Temperature-Stress Analysis of Rock-Shotcrete Structure under High Temperature Cooling Effect

Hui Su[1], Min Liang[2], Baowen Hu[3], ZhouXiang Xuan[4], Yue Xin[5], and Yi Zhu[6]
[1,2,3,4,5,6]*College of Water Resources and Hydropower, Hebei University of Engineering, Handan, Hebei 056000, China*
[3]*Key Laboratory of Ministry of Education for Efficient Mining and Safety of Metal Mines, USTB, Beijing 100083, China*
[3]*E-mail*: hubaowen1984@gmail.com
Corresponding Author: Baowen Hu

ABSTRACT: Take the diversion tunnel located in geothermal area as engineering background, the coupled temperature-stress analysis of rock-shotcrete structure with high temperature was performed under immersion action of cold water. The Physical and simulation experiment show that temperature evolution of rock-shotcrete structure can be classified into three stages, which are initial rapid decay stage, deceleration decay stage and the equilibrium stage; The stress simulation shows that the sharp change of stress will occur in the shotcrete layer during the first stage, and maximum principal stress is mainly manifested as tensile stress, which will easily lead to tensile failure of the shotcrete layer; the displacement simulation shows that the rock-shotcrete structure takes on overall shrinkage deformation in each temperature stage, and it is most obvious for shotcrete layer. The deformation of rock plate will not stop until temperature reaches stable state. Such kind of deformation law will weaken constraint on the shotcrete material, and therefore lead to stress relief in the shotcrete layer.

KEYWORDS: Temperature-stress coupling, Numerical simulation, Diversion tunnel, Rock-shotcrete structure, Attenuation stage

1. INTRODUCTION

In China, a lot of tunnels have been being subjected to high temperature environment, since with increase of underground projects in geothermal areas. The high geothermal environment not only deteriorates working conditions, reduces efficiency of construction but also influences stress distribution of surrounding rock and supporting structure through temperature-stress coupling effect. It is the stress redistribution that often brings about the insecure condition for tunnel. Therefore, an understanding of the evolution law of temperature and stress is quite important for underground engineering problems (Deng et al., 2017).

For the sake of understanding of coupling effect between temperature and stress, a key issue that is necessary to be addressed is to grasp the variation law of temperature in rock and supporting structure like lining concrete. Some laboratory and simulation experiments were conducted to study the temperature distribution law with respect to diversion tunnel located in high geothermal region. These studies showed that temperature boundary condition, fluid field distribution, material properties have great impact on the temperature evolution process, especially in the initial stage of thermal conduction, and final equilibrium state of temperature (Su et al., 2016; Shi et al., 2016; Wu and Wang, 2017). It is well known that the temperature variation of rock mass and its lining structure can often bring about deformation and redistribution of stress for the rock-ling system of tunnel. Cheng and Duan (2010) utilized the 3-D finite element method to simulate the construction process of free-flow tunnel while considered seasonal temperature variation with respect to air and rock mass. The results showed that there will be more cracks generated in lining concrete as rock mass and air in tunnel are in lower temperature state, especially in winter. Such phenomenon is mainly caused by the increase of tensile stress in concrete due to the decrease of temperature. However, their work didn’t involve geothermal environment and extreme temperature fluctuation, and lacked contrast with physical experiment. Over next few years, some literatures could be found in the field of coupling effect between temperature and stress, mainly took tunnel located in geothermal area as engineering background. Wang et al. (2013, 2014) carried out a series of studies on the stress characteristics of lining structures with respect to tunnel in geothermal areas. The studies revealed the stress variation tendency of different parts of lining concrete under temperature load, and found that to mount thermal insulating layer can remarkably improve the stress state of secondary lining. Zhang and Li (2012) analyzed the stability of tunnel with high temperature from various factors, of which the temperature and category of surrounding rocks are main ones. The simulation works showed that the higher temperature difference of initial temperature field, and higher category of rocks can lead to higher stress for surrounding rocks. Jia et al. (2014) established a new coupled thermo-mechanical damage model with improved Mohr-Coulomb criterion, which concluded that temperature has a great influence on rock properties and damage evolution, meanwhile, the damage and thermal stress can also influence heat conduction and diffusion. Although some valuable conclusions were drawn from these studies, for rock mass and concrete, there are still many questions that need to be investigated and solved in the field of coupling effect between temperature and stress (Wang et al., 2016; Schrefler et al., 2002; Lu et al., 2017). For instance, given the cooling effect of water flow, a key issue specific to diversion tunnel with high temperature is the evolving mechanism of temperature stress for surrounding rock and its lining concrete. In the early operational stage, a high temperature gradient will be formed in surrounding rock and its supporting layer due to cooling effect which is caused by influx of cold water flow. This will produce complicated stress sate, and result in spalling and damage of lining concrete.

