Measurement and analysis of thermal expansion coefficients of mortar and limestone cooled to cryogenic temperatures

Wenqi Feng*, Yang Li*, Qijie Yuan#, Zhongzhi Xie#, Geyuan Ding# and Chenyu Ji*

School of Civil Architecture and Environment, Hubei University of Technology, Wuhan, China

*Corresponding author e-mail: 409717673@qq.com, 2440248078@qq.com, 951524866@qq.com, 2025706931@qq.com, 1198713624@qq.com, 1663527926@qq.com

Abstract. The force caused by the difference of thermal expansion coefficient between concrete aggregates at ultra-low temperature will inevitably affect the structure and should be considered in the structural design. The coefficient of thermal expansion of cement mortar and stone was measured by resistance strain gage test technology in ultra-low temperature environment, and the variation law of average linear expansion coefficient with temperature was obtained. The results show that the thermal expansion coefficients of cement mortar and stone have similar variation rules with the change of temperature. The stress state of cement mortar and stone under ultra-low temperature does not affect their thermal expansion coefficient. Thermal expansion coefficient of cement mortar under ultra-low temperature is affected by size effect.

1. Introduction

With the implementation of China's liquefied natural gas (LNG) strategy, more and more LNG receiving stations have been constructed. Usually, 9%Ni steel with excellent mechanical properties is selected as the inner and outer tank materials of the storage tank, which can resist ultra-low temperature without being damaged, but at the same time it will increase the construction cost, which has become an obstacle to the development of natural gas. At present, researchers have noticed that the mechanical properties of concrete in ultra-low temperature environment are significantly improved compared with that at room temperature, and proposed the idea of using full concrete for LNG outer tank. This idea can bring huge economic benefits, but when LNG leaks, concrete will be directly exposed to ultra-low temperature environment. Stress and strain caused by different thermal expansion coefficients between concrete aggregates at ultra-low temperature exert an additional force on the outer tank, which should be considered in LNG tank design [1]. Therefore, it is of great practical engineering value to study the thermal expansion properties of materials at ultra-low temperature and the corresponding testing methods.
2. Experiment

2.1. Experimental Materials and Mix Proportion
The raw material and basic properties for prepare cement mortar are as follows: that cementing material is ordinary Portland cement, and the strength grade is 42.5; Mixing water is tap water; The aggregate is river sand with fineness modulus of 2.8. In this study, 304 steel is used as the research object to discuss the test method (the thermal expansion coefficient of steel at room temperature is $12 \times 10^{-6} / ^\circ C$ [2] according to the national standard).

2.2. Experimental scheme
The specific test conditions and sampling directions of the specimen are as follows: M-1 and M-2 are tested under the general conditions of Scheme 1. The sampling directions are in the four vertical centroids, and two pairs of edges are sampled in the lateral centroids. M-1-4 and R-1-4 are all sampled in this way. M-3 and M-4 are tested under extreme conditions of Scheme 2; RO-1 is tested under the general working condition of scheme 1; RO-2-4 shall be tested under the extreme working conditions of Scheme 2; The rest of the test pieces are tested under the general working condition of scheme 1, and samples are taken along the middle of the long side of the test pieces.

2.3. Test method for coefficient of thermal expansion at ultra-low temperature
The theoretical derivation and data processing method of resistance strain gage test thermal expansion at ultra-low temperature are as follows:

1. The strain gauge pasted on the piece to be tested is connected to the TDS-530 data acquisition instrument through a 1/4 bridging method (TDS-530 provides three virtual resistors to form a bridge circuit), and the data is cleared at 0$^\circ$C to balance the bridge. Considering the relative deformation caused by the difference in thermal expansion coefficient between the strain gauge, the piece to be tested and the primer, the heat output at a certain constant temperature at ultra-low temperature is as follows:

$$\varepsilon_{td} = \frac{1}{k_g} \frac{\Delta R}{R} = \frac{\Phi_g \Delta T}{k_g} + (\alpha_1 - \alpha_g) \Delta T$$

