Research on Testing Methods of Temperature Strain and Force Strain under Extreme Temperature Environment

Axel Tanguy, Yang Li*, Mengxi Tan
School of Civil Architecture and Environment, Hubei University of Technology, Wuhan, China
Email: 409717673@qq.com

Abstract. The traditional quartz differential method and the half-bridge connection temperature compensation test method are improved to realize the effective separation of the physical deformation of the material caused by the temperature effect and the deformation caused by the load under the coupling effect of temperature and load, so as to be the thermal expansion coefficient of the material at extreme temperatures. And provide the basis for the test and determination of mechanical performance parameters.

Keywords: extreme temperature, thermal expansion coefficient of concrete, mechanical parameters

1. Research Background and Meaning
At present, there are more in-depth studies on the expansion deformation of concrete at room temperature, but the expansion deformation of concrete at extreme temperature causes greater harm, the thermal stress caused by uneven strain of concrete components caused by extreme temperature is very high, the stress will soon exceed the shear stress in the weak area of the structure, resulting in cracks, the continuous development of cracks will cause the structural strength to decrease, weaken the bonding force between steel bars and concrete, so that the carrying capacity of the structure drops sharply and seriously endangers the safety of the building.

Free expansion deformation is a deformation caused only by the effect of temperature. It occupies a basic position in the study of expansion deformation. It is necessary to carry out research in this area. In the existing research, Maruyama [1] made the concrete into thin slices and heated it in a water bath, and controlled the temperature of the concrete to change evenly on the entire specimen by adjusting the water temperature and holding time. Fu Baohua, Hu Bao, and Li Jun [2] also used the method of heating the concrete block in a water bath to measure the elongation of the concrete block. Lucie Zuda [3] got thermal coffecient data of specimen by measuring the change of the end height of the ceramic rod with the dial indicator outside the box. Although a series of researches on the thermal expansion coefficient of concrete have been conducted at home and abroad, and certain results have been obtained, some methods and models for measuring and predicting the thermal expansion coefficient of concrete have been proposed. However, these studies still have some shortcomings, mainly in the domestic Most of the methods for directly measuring the thermal expansion coefficient of concrete are within the temperature range of 50°C to 100°C, and very few tests that directly measure the thermal expansion coefficient of high-temperature or low-temperature concrete require professional testing instruments, and the test costs are relatively high. Therefore, it is necessary to explore an economical and practical measurement method, and this article conducts research based on this.
2. Basic Principles and Methods of Electrical Measurement

The coefficient of thermal expansion is one of the basic thermal parameters of a material, which reflects the deformation of the material itself under the action of temperature. The size of the capacity. The coefficient of thermal expansion is defined as follows:

\[ \alpha = \frac{\Delta L}{L_0 \Delta T} = \frac{L - L_0}{L_0 (T - T_0)} = \frac{\varepsilon}{(T - T_0)} \]  

Where: \( \Delta T \) is the change in length, \( \Delta T \) is the change in temperature, \( T_0 \) is the reference temperature, \( T \) is the test temperature, \( L_0 \) is the original length of the test piece, \( L \) is the length of the test piece corresponding to the test temperature, \( \varepsilon \) is the amount of thermal strain change of the test piece.

The thermal expansion coefficient is linear expansion coefficient \( \alpha \), surface expansion coefficient \( \beta \) and volume expansion coefficient \( \gamma \). However, the experiment in this paper is the linear expansion coefficient in the thermal expansion coefficient.

2.1. Strain Gauge Heat Output

The sensitive grid of the test part of the strain gauge is made of metal foil by photolithography. So, during the test when the temperature changes, it will naturally cause the resistivity of the metal sensitive grid to change. This kind of change will cause the low temperature strain gauge attached to the component to have a strain output when the component is not subjected to external load. The relationship between the resistivity of metal materials and temperature can be expressed by the following formula:

\[ \rho = \rho_0 (1 + \varphi \Delta T) = \rho_0 (1 + \varphi_s (T - T_0)) \]  

In the formula, \( \rho \) and \( \rho_0 \) are the resistivity of the metal material at temperature \( T \) and \( T_0 \) respectively, the unit is \( \Omega \cdot m \), \( \varphi \) is the temperature coefficient of resistance of the metal material, the unit is \( T^{-1} \), \( \Delta T = T - T_0 \).

The strain caused by the sensitive grid can be expressed as the following formula:

\[ \Delta \varepsilon = \frac{(\Delta R)}{k_s} = \frac{\varphi_s}{k} \Delta T \]  

In the formula, \( \Delta \varepsilon \) is the strain caused by the resistivity change; \( \Delta R \) is the resistance change caused by the resistivity change of the strain gauge; \( R \) is the resistance value of the strain gauge itself; \( k_s \) is the sensitivity coefficient of the strain gauge itself.