However, such kind of question was not thoroughly and properly studied (Shi et al., 2008; Liu et al., 2014; Liu et al., 2015), because it was not easy to design an experimental model to reflect real physical environment, and adopted a reasonable method to analyze stress sate under cooling effect of cold water. In this paper, we take a high-temperature diversion tunnel servicing for Qire Hatar Hydropower Station located in Xinjiang of China as engineering background, and design experimental and numerical model made of rock plate and shotcrete (it can be referred to simply as rock-shotcrete structures) for probing into this question. We believe that, by our experimental and simulative methods, the study results can objectively reflect generic variation law which includes temperature field, stress field and the displacement field of the surrounding rock and lining concrete, when the diversion tunnel is in the early operational stage.

2. EXPERIMENTAL METHOD

2.1 Physical experiment of high geothermal environment

For truly embodying the high temperature environment of diversion tunnel, an experimental chamber simulating terrestrial heat was designed as demonstrated in Figure 1. Figure 1a shows that the experimental compartment consists of three parts including heating system, temperature control system, and curing box. Figure 1b displays that we were spraying concrete onto rock plates that were placed in the experimental compartment. As concrete spraying was finished, then the high-temperature curing with specified age would be carried out in the experimental compartment. Figure 1c shows that the granite plate was used to replace the surrounding rock, and its temperature was maintained in constant through heating rods and temperature control system. Figure 1d displays specimen, namely the rock-shotcrete, after finishing high-temperature curing.

(a) Experimental compartment

(b) Spraying concrete

(c) Rock plate with high temperature

(d) Rock-shotcrete structure

Figure 1 Physical experiment of high geothermal curing

The rock-shotcrete structure, whose temperature of rock plate is 90℃ and the curing period of shotcrete is 28 days, was used in the experiment that realized process of high-temperature cooling. The reason why we regulated such kind of temperature and curing period was because the experimental design was set in high-temperature diversion tunnel servicing for Qire Hatar Hydropower Station. The Table 1 shows the mix proportion of shotcrete.

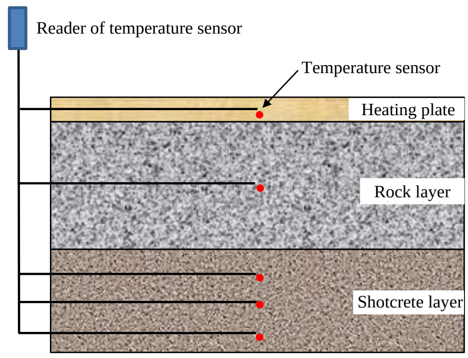
Table 1 Mix proportion of shotcrete

Material composition	Material dosage (kg/m^3)
Water	196
Cement	373
Flyash	93
Sand	895
Stone	860
Water-reducing admixture	3.27
Setting accelerator	18.67
Fibre	1

2.2 Physical experiment of sharp fall of high temperature

As the rock-shotcrete specimen met the specified curing age, we took it out of the environment chamber and immersed the shotcrete layer in cold water for performing high-temperature cooling test. As shown in Figure 2a, the inside and outside of water tank was covered by foam material with low thermal conductivity, which was for reducing thermal transmission between water and tank and air. The water temperature was real-time monitored through placing a temperature sensor in the tank. For keeping the water in low temperature state, around 4℃, the ice cubes would be appropriately added to the tank. Figure 2b shows that we pre-embed one temperature sensor in the rock plate and three temperature sensors in different locations of shotcrete layer, which was for acquiring temperature variation law under cooling effect. The locations of temperature sensors in shotcrete are 1cm, 3cm, 5cm, respectively, away from bottom surface of rock plate.

