Mechanical properties of ultra-low temperature mortar stone

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Abstract In order to study the mechanical properties of concrete materials in the normal operation phase of LNG tanks, the longitudinal strain of the loading direction and the transverse strain of the vertical loading at the corresponding temperature were measured by using the resistance strain gauge test technique. The elasticity of the mortar block and stone in the ultra-low temperature environment was studied. Modulus, Poisson's ratio and shear modulus are respectively related to temperature. The results show that the Poisson's ratio of stone and mortar is not obvious with temperature, which can be considered as a fixed value; the elastic modulus and shear modulus of mortar block increase linearly with the decrease of temperature, and the elastic modulus and shear modulus of stone The temperature decrease is a quadratic function relationship of decreasing first and then increasing. The elastic modulus and shear modulus of the stone are all the smallest at around -60 °C. It is concluded that the concrete material has better mechanical properties than the normal temperature environment in the ultra-low temperature environment, and can be used to further improve the design and construction of the LNG tank.

1. Introduction
The research background is based on the research conducted during the normal operation phase of LNG tanks. In order to reduce the construction cost, it is proposed to use concrete materials as the outer tank material of the LNG storage tank. Xie Jian et al research shows that: in the case of leakage, the concrete outer tank will be exposed to ultra-low temperature (-165 °C) environment, the temperature environment’s changes will inevitably affect the concrete mechanical properties[¹-⁴]. In order to ensure the long-term safe operation of LNG storage tanks, it is necessary to deeply understand the mechanical properties of the components in ultra-low temperature environment. This experiment is to study the elastic modulus, shear modulus and Poisson's ratio of mortar and stone in ultra-low temperature environment. Although China has made great achievements in the construction of LNG storage tanks, the mechanical properties of concrete materials in ultra-low temperature environment are still not very distinct. which brings great difficulties and safety hazards to the construction and operation of LNG storage tanks[⁵-¹¹]. Therefore, it is imperative to carry out a research on the
mechanical properties of concrete and other materials in ultra-low temperature environment. This research will help China's independent research and develop and maintenance of LNG storage tanks. This subject mainly tests the stress-strain relationship of mortar and stone in the temperature range of 0 °C to -165 °C, and analyzes the relationship between material elastic modulus, Poisson's ratio, shear modulus and temperature, which is the design of LNG storage tank. Providing theoretical basis for data on mechanical properties of materials. At present, there are not many studies on the mechanical properties and monitoring methods of mortar and stone in normal working stage in ultra-low temperature environment, which makes the characterization of concrete structure damage not very clear, especially for the normal working stage of stone in ultra-low temperature environment.彭 ratio, shear modulus and elastic modulus are rarely studied.

In this study, the mechanical properties of mortar and stone in the normal working stage were studied in a self-designed low-temperature box from 0 °C to -165 °C. The strain was measured by electric measurement method, and the temperature was caused by the in-situ compensation method during the constant temperature loading stage. Strain separation caused by strain and mechanical force, the transverse strain and longitudinal strain caused by mechanical force are measured, so that the elastic modulus of the test piece and the relationship between shear modulus and temperature can be obtained through an experiment, supplementing the blank in the normal service phase of concrete in an ultra-low temperature environment of the existing research.

2. Test equipment overview
In order to ensure the loading and unloading experiment conducted in a stable low temperature environment, the research team designed a set of ultra-low temperature mechanical loading test device, as shown in Figure 1 and Figure 2. It consists of three parts: test chamber, console and data acquisition instrument. Temperature control is carried out through the console. Ultra-low temperature loading and unloading of the test piece is carried out in the test chamber, and the temperature and corresponding strain data are collected by the data collector.

Through pre-experimental verification, the device can accurately control the temperature’s rise and fall, fully guarantee the ultra-low temperature environment of -165 °C, and can maintain the ultra-low temperature constant temperature environment for a long time, so that the temperature inside and outside the test piece is basically uniform, and the loading device can ensure accurate loading of mechanical force. Data acquisition accurately records the thermocouple output temperature and the heat output of the strain gage.
2.1. Test piece design test piece
Preparations of raw materials: river sand with a fineness modulus of 2.8, ordinary Portland cement with a strength grade of 42.5, proportioning water for stone test blocks: cement: sand = 1:2.5:4.65, test block size is 100×100× 100 mm. The standard maintenance of mortar is 28 d; the stone is limestone obtained from the processing of Xianning. All test pieces were placed in a high temperature chamber for 24 h before the test, and the temperature was set to 40 °C for drying.

