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Creep behaviors of methane hydrate coexisting with ice

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A B S T R A C T

A series of creep tests were carried out in order to clarify the creep behaviors of methane hydrate coexisting with ice, which may exist in the ice-bearing permafrost. Measurements on synthetic methane hydrate-ice specimens indicate that (1) higher external load will increase the initial strain and the axial strain during the whole creep test. And the creep strain rate will increase with the increase of external load; (2) the initial strain, axial strains and creep strain rate of the specimens under certain external load increase with the decrease of confining pressure; (3) temperature drop leads to the decrease of initial strain and axial strains of the specimens under certain external load. And the creep strain rate firstly increases and then decreases with the increase of temperature, due to the refreezing of dissociated water from methane hydrate; (4) the specimens run to the secondary creep stage earlier when they endure lower external load, higher confining pressure and lower temperature; (5) the specimens under higher confining pressure and lower temperature show higher failure strength.

1. Introduction

Methane hydrates are ice-like clathrate compounds formed by methane gas (the main component of natural gas) captured in well-defined cages in a lattice of water molecules (Sloan, 1998, 2003). They are stable under the conditions of low temperature and high pressure in two different geologic settings: in the permafrost regions and beneath the sea within sediments of outer continental margins (Dawe and Thomas, 2007; Milkov, 2004). The amount of methane (and other hydrocarbons) trapped in gas hydrates is enormous, which is estimated more than 1 trillion carbon tons and twice the amount of all the known conventional fossil fuels (Boswell and Collett, 2011). Methane hydrates are considered as a potential energy resource in the near future (Kvenvolden, 1988). However, methane hydrates represent a significant drilling and production hazard. Many researchers have described numerous problems associated with methane hydrates, including blowouts, casing failures and subsea landslides (Ning et al., 2012; Rutqvist et al., 2009). In view of the problems, the mechanical behaviors of a methane hydrate reservoir is really important, because they may affect the stability of the layers and the production well, and the gas productivity (Sakamoto et al., 2009).

To address this issue, many researchers have conducted a series of acoustic tests and triaxial shear tests on hydrate or hydrate-bearing sediments. For acoustic tests, Waite et al. (2000) measured the compressional wave speeds (V_P, 3650 ± 50 m/s) and shear wave speeds (V_S, 1890 ± 30 m/s) of synthesized methane hydrate with porosity below 2%, and V_P/V_S, Poisson's ratio, bulk, shear, and Young's moduli were derived from the results. Winters et al. (2007) studied the effects of methane gas hydrate and ice on the acoustic and strength properties of sediment, the results indicated that the presence of gas hydrate and ice would enhanced the shear strength of sediment. Priest et al. (2006) studied the attenuation of seismic waves in methane gas hydrate-bearing sand, and the results showed that the methane gas hydrate could have a dramatic effect on seismic wave attenuation in sand. For triaxial shear tests, Hyodo et al. (2005, 2013a, 2013b) studied the effects of temperature, pore pressure, confining pressure, hydrate saturation, pore fluid (gas/water) and fines content on the shear strength of methane hydrate-bearing sand under various conditions which similar to those found *in situ*. Also, they studied the dissociation characteristics of methane hydrate-bearing sediments by using thermal and depressurization methods, which indicated that the depressurization would not cause the failure of the sediments, but

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the water pressure recovery and thermal stimulation would lead to the collapse when the external load was higher than the strength of the sediments (Hyodo et al., 2014). Miyazaki et al. (2010, 2011a) studied the mechanical characteristics of both natural gas hydrate-bearing sediments and artificial methane hydrate-bearing sediments, they found that the strength and stiffness increased with the increase of hydrate saturation and effective confining pressure, while the Poisson's ratio decreased with the effective confining pressure. Yoneda et al. (2015a, 2015b) studied the mechanical properties of gas hydrate-bearing sandy and clayey-silty sediments, which were recovered by pressure coring in the Eastern Nankai Trough, the area of the first Japanese offshore production test. Also, Yoneda et al. (2011) studied the localized deformation behaviors of methane hydrate-bearing sand by the plane shear tests, the results showed that the compressive deformation by depressurization increased with the increase of initial shear strain, and the failure mode during water pressure recovery was the same as that in compression test. Li et al. (2015) studied the effect of different mining methods on the stability of clayey sediments containing methane hydrate and ice under below zero conditions. These studies are valuable; however, few studies have been reported on the creep behaviors of methane hydrate-bearing layers (Miyazaki et al., 2009, 2011b), although they are thought to have great significance in predicting the long-term stability of the layers over a time scale of decades. According to the literature (Mountjoy et al., 2013), the methane hydrate can itself destabilize the layers, and the methane hydrate-bearing layers could exhibit time-dependent plastic deformation (creep deformation) enabling glacial-style deformation. It is important to study the creep behaviors of methane hydrate-bearing layers.