(a) Experiment of cold water immersion



(b) Placement of temperature sensors in rock-shotcrete structure

Figure 2 Physical experiment of sharp fall of high temperature

2.3 Numerical simulation of sharp fall of high temperature

It can be seen from the experimental design above that temperature stress and strain are difficult to be measured, because the problem of temperature drift of sensor is difficult to be resolved. Moreover, the laboratory measurements of temperature only contrapose some local areas, it can't reflect temperature variation law of the whole rock-shotcrete structure. Therefore, based on laboratory measurements, we adopted numerical simulation to carry out coupled temperature-stress analysis for rock-shotcrete structure. The simulation work was finished by COMSOL Multiphysics software, which is relatively popular at present in the multi-field coupling. The detailed simulation schemes are as follows:

2.3.1 Constitutive equation of heat conduction

The heat conduction constitutive equation was used in this study as shown in Eq. (1). Based on the conservation law of energy, this governing equation describes the relationship between heat transfer and temperature (Zhu, 2012)

$$\frac{\partial T}{\partial t}-\frac{\lambda}{c\rho}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)=\frac{Q}{c\rho} \quad (1)$$

where ρ is the density (kg/m^3), c is the specific heat capacity (kJ/kg·℃), λ is the thermal conductivity (W/(m·K)), Q is heat flux (W/m^2), and T is the temperature (℃). The numerical values of c and λ are acquired by the measurement of Thermal Constants Analyzer.

2.3.2 Boundary condition of temperature

According to the theory of partial differential equation, if one wants to obtain specific numerical solution, the initial condition and boundary condition must be confirmed. Before the rock-shotcrete is immersed in cold water. Its initial temperature field distribution measured by sensors is chosen as the initial condition, which is denoted by

$$T_1|_{t=0}=c,\ T_2|_{t=0}=c_2,\ T_3|_{t=0}=c_3,\ T_4|_{t=0}=c_4 \quad (2)$$

where $T_1|_{t=0}$ is the initial temperature of the rock plate, $T_2|_{t=0}$, $T_3|_{t=0}$, and $T_4|_{t=0}$, correspond to the initial temperature of upper, middle and lower layers of the shotcrete. As mentioned in section 2.2, the temperature was measured by sensors, the values of which are shown in Table 2.

Table 2 Initial temperatures of shotcrete and rock plate

Measuring position	Temperature (°C)
Lower layer of shotcrete	58.1
Middle layer of shotcrete	67.6
Upper layer of shotcrete	89.1
Rock plate (°C)	90.4

In the process of heat conduction calculation, the lateral surface of rock-shotcrete is set to be adiabatic, which can be regarded as the second boundary condition. Therefore, the temperature field of lateral surface can be described by the following expression:

$$\frac{\partial T}{\partial n}=0 \quad (3)$$

where T is the temperature of lateral surface, n is normal vector of lateral surface. As the bottom of shotcrete is directly contact with cold water, the heat transfer will occur between rock-shotcrete structure and water. This can be treated as third boundary condition, which can be presented in the following form:

$$-\lambda\frac{\partial T}{\partial n}=\beta(T-T_\alpha) \quad (4)$$

where β is the surface exothermic coefficient, T is the temperature of bottom surface of shotcrete, T_a is the temperature of cold water, and n is normal vector of bottom surface of shotcrete.

Due to the full contact between the rock plate and the shotcrete, the heat exchange of the interface is a continuous physical process, which can be regarded as the fourth boundary condition and can be described by

$$T_a=T_b\ ,\ \lambda_a\frac{\partial T_a}{\partial n}=\lambda_b\frac{\partial T_b}{\partial n} \quad (5)$$

where T_a is the temperature of interface of the rock plate, T_b is the temperature of interface of the shotcrete, λ_a and λ_b are thermal conductivity of rock plate and concrete layer respectively.