2. The thermal output of the strain gauge pasted on the standard test piece at a certain constant temperature at ultra-low temperature $\varepsilon_{tb}$ is as follows:

$$\varepsilon_{tb} = \frac{1}{k_g} \frac{\Delta R}{R} = \frac{\Phi_g \Delta T}{k_g} + (\alpha_2 - \alpha_g) \Delta T$$

In this study, the average linear expansion coefficient of the test piece is measured through the above principle and data processing method. Its calculation formula is as follows:

$$\alpha_m = \alpha_2 + \left( \varepsilon_{td} - \varepsilon_{tb} \right) / (t_f - t_0)$$

2.4. Experimental Methods

2.4.1. Ocation of measuring points. Before the measuring points are arranged, sandpaper is used to polish the patch position of the test piece to facilitate the joint of the strain gauge and the test piece. In the process of measuring point arrangement, glue a and glue b in the primer are mixed evenly at a ratio of 2:1, then a thin layer is coated on the bottom of the strain gauge, and the strain gauge is pressed through cellophane for not less than 24 hours. Then, the surface of strain gauge was coated with K-1 waterproof material produced by Japan TML Research Institute, and allowed to stand for 24 hours. Finally, wire bonding is carried out to complete measuring point arrangement. See Figure 1 for the flow chart of measuring point arrangement of test pieces.
2.4.2. **Device design.** In order to find out the influence of the coupling effect of temperature field and stress field on the thermal expansion coefficient of cement mortar and stone, the author has designed a kind of ultra-low temperature experimental box which can create the coupling environment working condition. The device uses liquid nitrogen for heat exchange to achieve the purpose of cooling (the test piece is not directly soaked in liquid nitrogen). The whole cooling process is very slow, and the cooling rate is about 0.1°C/min. The counterweight outside the box is hinged with the pressurizing device inside the box to form a whole body, which applies force to the test piece at the pressurizing device together. The applied force in this study is 30KN. In addition, in order to ensure the integrity of the test chamber, the openings in the chamber are blocked with insulation cotto.

2.4.3. **Experimental process.** The specific counterweight pressurization scheme is as follows: one forklift is equipped on each side of the counterweight, and the forklifts on both sides simultaneously lift the counterweight to extract the steel bar on the support ladder and then slowly lower it. The gravity of the counterweight forms pressure on the test piece through the bottom bolt, the pressurization device in the test box and the support beam. In addition, a reference mortar cube test block is additionally arranged beside the test piece to be tested, and a thermocouple is embedded at the centroid of the test block to monitor the temperature of the cube core. Because the temperature in the test chamber is slow, the ambient temperature at each measuring point is almost the same at the same time, and the heat transfer performance of the stone is better than that of mortar, it can be considered that the stone core temperature has reached the same temperature or slightly exceeded when the mortar is cooled to the specified temperature, and all cube test blocks take the reference mortar cube core temperature as the real-time core temperature.

3. **Results and analysis**

3.1. **Feasibility Verification of Test Methods**

In order to verify whether the thermal expansion coefficient of the material can be obtained at ultra-low temperature according to the above data processing method, parallel experiments were carried out to measure the thermal expansion coefficient of the steel bars (4). Table 1 shows the average linear expansion coefficient of steel bars obtained by the above method and the average linear expansion coefficient of steel strands measured experimentally in reference [3-4]. Through comparison, it is found that the test results of this study are consistent with the change rule of average linear expansion coefficient with temperature in previous studies, which reflects the physical characteristics of steel with decreasing shrinkage rate with decreasing temperature.
Table 1. Comparison of test results [3-4]