2.2. Strain gauge thermocouple arrangement
The strain gauges were CFLA-6-350-11 ultra-low temperature strain gauges, and a PT100 thermocouple was placed near each measurement point. In addition, six mortar test blocks and six stone test blocks with the same curing conditions were selected and drilled to the inner center respectively, and a thermocouple was arranged at the center of the twelve test pieces to determine the internal temperature of the test piece. In addition, a PT100 thermocouple is arranged on each of the four external sides. When the internal and external temperatures are the same, the loading experiment is performed to ensure that the temperature of the test piece is uniform.

The lateral strain gauges are attached to the four lateral centripets along the loading direction and perpendicular to the loading direction, and the longitudinal strain and the transverse strain are measured, and the measurement points are shown in Fig.3.

![Fig.3 Mortar test piece placement point arrangement](image)

2.3. Ultra-low temperature control scheme
The liquid nitrogen is used to provide an ultra-low temperature environment, and the temperature is adjusted by the system to control the liquid nitrogen injection rate. Because the material is a thermally inert material, it is necessary to wait for the temperature inside and outside the test piece to be consistent before loading and unloading. Select 0 °C, -10 °C, -20 °C, -30 °C, -40 °C, -50 °C, -60 °C, -70 °C, -80 °C, -90 °C, -110 °C, -120 °C, -130 °C, -140 °C, -150 °C, -160 °C, -165 °C, as the test temperature point. After the temperature at the centroid of the test piece reaches the test temperature point above, it is stabilized for 30 minutes to ensure that the temperature difference between the inside and outside of the test piece is small enough. And it should be guaranteed that the temperature of the test piece is uniform before the loading and unloading experiment.

2.4. loading scheme
During the cooling process, seven stages of loading are applied to the test piece after the temperature is stable and uniform, and the stress applied to the test piece is calculated shown in Table 1 below.

| Pressure Level | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|---------------|-----|-----|-----|-----|-----|-----|-----|
| stress/MPa    | 0.49| 0.96| 1.38| 1.82| 2.26| 2.7 | 3.14|

Wait a minute or so after each load, so that the test system records enough valid data after the test piece is stabilized.
2.5. Measurement principle
During the loading phase: the strain we output through the strain gauges generally consists of two major parts. The first part is the strain generated by mechanical force, which is the basis for calculating the elastic modulus, Poisson's ratio and shear modulus. The second part is the strain caused by other factors caused by temperature changes. In order to obtain the strain caused by mechanical force, we eliminate the influence of non-mechanical force factors by the strain difference between the strain and non-loading stages in the loading phase under the same temperature environment. Formulated as follows:

When the specimen temperature is T, the total strain output during the loading phase is:

\[ \varepsilon_T = \varepsilon_{MT} + \varepsilon_0 \]  

(1)

In equation (1):
\( \varepsilon_T \) is: output total strain;
\( \varepsilon_{MT} \) is: strain caused by mechanical load;
\( \varepsilon_0 \) is: strain caused by many non-mechanical forces.

When the temperature of the test piece is T, the total strain output at the no-load stage is:

\[ \varepsilon'_T = \varepsilon_0 \]  

(2)

The above formula is poor: (1) - (2), the strain caused by simple mechanical force:

\[ \varepsilon'_{MT} = \varepsilon_T - \varepsilon'_T \]  

(3)

\( \varepsilon'_{MT} \)is the strain caused by simple mechanical force at this temperature point.

3. test results and analysis

3.1. Macroscopic phenomena and analysis
The specimen did not break during the experiment. No obvious cracks were found on the surface of the specimen after the test. There was no significant change in the quality of the specimen before and after the experiment. Before the experiment, the color of the test piece was grayish white. After the test, the color of the test piece changed slightly, which was slightly blue-gray. It is pointed out in the literature that when Ca(OH)2 crystals are precipitated on the surface of the test piece, the color is grayish white. When less Ca(OH)2 crystals are deposited on the surface of the test piece, the color tends to be the color of the aggregate\(^{[12]}\).

3.2. Change of elastic modulus of stone and mortar with temperature and analysis
Through the experiment, the stress-strain relationship of the stone and the stress-strain relationship of the mortar are shown in Figure 4 and Figure 5:

![Fig.4 Stone stress-strain curve](image1)

![Fig.5 Mortar stress-strain curve](image2)

According to the stress-strain relationship diagram, the stress and strain at different temperatures are basically linear, indicating that the mortar specimen is in the elastic deformation stage and is in the
normal service stage, which can be used to calculate the elastic modulus at the corresponding temperature.

Further, the change of the elastic modulus \( E \) of the stone with the temperature \( T \) is shown in Fig. 6:

\[
E = 0.0006T^2 + 0.0715T + 82.3824 \quad (4)
\]

It is known that the elastic modulus \( E \) has a quadratic function relationship with the temperature \( T \). The correlation coefficient is 0.9989. It can be seen that there is a strong correlation between the two. When the temperature is about \(-60 \, ^\circ C\), the elastic modulus is about 80.25 MPa. Similarly.