2.3.3 Temperature-stress coupling

Thermal strains are produced in the continuous medium by accounting for the thermal expansion of material element. Assuming the rock-shotcrete structure occurs small deformation under temperature effect, the thermal expansion can be applied as follows:

$$\Delta\varepsilon_{ij}=\alpha\Delta T\delta_{ij} \quad (6)$$

where $\Delta\varepsilon_{ij}$ is the change of strain tensor, α is the coefficient of thermal expansion, ΔT is the temperature change, and δ_{ij} is the Kronecker symbol. As the change of strain tensor is obtained by Eq. (6), the stress tensor can be calculated by the following constitutive equation:

$$\sigma_{ij}=D_{ijkl}\varepsilon_{kl} \quad (7)$$

where σ_{ij} is stress tensor, D_{ijkl} is elastic tensor, and ε_{kl} is strain tensor. As we know the elastic tensor is a fourth order tensor, however, we assume the rock and shotcrete are isotropic material in this simulation, therefore, elastic tensor only contains two elastic constants which are Elastic modulus and Poisson ratio respectively.

In summary, the finite element model can be established according to the geometrical size of model and the related physical parameters, after determining the heat conduction equation, temperature boundary condition, and coupling relation between temperature and stress. The specific geometric dimensions and physical parameters are shown in Table 3.

Table 3 Physical parameters and geometric size

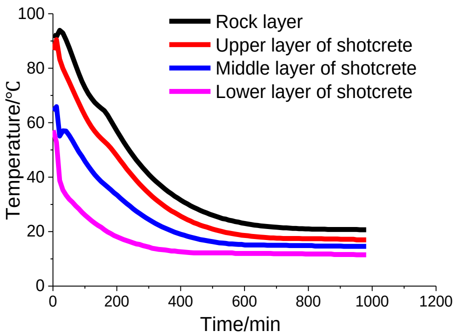
Contents	Rock plate	Shotcrete
Thermal conductivity/W·(m·K)$^{-1}$	2.3	1.8
Elastic modulus /Pa	50e9	18e9
Coefficient of thermal expansion /℃	14e-7	2e-6
Specific heat capacity / kJ(kg·℃)$^{-1}$	0.85	0.88
Density /Kg·m^{-3}	2600	2300
Poisson ratio	0.25	0.33
Length/mm	400	400
Hight/mm	300	300
Thickness/mm	100	60

3 RESULTS

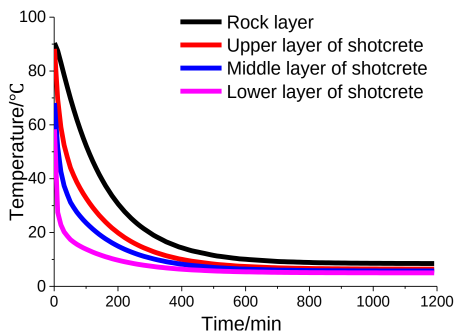
3.1 Temperature analysis

According to the high-temperature cooling test described in section 2.2, it is known that we pre-embed four temperature sensors in the rock-shotcrete structure for monitoring the temperature variation with time.

As shown in Figure 3a, the temperature of each monitoring point shows exponential attenuation law with increasing of time, the physical process can be roughly divided into three attenuation stages. The initial rapid decay stage: the temperature curve of each monitoring point shows a sharp decline and has a high decay rate, especially for the shotcrete layer closest to the water. This is mainly determined by the high temperature difference between rock-shotcrete structure and cold water. It is known from Fourier's law of heat conduction that if the thermal conductivity is kept at constant, the higher the temperature gradient inside the substance, the greater the heat transfer rate, namely the more intense the heat exchange. The deceleration decay stage: the temperature of each monitoring point continues declining, but the decay rate decreases with increase of time due to the decrease of temperature gradient. In this stage, the heat exchange gradually tends to be stable. The equilibrium stage: the temperature of each monitoring point tends to be constant and the decay rate tends to be zero, finally the shotcrete layer gets to uniform temperature field. In this stage, the temperature gradient is basically not changeable, and heat exchange exhibits a stable equilibrium state. As shown in Figure 3b, the temperature variation law obtained by simulation method shows a high consistency with the physical test, which also indicates the evolution of temperature field of the rock-shotcrete can be better described by the numerical test.