On the other hand, the measured material itself and the low-temperature strain gauge will also expand or contract with the change of temperature. The difference between the deformation of these two parts will also cause the strain gauge to have a strain output, due to the thermal expansion coefficient of the strain gauge sensitive grid and the measured material. The strain caused by the difference can be expressed as the following formula:

\[ \Delta \varepsilon = \frac{\Delta R}{k_s} = (\alpha_e - \alpha_g) \Delta T \]  

\( \varepsilon_E \) is the strain caused by the difference between the strain gauge's sensitive grid and the thermal expansion coefficient of the material to be measured; \( \Delta T \) is the resistance change caused by the difference between the strain gauge's sensitive grid and the substrate material being bonded; \( \alpha_e \) is the linear expansion coefficient of the substrate material; \( \alpha_g \) is the linear expansion coefficient of the sensitive grid material.

The strain of these two parts is not caused by the force of the component itself, but caused by the effect of temperature, which is collectively called the heat output of the temperature strain gauge. The expression is as follows:

\[ \varepsilon_T = \varepsilon_E - \varepsilon_M = \frac{\varphi_s}{k_s} \Delta T + (\alpha_e - \alpha_g) \Delta T \]
In the formula, $\varepsilon_T$ is the heat output of the strain gauge.

2.2. The Principle of Electrical Measurement of Thermal Expansion Coefficient

The basic idea of measuring the thermal expansion coefficient of materials by the electrical measurement method is to select a standard material specimen, and use a strain gauge to measure the thermal strain difference between the measured material and the standard material specimen at the same reference temperature and the same temperature change (that is, relative Thermal strain), combined with the true thermal strain of the standard material specimen to finally obtain the true thermal strain of the tested material.

It can be known from the literature that high-purity quartz glass has a very low thermal expansion coefficient and changes little by temperature. Within a certain temperature range, the thermal expansion coefficient of quartz glass can be considered to be a constant value, so high-purity quartz glass can be used as Standard material test piece.

The strain gauge can be used to measure the thermal strain of the measured material and the quartz glass, as shown in equations 6 and 7:

$$\varepsilon_M = \frac{\varphi_s}{k_s} \Delta T + (\alpha_M - \alpha_0) \Delta T$$

$$\varepsilon_G = \frac{\varphi_s}{k_s} \Delta T + (\alpha_G - \alpha_0) \Delta T$$

In the formula, $\varepsilon_M$ is the heat output of the surface strain gauge of the measured material; $\varepsilon_G$ is the heat output of the quartz glass surface strain gauge; $\alpha_M$ is the thermal expansion coefficient of the measured material; $\alpha_G$ is the thermal expansion coefficient of the quartz glass.

Connect the strain gauge on the surface of the test piece with the strain gauge on the surface of the quartz glass in a half-bridge manner. At this time, the output result of the strain gauge is shown in Equation 8:

$$\varepsilon_\Delta = \varepsilon_M - \varepsilon_G = (\alpha_M - \alpha_G) \Delta T$$

In the formula, $\varepsilon_\Delta$ is the output result of the strain gauge, which represents the difference between the thermal strain of the measured material and the quartz glass. Simplify the above formula to obtain the calculation formula of the thermal expansion coefficient of the tested material:

$$\alpha_M = \frac{\varepsilon_\Delta}{\Delta T} + \alpha_G = \frac{\varepsilon_M - \varepsilon_G}{\Delta T} + \alpha_G$$

3. Experimentation Test

3.1. Specimen Production

Rebar test pieces: Cut Φ12 304 stainless steel rebar into several test pieces with a length of 300mm.

Quartz glass: Quartz glass (purity 99.99%) is customized by Donghai Haotian Quartz Glass Products Co., Ltd., with a size of 50mm×50mm×3mm. For easy patching, the surface is polished with a sharpening stone until the surface of the quartz glass to get scratchy, use a glass knife to draw parallel lines perpendicular to each other where the strain gauge needs to be pasted on the surface of the quartz glass to increase the roughness of the contact surface. Selected quartz glass as standard part.

3.2. Experiment Procedure

Take heating as an example to give steps

(1) The test piece is put into the box. First, take out the specimens that have been cured and formed and have completed the pre-embedded arrangement of the measuring points and placed them near the test box.

(2) Test system debugging. Complete the connection of the corresponding measuring points in the box. Lead the corresponding wires through the test hole of the test box and connect the data acquisition system and data recording equipment, and debug the test system before cooling down.
(3) Pre-test of heating and cooling. In the low temperature box, connect the liquid nitrogen tank liquid phase valve with the low temperature box to cool down, and slowly unscrew the liquid nitrogen liquid phase outlet valve before cooling down. After the temperature loading starts, record the strain value and the corresponding temperature at each measuring point at this time. Set the target temperature to 20°C through the console, click to run the system, after the test box fan starts, test the specimen, and test the data every 30 seconds.

