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*Zhishu Yao**, *Haiqing Song**, *Hua Cheng**, *Chuanxin Rong**

THE EXPERIMENTAL STUDY ON INNER SHIFT LINING STRUCTURE OF FREEZING SHAFT IN DEEP THICK AQUIFEROUS SOFT ROCK**

In recent years, with the implementation of China's Great Western Development Strategy, the western coal resource is developing massively. The shafts have wide diameter, the cretaceous formation and the jurassic formation diagenesis later, lower strength, the pore type of aquifer thickness, water, buried deeper and high water head compared to construction of new wells in mid-eastern China. Because of strata is dominated by porous aquifer, bad grouting, serious risks to using grouting system, and the freezing shaft sinking has reliable water tight effect and mature construction techniques, it has been extended and applied.

On the structure design of deep freezing side-wall, the related parameters in our country existing design of specifications and manuals that people get from those freezing shaft wall force-mechanism and measure data of the deep alluvium in mid-eastern China, due to the differences in strata's freezing characteristics and hydrological conditions, it is lacks pertinence on design for shift lining structure of freezing shaft in western deep thick aquiferous soft rock. So we must be further study on frozen shaft lining structure in deep bedrock, find out the mechanical mechanism, design the structure of side-wall properly. For this reason, this article showed the experimental study on inner shaft lining structure of freezing shaft in water-bearing soft rock.

* School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan, Anhui 232001, China

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1. Model design and Test method

It is not practical to conduct experiments with full-sized prototypes of a high strength reinforced concrete sidewall because of the great strength and large size of the structures.

According to the testing purpose, the model test not only make clear the stress distribution of shaft lining section during loading process, but also need to measure the failure load of shaft lining model. So, the designed shaft lining model not only satisfies the similar conditions of stress and deformation, but also meets the similar conditions of shaft lining strength. On the basis of the basic principle of a similarity theory [6], the available similarity constant was obtained as follows.

$$C_E = C_\sigma = C_p = C_R = 1;\ C_\varepsilon = 1;\ C_\nu = 1; C_\mu = 1; C_l = C_\delta;\ C_\varepsilon = 1$$

Where:

C_E — is similar constant of elastic modulus;
C_σ — is similar constant of stress;
C_P — is similar constant of load;
C_ν — is similar constant of Poisson ratio;
C_R — is similar constant of intensity;
C_μ — is similar constant of steel ratio;
C_δ — is similar constant of displacement;
C_l — is similar constant of geometry;
C_ε — is similar constant of strain.

In this condition, simply make sure appropriate geometric similar constants. In order to make results comprehensive, there is no test to some specific shaft tube as simulate the object, but consider the range of applications of the ratio of shaft lining thickness h to inner radius (λ, the diameter-thickness ratio) that is a dimensionless quantity and whose similar constant (C_λ) is 1. According to design parameters of shaft lining in deep thick aquiferous soft rock, we may take thin, middling and thick three thickness as the simulated prototype. With the test loading devices size, the parameters of model specimen of a shaft lining designed are shown in Table 1. Among them, the diameter and height of model specimen is 925.0 and 562.5 mm respectively, the model specimen of a shaft lining is shown in Figure 1. Compressive strength of concrete cube is designed as R = 60–70 MPa, reinforcement ratio is ρ = 0.4–0.6%.

Pouring model specimen adopts special processing mould. In order to ensure that the boundary conditions of both upper and lower surfaces of a shaft lining model are similar and sealed, the specimen poured need to be conserved for a period of time. From then on, at first put it on the lathe and grinder to process precisely both upper and lower surfaces to obtain high clarity. Then during the test, two rubber seals are installed on upper and lower surfaces of a shaft lining model, and its deformation can eliminate the friction of end faces, so that it ensures that the shaft lining specimen can slide freely and seal in radial direction. The loading test is conducted in a loading device designed specially for high strength shaft lining. Hydraulic oil is used in the tests to simulate the horizontal load of the shaft lining, the vertical load constrained by the cover board and bolt. Because the stiffness of cover and bolt is larger, a shaft lining model is basically a plane strain state during the loading process.

TABLE 1
Model design of shaft lining test

Model numbers	***H*, mm**	***a*, mm**	C_l	**λ**	**ρ, %**	***R***
N-1	86.0	376.5	13.946	0.2284	0.4	C60
N-2	86.0	376.5	13.946	0.2284	0.4	C70
N-3	100	362.5	14.486	0.2758	0.46	C60
N-4	100	362.5	14.486	0.2758	0.46	C70
N-5	108	354.5	14.81	0.3047	0.5	C60
N-6	108	354.5	14.81	0.3047	0.5	C70
N-7	118	344.5	15.243	0.3425	0.6	C60
N-8	118	344.5	15.243	0.3425	0.6	C70
N-9	127.6	344.9	15.675	0.3810	0.6	C70
N-10	134.0	344.9	15.861	0.4079	0.6	C70