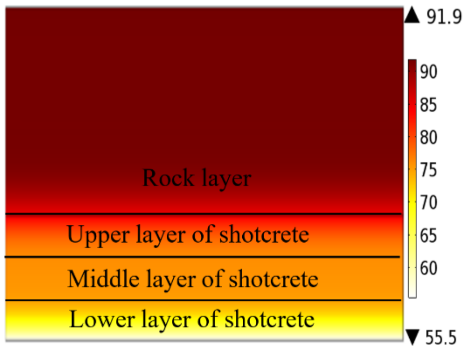
(a) The measured value



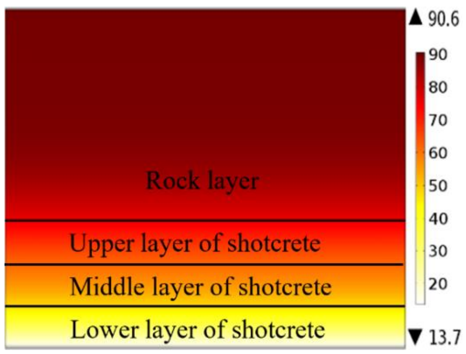
(b) The simulated value

Figure 3 The Variation law of temperature of rock-shotcrete with time under immersing action of cold water

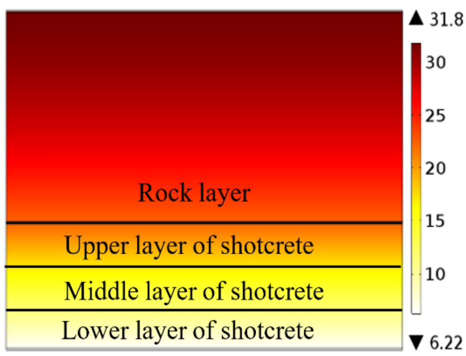
Figure 4 shows that the temperature nephograms which include initial time and other three stages can all clearly demonstrate temperature variation law in different parts of rock-shotcrete. As we can see, the shotcrete layer is at low temperature state in each stage, especially for the lower layer of shotcrete. Figure 4a-b shows that the attenuation amplitude of the shotcrete layer is the largest in the initial rapid stage, compared with rock plate. It means the shotcrete layer experiences high temperature drop in a short period. As the temperature goes into the other two stages, the attenuation amplitude is significantly reduced (Figure 4c-d).



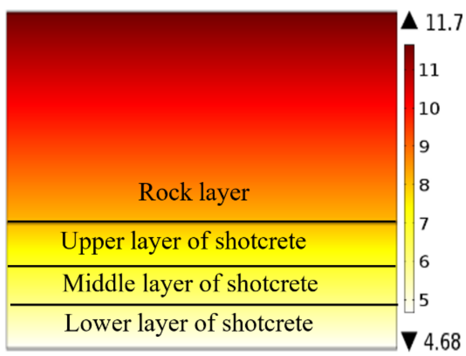
(a) Initial time



(b) Initial Rapid decay stage



(c) Deceleration decay stage



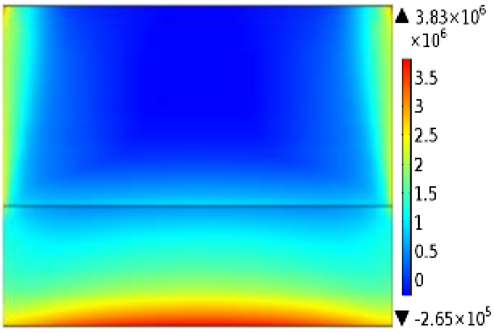
(d) Equilibrium stage

Figure 4 Temperature field of rock-shotcrete structure in different stage (Unit: °C)

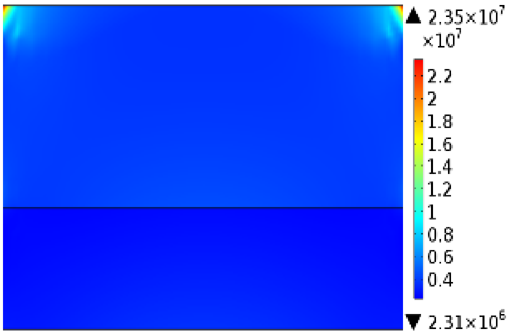
We think these experiment phenomena indicates the deformation caused by temperature variation mainly occurs in initial rapid decay stage. This stage has a great impact on mechanical properties and stress field for the rock-shotcrete material.