| Temperature (°C) | S-1 | S-2 | S-3 | S-4 | Average value | Steel strand |
|------------------|-----|-----|-----|-----|---------------|--------------|
| 0~20             | 13.46 | 15.15 | 14.20 | 15.05 | 14.72          | 11.81        |
| 0~40             | 13.58 | 14.42 | 13.58 | 14.47 | 14.01          | 11.50        |
| 0~60             | 12.76 | 13.62 | 11.86 | 13.79 | 14.26          | 11.19        |
| 0~80             | 12.59 | 12.51 | 12.12 | 13.07 | 12.57          | 10.88        |
| 0~100            | 11.09 | 12.05 | 11.68 | 12.64 | 11.87          | 10.57        |
| 0~120            | 10.44 | 11.43 | 11.07 | 12.03 | 11.24          | 10.26        |
| 0~140            | 9.55  | 10.55 | 10.32 | 11.34 | 10.44          | 9.95         |
| 0~165            | 8.37  | 9.39  | 9.13  | 10.35 | 9.31           | 9.56         |

3.2. Effect of Coupling of Temperature Field and Stress Field on Thermal Expansion Coefficient
Taking cement mortar numbered M-1~4 and stone numbered L-1~4 as examples, the test conditions are only temperature field effect and temperature field and stress field coupling effect respectively. It is not difficult to find that the thermal output and thermal expansion coefficient of cement mortar and stone have similar variation rules and similar values under any working condition. In general, the thermal expansion coefficient of cement mortar and stone under the coupling effect of temperature field and stress field is consistent with that under the single effect of temperature field, which reflects that the thermal expansion and shrinkage characteristics of cement mortar and stone do not change with the external stress state. This point can be considered for relevant simplified treatment in LNG tank design.

3.3. Influence of Sampling Direction on Thermal Expansion Coefficient
Cement mortar and stone are anisotropic materials at room temperature, and their physical properties in different directions are generally different. In order to study the influence of the sampling direction on the thermal expansion coefficient of materials under ultra-low temperature, the cement mortar and stone cube specimens were vertically sampled respectively, and the relationship between the average linear expansion coefficient and temperature was measured and compared. The average linear expansion coefficient of cement mortar measured in two vertical directions is the same at 0~60°C, the vertical expansion coefficient is greater than the transverse expansion coefficient after 60°C, and the thermal expansion coefficient of cement mortar is anisotropic at ultra-low temperature. The thermal expansion coefficient of stone material shows great anisotropy at the beginning of cooling. As the temperature decreases, the difference between the thermal expansion coefficients in the horizontal and vertical directions gradually decreases. The transverse thermal expansion coefficient is always greater than the longitudinal thermal expansion coefficient in the cooling process. The thermal expansion coefficient of stone material is anisotropic at ultra-low temperature.

4. Conclusion
The coefficient of thermal expansion of cement mortar and stone at ultra-low temperature is obtained by resistance strain gage test technology, which provides experimental basis for LNG tank design. The following conclusions can be drawn within the scope of this study:

1) The adopted test method can accurately measure the thermal expansion coefficient of materials at ultra-low temperature.

2) The stress state of cement mortar and stone has no influence on the thermal expansion coefficient at ultra-low temperature.

3) Size effect has influence on the thermal expansion coefficient of cement mortar at ultra-low temperature, but has little influence on the thermal expansion coefficient of stone.

4) The thermal expansion coefficient of cement mortar and stone is anisotropic at ultra-low temperature.
Acknowledgements
This paper is supported by “Open fund of Hubei province bridge safety monitoring technology and equipment engineering technology research center” (QLZX2014001), “Science and technology research projects for youth talent of Science and Technology Department of Hubei Province” (2018CFB287). The author would like to express his gratitude to their support to current research.

References
[1] SHUI Z H, CAO B B. Study on Thermal Expansion Property of Cement Concrete Materials [C]. Guangzhou: The 9th National Conference on Cement and Concrete Chemistry and Applied Technology, 2005, 9: 429 - 435.
[2] GB 50017-2017, Steel structure design standard [S].
[3] DING Yanran. D Tianjin University, 2016.
[4] Jian Xie, Jiabao Yan. Tests and analysis on thermal expansion behaviour of Steel Strand used in prestressed concrete structure under low temperatures [J]. International Journal of Concrete Structures and Materials, 2018. (DOI: 10.1186/s40069-018-0236-9).