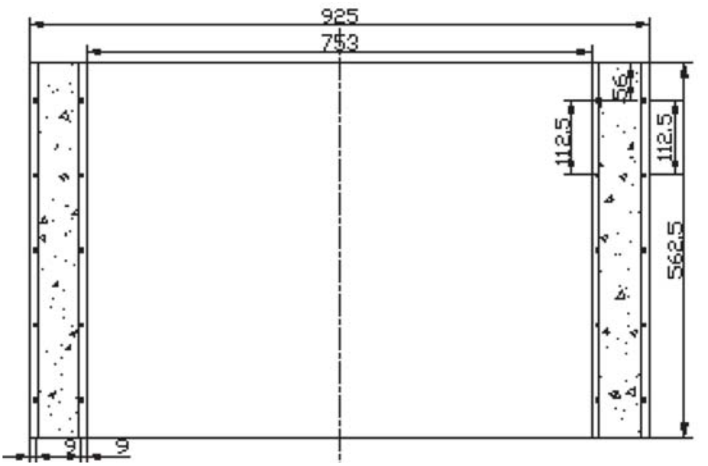

Fig. 1. Shift lining structure diagram of model (unit: mm)

In order to perform the experimental to analyze the stress, pasting resistance strain gauge and embedding concrete strain brick are carried out in each model test on inner and outer steel before the test, while hydraulic values are measured by precision pressure gauges and oil pressure sensor and the radial displacement of a shaft lining model is measured by disposing displacement meters. In test, firstly preload, then loading is graded in stabilivolt and record the strain value per level load and the last failure load.

2. Test results and Analysis

2.1. Characteristics of the Shaft Lining Deformation

Shaft lining specimen is measured in the loading process on the strain curve of steel bars and concrete shown in Figure 2 and 3.

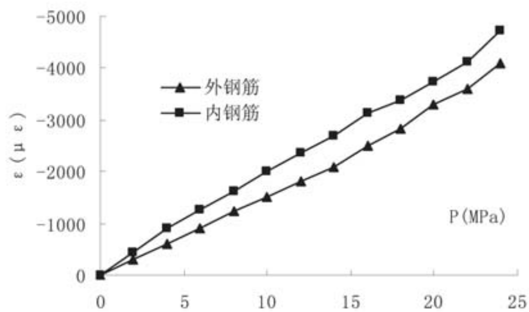

Fig. 2. Curves of load and circular strain of steel bars of N-6

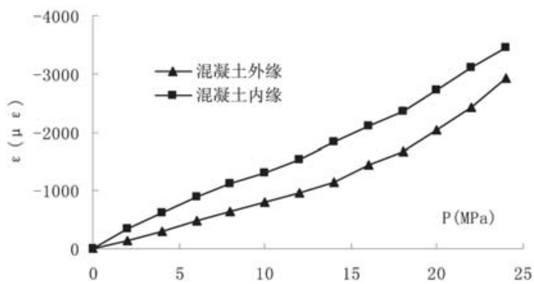

Fig. 3. Curve of load and circular strain of concrete of N-6

As shown here, the whole stressed process of high-strength reinforced concrete shaft lining can be divided into two stages: during lower load, the relationship of annular strain of steel and concrete and load is approximate linear, which is considered as elastic stage of the shaft lining, when the elastic limit load of the shaft lining is about 40% of the failure load. When the outer load exceeds 40% than the failure load, the relationship of annular strain and load becomes from straight line for curve. With the increasing load, the change of strain accelerates gradually, which is considered as plastic stage of the shaft lining.

It can be seen from Figure 2 and 3 that annular strain curves of steel bars and concrete maintain similar basically, which illustrates that steel bars have very good composite effect for concrete so that they achieve deformation coordination. Moreover, multiaxial state of stress play a good part in the constraint for concrete, plastic deformation showed obvious feature, when shaft lining model becomes destroyed, the measured compressive strain of concrete average can reach –3500 $\mu\varepsilon$. It shows that the deformation ability of concrete get improved greatly.

2.2. The Section Stress of Shaft Lining

Now take the test results of the resistance strain gauge to process, when the relationship of model test loading and the hoop stress of reinforced and concrete are shown in Figure 4 and 5.

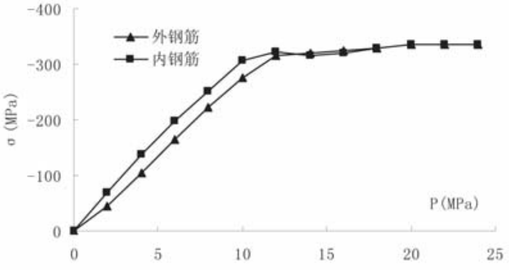

Fig. 4. Curve of load and circular stress of steel bar of N-6

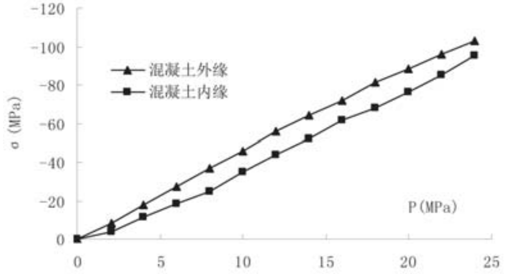

Fig. 5. Curves of load and circular stress of concrete of N-6

The following Figure shows that when the load is lesser, the shaft lining stays in the elastic stage. The hoop stress of reinforced and concrete which is approximating linear may be calculated by the elastic combination cylinder method, at this time, the hoop stress of shaft lining section stress the distribution of large inner edge and small outer edge; when the load is larger, the material is in the plastic stage and the stress of shaft lining section stress redistribution. At that moment, the hoop stress of inner edge grows slowly; however, the hoop stress of outer edge grows quickly significantly.