3.2 Stress and displacement analysis

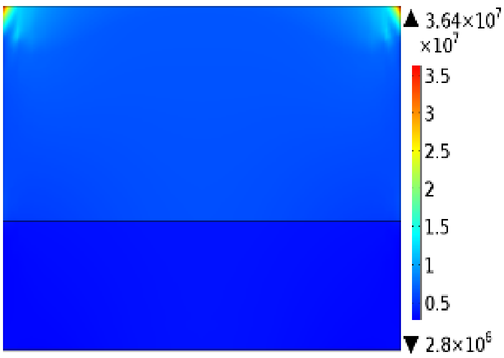
The maximum principal stress nephograms at three temperature evolution stages are shown in Figure 5a-c, and the principal stress curves along the bottom surface of shotcrete layer are shown in Figure 5d.



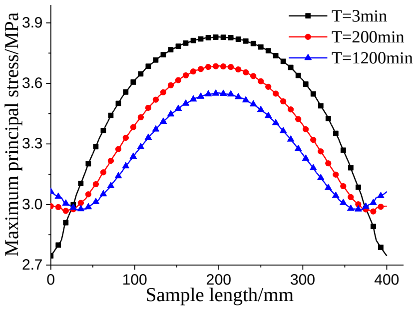
(a) Initial Rapid decay stage (Unit: Pa)



(b) Deceleration decay stage (Unit: Pa)



(c) Equilibrium stage (Unit: Pa)



(d) Maximum principal stress

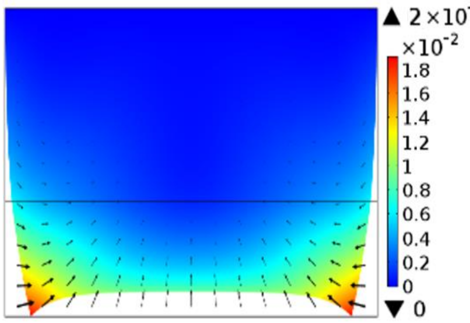
Figure 5 Maximum principal stress nephograms and stress curves (Unit: MPa)

It can be seen from the stress nephogram in initial rapid decay stage (Figure 5a) that the maximum principal stress inside the shotcrete layer is manifested as tensile stress, and the stress value is gradually reduced and tend to be steady state. As the temperature goes into the other two stages, the maximum principal stress is more evenly distributed inside the rock-shotcrete structure due to the decrease of stress gradient, and it is still manifested as tensile stress.

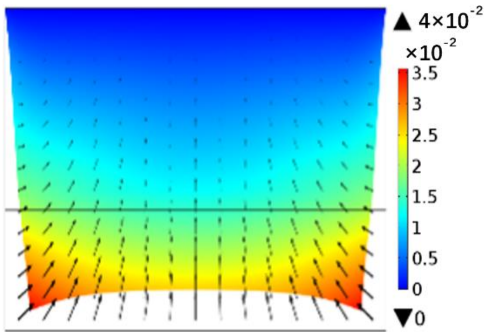
According to maximum stress curves along the bottom surface of shotcrete layer (Figure 5d), the stress values present overall attenuation with the evolution of temperature, but variation trend remains unchanged, that is tensile stress in middle area of shotcrete layer is the largest, and the both sides are relatively small. In summary, we can infer from the study results that the sharp change of stress will occur in the shotcrete layer as the high-temperature diversion tunnel is in the early stages of diversion (i.e., the initial rapid decay stage), and the maximum principal stress is manifested as tensile stress. In this stage, the tensile damage will be easily generated in shotcrete layer. After this stage, the internal stress field in shotcrete will be gradually released with temperature evolving.

