The Study on Tunnel Fire Resistance Layer of Lightweight Aggregate Concrete based on Finite Element Thermal Analysis

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Abstract. Fire resistance of tunnel structure is paid more and more attentions in recent years. Lightweight aggregate concrete has low bulk density and good thermal insulation property. This paper is first time to propose the design of lightweight aggregate concrete as fire resistance layer for tunnel. Thermal analysis function of ANASYS14.0 finite element analysis program is used to calculate temperature gradient field and heat flux of tunnel structure fire resistance layer under different temperatures, and the results of lightweight aggregate concrete fire resistance layer is compared to those of fire-retardant coatings commonly used. This analysis will provide technical basis for the application of lightweight aggregate concrete under high temperature environments in the future.

Introduction

With a great development of underground space and tunnels, the safety of tunnel has attracted more and more attentions today. Statistic data from the China ministry of construction showed that by the end of 2013, there has been 2366 km subway line across the country and 11359 highway tunnels with a total length of 8610 km. The above projects are facing enormous fire hazard in construction and use. Tunnel structure is usually based with stone block and reinforced concrete is used as lining. Generally, when temperature rises to 600℃, concrete will lose more than 50% of its strength , yield strength of steel reduces to below 1/3 of the value at room temperature [1-2]. Temperature of fire is generally above 1000℃, which would make tunnel structure to suffer a significant loss of mechanical properties. Consequently, considerable difficulties would be brought for evacuation and extinguishing, causing heavy loss of life and property.

At present, the mainly measure for tunnel structure fire protect is using fire-retardant coatings as the tunnel structure fire resistance layer, which is coated on the surface of hardened concrete of lining structures. However, the basic research on the existing tunnel fire-retardant coatings is weak, such as toxic, deficiencies in fire resistance and bond strength [3]. It is imperative to develop a new fireproof material. Lightweight aggregate concrete has the advantages of light weight, high strength, permeability and good high temperature performance [4]. In laboratory electric heating conditions, after about 800-1000℃, the relative residual mechanical properties of lightweight aggregate concrete is significantly better than that of normal aggregate concrete, which still have a certain bearing capacity [5-6], and displays a great potential effect of applied in the tunnel fire resistance layer.

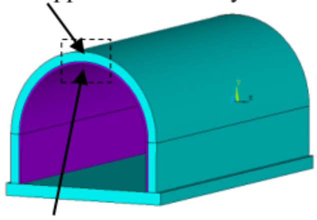
ANSYS has been more widely promoted the analysis on structure, thermal analysis, electric field, magnetic field and fluid field in recent years. Study on the compared analysis of the temperature gradient field and heat flux of both lightweight aggregate concrete fire resistance layer and fire-retardant coatings under different temperature based on the thermal analysis of finite element method in the ANSYS, which will provide technical basis for the application of lightweight aggregate concrete under high temperature environments in the future.

Establishing finite element model of tunnel structure fire resistance layer

Models and Materials

Referring to engineering example, the tunnel model is established and its finite element meshing model is shown in Fig. 1and Fig. 2. In order to simplify the calculation, the three-dimensional model was simplified to a two-dimensional plane model. Plane X-Y, intercepting the top of the arc of tunnel model for $\pi/13$(rad) as the research object, as shown in Fig. 2. The thickness of tunnel lining support structure layer is 0.4m, the thickness of both tunnel lightweight aggregate concrete fire resistance layer and fire-retardant coatings layer is 0.03m. The thermal analysis model uses the planar 8 node element. Each node has only one degree of temperature, so it has good convergence property.

In this model, the material of tunnel lining support structure layer is ordinary portland concrete (material 1 for short), whose dry apparent density is 2500kg/m^3, elastic modulus is 32000MPa and poisson ratio is 0.2. One of the materials of tunnel fire resistance layer is insulating lightweight aggregate concrete (material 2 for short), whose dry apparent density is 700kg/m^3, elastic modulus is 6500MPa and poisson ratio is 0.2 [7]. Another material of tunnel fire resistance layer is tunnel fire-retardant coatings (material 3 for short), whose actual thermal parameters are provided by producers [8]. The thermal parameters of the materials are shown in Table 1. Because of the temperature field of tunnel fire belongs to the highly nonlinear transient problem, ignored the effect of temperature changes on the thermal performance of materials in the analysis.