The elastic modulus \( E \) of the mortar is varied with temperature \( T \) shown in Figure 7 below:

\[
E = -0.1588T + 34.9714 \quad (5)
\]

The correlation coefficient is 0.9898. It is known that the elastic modulus \( E \) has a linear relationship with the temperature \( T \), and there is a strong correlation. At 0 \, ^\circ C\), the mortar elastic modulus is the smallest, the minimum is about 34.971 MPa, and the elastic modulus is maximum at -165 \, ^\circ C\). The maximum is about 61.173 MPa.

This phenomenon is explained by the analysis in Fig. 7: because the mortar specimen has a large number of tiny pores inside, and contains a large amount of pore water. At normal temperature, the
mortar specimen is mainly subjected to external stress by the skeleton to produce an elastic modulus. However, as the temperature decreases, the pore water gradually freezes, and the solid ice also has a large pressure bearing capacity, so the elastic modulus increases. Therefore, as the temperature decreases, the elastic modulus of the mortar test piece increases. In addition, the temperature point at which larger pore water freezes is higher than the temperature at which the smaller void water freezes. That is, the lower the temperature, the more the pore water is converted into solid ice, which indicates that the lower the temperature, the higher the water content of the test piece, and the higher the elastic modulus of the test piece.

It has been confirmed in the literature that the elastic modulus of ice increases with decreasing temperature and reaches a maximum value at around -35 °C. The strength of ice formed at different temperatures is also different. The lower the temperature, the higher the compressive strength of ice. In ultra-low temperature environment, the larger the water content, the greater the increase of elastic modulus; this experimental phenomenon is consistent with this conclusion. It can also be explained from the existing conclusion that the phenomenon that the elastic modulus reflected by the decrease in temperature as shown in Fig. 7 does have a great relationship with "porous water icing" and "voidal ice elastic modulus increases with decreasing temperature" relationship.

3.3. Stone and mortar Poisson's ratio with temperature changes and analysis

Through the experimental measurement of transverse strain and longitudinal strain, it is concluded that the Poisson's ratio of stone and mortar has no obvious relationship with temperature. The Poisson's ratio remains basically constant, so the average value is taken as Poisson's ratio. The stone Poisson's ratio is 0.12, and the mortar Poisson's ratio is 0.15. Further, from $G = E/2(1+v)$, the relationship between the shear modulus $G$ of the stone and the mortar and the temperature is obtained.

3.4. Change of shear modulus of stone and mortar with temperature and analysis

It has been found from experiments that the relationship between the elastic modulus of the stone and the temperature is: $E = 0.0006T^2 + 0.0715T + 82.382$. According to $G = E/2(1+v)$, the relationship between the shear modulus $G$ of the stone and the temperature $T$ in the range of 0 °C to -165 °C is:

$$G = 0.000268T^2 + 0.0319T + 36.7777$$

It is obvious that in the range of 0 °C to -165 °C, as the temperature decreases, the shear modulus of the stone specimen decreases first and then increases. At about -60 °C, the shear modulus is the smallest, and the minimum is about 35.83 MPa.

The relationship between mortar elastic modulus and temperature is: $E = -0.1588T + 34.971$. According to $G = E/2(1+v)$, the relationship between the shear modulus $G$ of the mortar and the temperature $T$ in the range of 0 °C to -165 °C is obtained as follows:

$$G = -0.069T + 15.205$$

It is obvious that in the range of 0 °C to -165 °C, as the temperature decreases, the shear modulus of the mortar specimen increases linearly, with a minimum of about 15.205 MPa and a maximum of about 26.59 MPa.

4. Conclusion

The following conclusions can be obtained by uniaxial loading and unloading tests on mortar blocks and stone blocks in an ultra-low temperature environment.

(1) In the ultra-low temperature environment, the elastic modulus of the mortar increases with the decrease of temperature, and the two have linear dependence.

(2) In the ultra-low temperature environment, the shear modulus of the mortar increases with the decrease of temperature, and the two have linear dependence.

(3) In the ultra-low temperature environment, the elastic modulus of the stone decreases first and then increases with the decrease of temperature, and the two have a secondary relationship. The stone mold is the smallest at about -60 °C.
(4) In the ultra-low temperature environment, the shear modulus of the stone decreases first and then increases with the decrease of temperature, and the two have a quadratic relationship. The stone mold is the smallest at about -60 °C.

(5) In the ultra-low temperature environment, the Poisson's ratio of stone and mortar has no obvious relationship with temperature, and it can be considered that the Poisson's ratio is a fixed value.

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