From Figure 6a-c, it can be clearly found that the shotcrete layer appears shrinkage deformation directing to the rock plate, and appears symmetrical shrinkage deformation in the horizontal direction. It is known that Young's modulus of the rock material is larger than the shotcrete material, therefore the rock plate plays a role in constraining shrinkage of the shotcrete, which is the reason why the maximum principal stress is tensile stress.

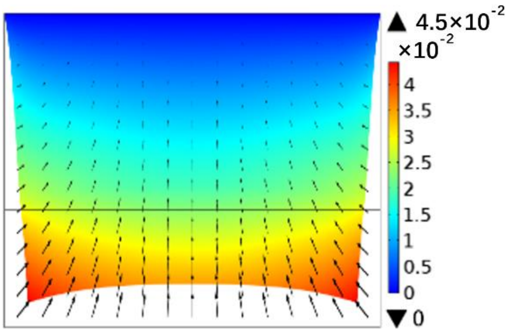
As we can see from Figure 6d (Total displacement curves along the bottom surface of shotcrete layer), the overall deformation of shotcrete is increased with heat transfer going, it seems that tensile stress in shotcrete should be increased. However, it is diametrically opposed to our inference. This is mainly due to the fact that the tensile stress in shotcrete is determined by relative deformation between rock plate and shotcrete. It can be seen from Figure 6a-c that shrinkage deformation of the rock plate is also increased with heat transfer going. It is such increasing in deformation that reduces the relative deformation, which leads to the decrease of tensile stress. Therefore, we can think that the increased deformation of rock plate actually weakens constraint to the shotcrete layer. Finally, the temperature gradient of rock-shotcrete structure is gradually reduced, and the rate of heat exchange is thereby decreased, which results in the cease of deformation if we don't consider rheological damage factors and so on.



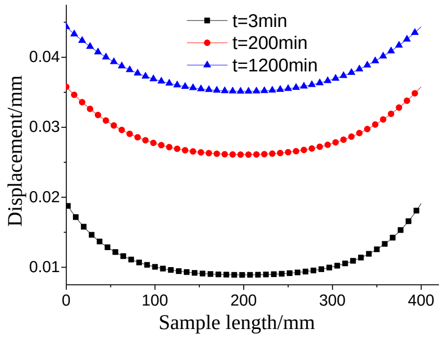
(a) Initial Rapid decay stage (Unit: mm)



(b) Deceleration decay stage (Unit: mm)



(c) Equilibrium stage (Unit: mm)



(d) Total displacement

Figure 6 Displacement nephograms and total displacement curves (Unit: mm)

4. CONCLUSIONS

(1) After the rock-shotcrete structure with high temperature undergoes immersion of cold water, the temperature evolution can be roughly divided into three stages which include the initial rapid decay stage, the deceleration decay stage, and the equilibrium stage. The attenuation amplitude of shotcrete layer is the largest in the initial stage, compared with other two stages, namely experience a sharp fall process for temperature.

(2) The stress in the shotcrete layer will be drastically changed, resulting from the sharp fall of temperature during the initial stage. The maximum principal stress will be manifested as tensile stress which easily results in tensile damage to the shotcrete layer, especially for the shallow part. However, with temperature continuously evolving, the maximum principal stress will be gradually released, which will reduce such kind of tensile damage. Therefore, how to increase tensile strength of shotcrete and control water diversion flow reasonably in the early operational stage for the tunnel in geothermal areas are very important for reducing damage of shotcrete layer.

(3) The rock-shotcrete structure appears shrinkage deformation in all three stages of temperature evolution, and the deformation increases with temperature evolution. It needs to be emphasized that the increase of deformation of rock plate in the last two stages can weaken constraint to the shotcrete layer, this is the reason why the phenomenon of stress relief appears in the shotcrete layer. Therefore, the rock bolt and mesh support are also necessary to be considered, which for reinforcing the strength and stiffness of shotcrete and rock, and thereby reduce shrinkage deformation of shotcrete, especially in the early operational stage for the tunnel.

