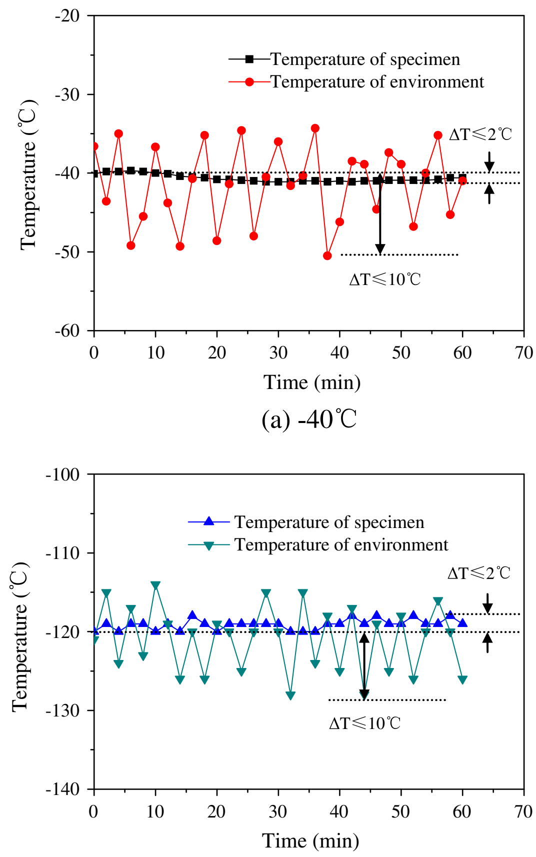

Fig. 2. Relationship between the environment temperature and the temperature at the specimen center with cold insulation (specimen size is 150 mm × 150 mm × 550 mm).

investigation. All specimens were of prism shape, which included 18 plain-concrete specimens (A-1 to A-6, with a size of 100 mm × 100 mm × 300 mm) and 18 confined specimens (B–D, with a size of 150 mm × 150 mm × 550 mm). A concrete cover of 20 mm was provided in all confined-concrete specimens. The design strength grade of concrete was C60. The experimental variables included the temperatures (20 °C, 0 °C, −40 °C, −80 °C, −120 °C and −160 °C, 6 in total) and the stirrup characteristic values (0, 0.086, 0.131 and 0.172; 4 in total). The effects of temperature on the concrete strength, stress–strain curve, and peak strain and the effects of the stirrup characteristic value on the peak stress, peak strain, and ductility were investigated. The specimens of Group A (plain concrete, 0, 0) [(, ρ,λ_v,) ρ is the reinforcement ratio, λ_v is the stirrup characteristic value. Hereinafter is the same] were cast and tested in triplicate for each group to obtain the average of three results; when the result deviation was more than 15%, the intermediate value was taken. Various relevant details of the specimens are listed in Table 1.

3.2. Test equipment

This test was operated in Tianjin Key Laboratory of Civil Engineering and New Materials. First, the test specimens were cooled to the design temperature and placed in the cold insulation box; next, a monotonically increasing axial pressure was applied until the specimens broke. The vertical pressure of Group A (plain concrete, 0, 0) was measured using a BHR4/100t load sensor, which was placed in an elastic element; the vertical pressure of Groups