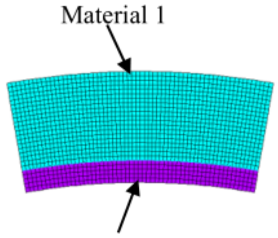


Fig. 1 Three-dimensional tunnel model   Fig. 2 Simplified finite element model

Table 1: The materials of tunnel and their thermal parameters

Part name	Material	Density (kg/m^3)	Thermal conductivity w/(m·k)	specific heat (J/kg·k)
Ordinary Portland Concrete	1	2500	2	970
Lightweight Aggregate Concrete	2	700	0.27	920
Tunnel Fire-retardant Coating	3	680	0.188	1050

Loading and boundary conditions

In order to calculate the temperature gradient field and heat flux of both materials of tunnel fire resistance layer under different temperatures, temperature load were applied in the interior surface of the simplified tunnel model. Considering the tunnel structure support system is long-term in a moist environment, applying temperature loading of 5℃ on the top surface of material 1 and temperature loading of 400℃, 600℃ or 800℃ on the bottom of material 2 or material 3. The boundary nodes were fixed constraint under loading. When the boundary conditions is defined, nodes of the plane model are fixed in order to constrain translational movement in X, Y, Z directions; In order to ensure that the deformation behaviour of the established symmetric model is consistent with the entire part.

Heat transfer in tunnel structure fire resistance layer

In case of fire, the modes of heat energy transfer between the thermal environment and tunnel structure layer have the heat conduction, heat convection and heat radiation. These three ways of heat transfer process are often not exist alone, but it has the distinction between the primary and the secondary. This paper is considered that the heat conduction is the major influence mode in the tunnel fire resistance layer. According to the general treatment on heat transfer problem, ignoring the heat transfer along the length of the member, thus the heat transfer of the tunnel fire resistance layer is changed into two-dimensional simulation model of heat conduction, as shown in Fig. 3. Thermal conduction differential equation can be derived by the Fourier law and heat balance principle, as Eq. 1.

$$\rho \cdot c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) \tag{1}$$

Where

ρ is material density, [kg/m3];

c is specific heat of material, [J/(kg·℃)];

λ is thermal conductivity of material, [w/(m·k)];

T is the temperature of point(x, y) at time t, (℃);

t is heating time, [s].

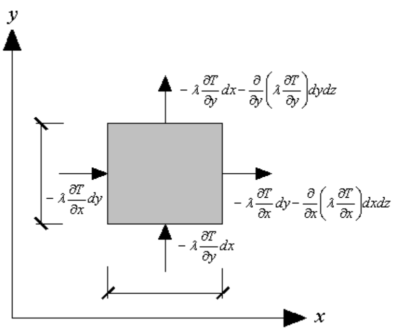


Fig. 3 two-dimensional heat conduction unit model of tunnel fire resistance layer

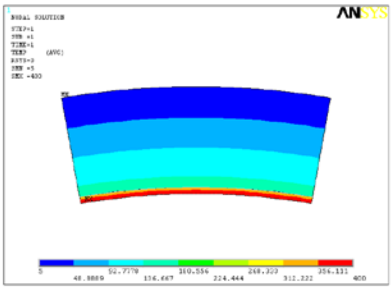
The first law of thermodynamics is used in the thermal analysis of ANSYS, and the closed systems were analyzed by energy conservation principle.

$$Q–W=\Delta U+\Delta KE+\Delta PE \tag{2}$$

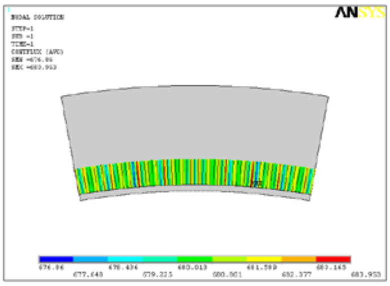
In the Eq. 2, Q and W are respectively represent the energy of heat and system, ΔU, ΔKE and ΔPE is respectively represents internal energy, kinetic energy and potential energy of the system. In the actual tunnel engineering, the concrete of tunnel fire resistance layer had hardened early, so ΔKE+ΔPE=0. If the system do not work, where W=0, then Q=ΔU. When a fire started, the inflow or outflow rate of heat transfer of the system is equal to the rate of change of the internal energy of the system, then q=dU/dt. Analysis of tunnel fire simulation model is clearly belongs to the transient thermal analysis. Furthermore, with the change of temperature, the thermal properties of concrete (material 1 & 2) and fire-retardant coatings would be change [9]. Obviously, the heat transfer between tunnel fire resistance layer and tunnel lining structure layer is a complex transient process.

However, the study purpose of this paper is compared analysis on the thermal performance between lightweight aggregate concrete fire resistance layer and fire-retardant coatings in specific conditions based on finite element thermal analysis. If it is considered as steady state thermal analysis, that is Q=ΔU=0. By setting the goal temperature of 400℃, 600℃ and 800℃ and the corresponding thermal parameters of the materials in ANASYS14.0 program, the temperature gradient chart and heat flux chart of tunnel fire resistance layer under the different temperature can be obtained, so as to simplify calculation and reaches the expected effects. On the Basic Hypothesis of finite element analysis as follow: (a) Assumed that concrete (material 1 & 2) and fire-retardant coatings are isotropic materials; (b) The surface of the different materials are in intimate contact; (c) Assumed that the heat of tunnel fire resistance layer transfers along one direction, namely the heat from the bottom surface of the fireproof layer through the internal lining structure layer transfers to the top surface, considered as one-dimensional simulation model of heat conduction.