5. ACKNOWLEDGMENTS

The authors acknowledge the anonymous reviewers and the editor for their valuable comments and suggestions. This study was funded by the open Foundation from Key Laboratory of Ministry of Education for Efficient Mining and Safety of Metal Mines, USTB (ustbmslab201706); the Handan City Science and Technology Project (1721211050-4).

6. REFERENCES

Chen Q. and Duan Y. H. (2010) " Influence of temperature in tunnel and surrounding rock on temperature and thermal stress of lining concrete of flood discharge tunnel". Rock and Soil Mechanics, 31, Issues 3, pp986-992.

Deng T. F., Wu D., Zhao R. and Wang Y. H. (2017) "THM modeling of ground subsidence induced by excavation of subway tunnel". Computers and Geotechnics, 88, Issues 8, pp1-11.

Jia S. P., Wu B., Chen W. Z., Wu G. J. and Gao M. (2014) "Study of thermo-mechano-damage coupling behavior of surrounding rock of deep tunnel". Rock and Soil Mechanics, 35, Issues 8, pp2375-2384.

Liu C. L., Zhang Y. S., Yuan J. G., Zhong Y. and Zhang Y. (2015) " Study on the distribution of stress field in high-temperature diversion tunnels". Journal of Water Resources and Architectural Engineering, 13, Issues 4, pp66-71.

Liu N. F., Li N., Yu C. H., Yao X. C and Liu J. P. (2014) "Analysis of mechanical characteristics for high-temperature diversion tunnel of Bulunkou hydropower station". Hydro-Science and Engineering, 39, Issues 4, pp14-24.

Lu L. J., Xu J., Liu J. Y. and Yan Y. B. (2017) "Numerical analysis of frozen construction in water bearing loose sandstone tunnel based on thermal-structure coupling". Journal of Northwest A & F University (Natural Science Edition), 45, Issues 4, pp1-7.

Schrefler B. A., Brunello P., Gawin D., Majorana C. E. and Pesavento F. (2002) "Concrete at high temperature with application to tunnel fire". Computational Mechanics, 29, Issues 1, pp43-51.

Shi M. Y., Ma C. H., Su H. and Qu C. L. (2016) "High geothermal water diversion tunnel supporting concrete test and numerical simulation research". Science Technology and Engineering, 16, Issues 33, pp302-306.

Shi Y., Zhu Z. D. and Li Z. J. (2008) "Deformation characteristics of deep buried caverns considering thermal effect". Advances in Science and Technology of Water Resources, 28, Issues 3, pp33-36.

Su H., Ma C. H. and Ma F. (2016) " Numerical simulation study on temperature field of water diversion tunnel under high geothermal temperature". Water Resources and Hydropower Engineering, 47, Issues 4, pp34-37.

Wang T., Zhou G. Q., Wang J. Z. and Zhao X. D. (2016) "Stochastic analysis for the uncertain temperature field of tunnel in cold regions". Tunnelling and Underground Space Technology, 59, Issues 10, pp7-15.

Wang Y. S., Yang C., Ye Y. Z., Tang J. H., and Chen L. (2013) "Experimental study on stress characteristics of lining structures of tunnels in high geo-temperature environment". Tunnel Construction, 33, Issues 10, pp809-813.

Wang Y. S., Ye Y. Z., Yang C. Tang J. H. and Chen L. (2014) "Stress mechanism of lining structure of high geothermal and deep-buried tunnel". Journal of Southwest Jiaotong University, 49, Issues 2, pp260-267.

Wu Wenli and Wang Lei. (2017). "Comparative analysis of numerical and analytical solutions of temperature field in high temperature tunnel". Journal of Yanan University (Natural Science Edition), 36, Issues 1, pp47-49.

Zhang Y. and Ling N. (2012) "Influence of various factors on tunnel stability in temperature field". Journal of

Northwest A & F University (Natural Science Edition), 40, Issues 2, pp219-234.

Zhu Bofang. (2012) "Temperature stress and temperature control of mass concrete". Beijing: China Water Conservancy and Hydropower Publishing House, pp39-42.