Parameswaran et al. (1989) and Cameron et al. (1990) investigated the compressive strength and creep behaviors of sand consolidated the tetrahydrofuran hydrate or ice under uniaxial compression, and the results showed that the strength of hydrate-consolidated sand was much higher than that of ice-consolidated sand. Miyazaki et al. (2011b) conducted the constant-strain-rate tests and creep tests on artificial methane hydrate-bearing sand under triaxial compression, which indicated that the hydrate-bearing sand specimens had considerable time dependence, and the strain rate dependence of the hydrate-bearing sand specimens was as strong as that of frozen sand and stronger than that of the sand specimens, but weaker than that of ice and methane hydrate. Durham et al. (2003) also considered that hydrate should be more creep resistant than ice. As shown above, the creep behaviors of methane hydrate or methane hydrate-bearing sediments are still not well investigated or understood, especially that of methane hydrate be occurred associating with ice-bearing permafrost, in which the methane hydrate may coexist with ice (Dallimore and Collett, 1998; Yakushev and Chuvilin, 2000). The creep behaviors of methane hydrate coexisting with ice need to be investigated before commercial scale gas production from permafrost deposits. In this paper, the effects of deviator stress, confining pressure and temperature on the creep behaviors of methane hydrate coexisting with ice were investigated.

2. Testing methods

2.1. Testing apparatus

The creep tests of methane hydrate coexisting with ice were performed by a self-developed TAW-60 triaxial testing device at low temperature and high pressure. Fig. 1 shows the schematic diagram of the TAW-60, which has been introduced in our early studies (Li et al., 2012a; Song et al., 2010).

This TAW-60 triaxial testing device has the following characteristics and functions: (1) it can reproduce the *in situ* conditions of gas hydrate-bearing layers in a cylindrical sample (ϕ50 × 100); (2) the temperature ranged from −20 °C to 25 °C with an accuracy of ±0.5 °C in the test chamber; (3) the confining pressure capacity is 30 MPa, and it is controlled by a syringe pump with an accuracy of ±0.3 MPa; (4) the maximum axial load is 60 kN; (5) the process of the test is pre-set by computer, and the data are collected by computer automatically.

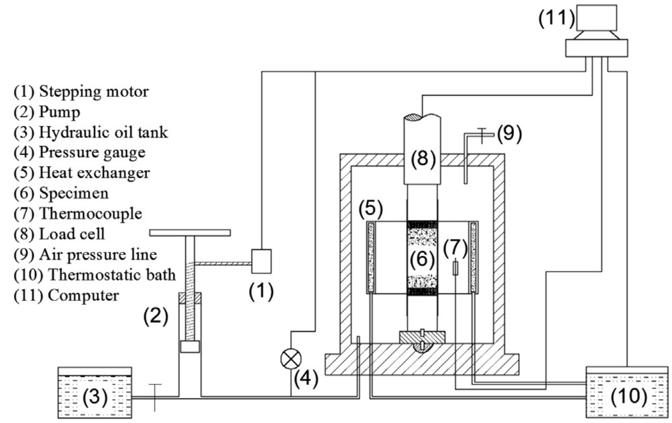

Fig. 1. The schematic diagram of TAW-60 triaxial testing device.

2.2. Specimen preparation

In this study, methane hydrate was formed in a high-pressure reaction chamber by mixing ice powder (with average grain size less than 250 μm) and methane gas (Li et al., 2012a). Firstly, distilled water was used to form ice in a refrigerator at a low temperature of −5 °C. Secondly, the ice was smashed by the ice crusher and then sieved on a standard 60 mesh sieve in a cold room with a temperature of −10 °C to obtain the ice powder with grain size less than 250 μm. Thirdly, the high pressure methane gas of 10 MPa was injected into the high-pressure reaction chamber to mix with the ice powder, and kept the temperature at −5 °C in the refrigerator. Such condition was maintained for 48 h, and the reaction was considered complete when the pressure was stable in the chamber. The composition proportion of methane hydrate to ice was about 3:7 ($\frac{V_h}{V_{ice}}$, here, V_h and V_{ice} are the volumes of methane hydrate and ice respectively), which was calculated by the mass difference of the sample before and after hydrate dissociation at room temperature and atmospheric pressure ($\frac{V_h}{V_{ice}} = \frac{m_h/\rho_h}{(m_{spl.bef} - m_h)/\rho_{ice}}$, and $m_h = \frac{M_h}{M_{gas}} \times (m_{spl.bef} - m_{spl.aft})$, here, m_h is the mass of methane hydrate, ρ_h and ρ_{ice} are the densities of methane hydrate and ice respectively, M_h and M_{gas} are the molar masses of methane hydrate and methane gas respectively, $m_{spl.bef}$ and $m_{spl.aft}$ are the masses of sample before and after hydrate dissociation respectively). Finally, the obtained methane hydrate-ice mixture was compacted by a pressure crystal device under a pressure of 10 MPa in the cold room (Li et al., 2012a). The size of the obtained cylindrical specimen was 50 mm in diameter and 100 mm in height. The bulk density of specimens was 0.9 g/cm^3.

2.3. Creep tests

The prepared specimen was covered with a rubber membrane of 0.5 mm in thickness, and placed on the pedestal of the TAW-60. When the temperature of hydraulic oil and specimen reached the designated value, the confining pressure and axial load was applied, then the creep tests started. In this study, the creep tests on