It can be seen from the above fig that, when the shaft lining strength come to destroy, the hoop stresses of the inner and the outer concrete gradually approaches the same value. This value is significantly higher than the uni-axial compressive strength of the concrete. For instance when measured on a cube the uni-axial compressive strength of concrete used in the HN-4 model is 72 MPa: the ultimate circumferential stress in the shaft lining is 101 MPa; when measured on a cube the uni-axial compressive strength of concrete used in the HN-6 model is 70.3 MPa, the ultimate circular stress in the shaft lining is 103MPa.This is because the concrete in the shaft lining is in complex stress state, which greatly increases the strength.

2.3. The Maximum Strength of Shaft Lining

The maximum strength values of shaft lining model are listed in Table 2 by processing the load test.

TABLE 2

Test results of shaft lining bearing capacity

Model numbers	**λ**	***R*, MPa**	**ρ, %**	**P_b, MPa**	***m***
N-1	0.2284	59.8	0.4	13.8	1.562
N-2	0.2284	71.9	0.4	18.0	1.659
N-3	0.2758	62.5	0.46	19.5	1.818
N-4	0.2758	72.0	0.46	22.0	1.739
N-5	0.3047	60.6	0.5	20.4	1.812
N-6	0.3047	70.3	0.5	24.2	1.859
N-7	0.3425	61.7	0.6	23.0	1.831
N-8	0.3425	70.9	0.6	25.5	1.726
N-9	0.3810	72.6	0.6	27.3	1.669
N-10	0.4079	70.5	0.6	29.5	1.769

As the Table 2 shows, under the equality lateral loads, high-strength shaft structure reinforced concrete has very high maximum strength, which is more than design standard load.

Test results depending on variation laws of shaft lining and ultimate capacity shows that: due to multiaxial state of stress play a good part in the constraint for concrete, when the shaft lining is destroyed, the strength of concrete has more greatly increase than uni-axial compressive strength. The real bearing capability strength of shaft lining has greatly improved because the pressured strength of concrete raises m times.

Based on the limit equilibrium condition and the strength theory of concrete in a multi-axial stressed state, a formula for calculating the load-bearing capacity of the shaft lining can be deduced:

$$P_b = h\left(mR_a + \mu R_g\right)/b \tag{1}$$

where:

b — is outside radius of shaft lining;

h — is total thickness of shaft lining;

R_a — is the axial compressive strength of the concrete

$$R_a = (0.78–0.80)\ R$$

R — is concrete cubic compression strength;

R_g — is the compressive strength of the steel bars;

μ — is ratio of reinforcement;

m — is the gain factor for the concrete strength.

Based on the result of high strength reinforced concrete sidewall of frozen shaft model test, with back calculation formula (1), it can reach the enhanced coefficient of concrete compressive strength on inner shift lining structure in Table 2.

On the basis of a dimensional analysis theory and experiment model results, the computational formula for the enhanced coefficient of concrete compressive strength m is obtained:

$$m = a \cdot \lambda^b \cdot \left(R/R_g\right)^c \cdot \mu^d \tag{2}$$

where a, b, c and d are stay for coefficient.

By calculation, we get a =1.7418; b = 0.1241; c = –0.13154; d = 0.01202.

The enhanced coefficient of concrete compressive strength m can be provided as calculated on the basis of design for shaft lining structure.

3. Conclusions

By the above test study and analysis on inner shift lining structure of freezing shaft in deep thick aquiferous soft rock, the following conclusions are obtained:

1) The characteristics of frozen shaft lining in deep thick aquiferous soft rock as stress, deforms and strength are obtained, its mechanism has been clarified, this is provided scientific evidence for design optimization.
2) Under the action of load, concrete of high strength reinforced concrete shaft linings in multi-axial compressive stress state, concrete's deformation has been limited and plastic deformation showed obvious feature, when shaft lining model becomes fractured, the ultimate compressive strain of concrete average can reach –3500 $\mu\varepsilon$.
3) In inner shaft lining structure, the concrete compression strength can achieve 1.652–1.859 times which is more than the axial compressive strength, this suggests that the reinforcing effect is obvious, and it also makes that the carrying capacity of the shaft lining has improved dramatically.
4) On the basis of a dimensional analysis theory and experiment model results, we obtained the enhanced coefficient of concrete compressive strength m, which can be provided as calculated on the basis of design for shaft lining structure.

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