(4) The temperature is officially raised and lowered. Confirm that the test system is correct and start the formal temperature loading. During the heating or cooling process, the temperature measured at the measuring point and the target temperature rise or fall of the console should not exceed 15°C as the benchmark, thereby realizing the control of the cooling speed. Throughout the test process, the data is tested every 30 seconds.

(5) Rewarming. When the temperature at the measuring point reaches 500°C or -165°C, close the valve of the liquid nitrogen tank in the low temperature box, turn off the electric heating in the high temperature box, and return to room temperature through the console.

4. Results and Rationality Analysis
(1) Analysis of the thermal expansion coefficient of steel bars under ultra-low temperature. The three sets of specimens selected for the steel bars were processed according to the method described in the principle, and according to the definition of the thermal expansion coefficient, the thermal strain temperature curve and the thermal expansion coefficient temperature relationship curve of the steel bar were obtained based on 20°C.

![Figure 1](image1.png)
**Figure 1.** Heat output-temperature curve of steel bar specimens under ultra-low temperature.

![Figure 2](image2.png)
**Figure 2.** Temperature relationship curve of thermal expansion coefficient of steel bar specimens under ultra-low temperature.
According to the analysis of the temperature curve obtained by the principle method, it can be seen that in figure 1, the heat output of the steel bar decreases monotonously with the decrease of temperature, and the linear relationship is good. In figure 2, the thermal expansion coefficient of the steel bar decreases with the decrease of temperature, but the change of the thermal expansion coefficient is very small. The overall thermal expansion coefficient is between \(12 \mu \varepsilon \cdot ^\circ C^{-1}\) and \(9 \mu \varepsilon \cdot ^\circ C^{-1}\), indicating that the steel is stable at low temperatures. The thermodynamic properties. From the previous foreign research literature on stainless steel, it can be seen that in the temperature range of 100K to 293K, the thermal expansion coefficient of steel bars increases with temperature \([4-5]\). The research results are basically consistent with the test results and change rules of the thermal expansion coefficient of the steel bar at low temperature in this test research. This verifies the correctness and rationality of the electrical measurement and processing methods in this experiment under ultra-low temperature.

According to the thermal expansion coefficient-temperature relationship curve of the steel bar under ultra-low temperature, the average fitting relationship of the thermal expansion coefficient of the steel bar is further obtained from the three sets of test pieces as follows.

The fitting relationship between the average thermal expansion coefficient of steel bar specimens and temperature at ultra-low temperature:

\[
\alpha_s(T) = -3 \times 10^{-5}T^2 + 0.0075T + 11.511 \quad (\mu \varepsilon \cdot ^\circ C^{-1}); \quad R^2 = 0.9694 \quad (10)
\]

Where \(\alpha_s\) is the thermal expansion coefficient of steel bars; \(T\)—Temperature (-170°C≤T≤0°C).

5. Conclusion
Establish the relationship model of the thermal expansion coefficient of steel bar with temperature. Studies have shown that the thermal expansion coefficient of steel bars decreases linearly with the decrease of temperature from 0°C to -165°C, and the minimum is about \(9 \mu \varepsilon \cdot ^\circ C^{-1}\), which is reduced by about 24%; from normal temperature to 500°C, the thermal expansion coefficient of steel bars increases with the temperature increases, and the maximum is about \(14 \mu \varepsilon \cdot ^\circ C^{-1}\), which is about 70% higher than that of 50°C.

References
[1] Maruyama I, Teramoto A 2011 Impact of time-dependent thermal expansion coefficient on the early-age volume changes in cement pastes [J] Cement and Concrete Research 41(4): 380-391.
[2] Fu B H, Hu B, Li J 2016 Effect of aggregate on thermal expansion coefficient of concrete [J] Create Living (8): 40-42.
[3] Zuda L, Černý R 2009 Measurement of linear thermal expansion coefficient of alkali-activated aluminosilicate composites up to 1000°C [J] Cement & Concrete Composites 31(4): 263-267.
[4] Skibina L V, Ilichev V Y, Chernik M M, et al. 1985 Thermal expansion of the austenitic stainless steels and titanium alloys in the temperature range 5-300K [J] Cryogenics 25(1): 31-32.
[5] Manelli V, Bianchilli G, Ventura G 2014 Measurement of the thermal expansion coefficient of AISI 420 stainless steel between 20 and 293K [J] Cryogenics 62: 94-36.