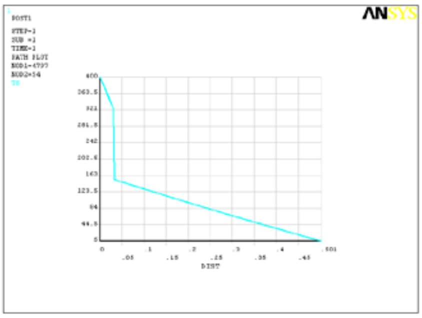
Results and Discussions



(a) Temperature gradient cloud chart



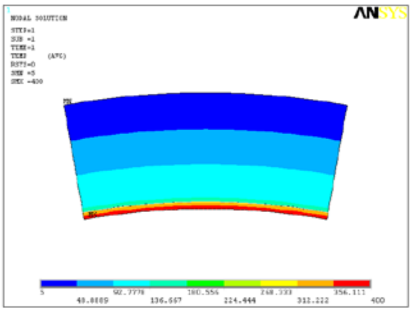
(b) Heat flux cloud chart



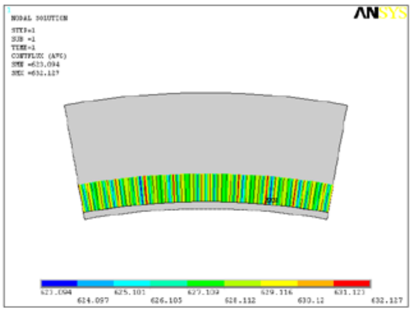
(c) Temperature and distance curve graph

Fig. 4: Tunnel lightweight aggregate concrete fire resistance layer under 400℃

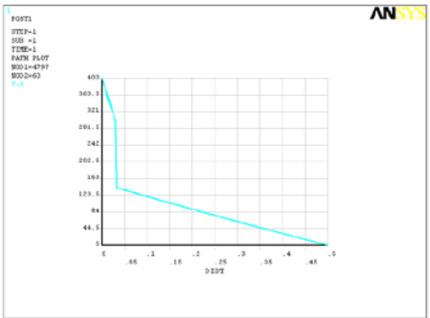
Heat flux is a vector quantity, and its size is equal to the rate of heat energy transfer through per unit surface. Usually, temperature is one of the basic attributes of material. But only measuring temperature is not enough to characterize the most of thermal systems. Hence, the circulation pattern and position of heat flux are same important as temperature, and even more important. The size of heat flux can be used to characterize the transfer degree of heat energy. The contact temperature gradient cloud chart, heat flux cloud chart, thermal contact temperature and distance curve graph under different temperature can be obtained by using ANSYS's general post processing function POST and time course processor processing on the results data visualization related analysis. As shown in Fig. 4 and Fig. 5.



(a) Temperature gradient cloud chart



(b) Heat flux cloud chart



(c) Temperature and distance curve graph

Fig. 5: Tunnel fire-retardant coatings under 400℃

When temperature of tunnel fire is 400℃, Fig. 4(a) shows that the heat from the bottom surface of the light aggregate concrete fire resistance layer through the contact interface transfers to the lining structure support layer. The temperature gradient distribution decreases from the inner to the outer. Likewise, Fig. 5 (a) shows that the heat from the bottom surface of the tunnel fire-retardant coatings through the contact interface transfers to the lining structure support layer. The temperature gradient distribution decreases from the inner to the outer as well. Meanwhile, Fig. 4(b) and Fig. 5(b) show that the heat flux of the thickness of 30mm lightweight aggregate concrete fire resistance layer and the thickness of 30mm tunnel fire-retardant coatings is respectively 683.95W/m^2 and 632.13W/m^2. Beside, Fig. 4(c) shows that the temperature changes in thermal contact interface between material 1 and material 2 (i.e. distance lower side 0.03m). The change of the temperature difference is about 171℃. Fig. 5(c) shows that the temperature changes in thermal contact interface between material 1 and material 3 (i.e. distance lower side 0.03m). The change of the temperature difference is about 158℃. These two curves are continuous, indicating that the materials are in intimate contact. The results that compared with the thickness of 30mm lightweight aggregate concrete fire resistance layer and the thickness of 30mm tunnel fire-retardant coatings under 400℃, the change of temperature difference and the heat flux are similar.

As shown in Table. 2 and Table. 3, when temperature on tunnel fire resistance layer is 600℃ and 800℃, the change of temperature in thermal contact interface and internal average temperature are also similar for both the materials. With the increase of temperature, heat flux of both the materials increases with insignificantly different levels. The analysis results indicated that lightweight aggregate concrete has similar thermal performance to the fire-retardant coatings commonly used.

Table 2: Results for thermal analysis of tunnel lightweight aggregate concrete fire resistance layer under elevated temperature

Temperature (℃)	Interface maximum Heat flux (W/m^2)	Interface change temperature (℃)	Internal average temperature(℃)
600	1030.26	257	414
800	1376.56	344	551

Table 3: Results for thermal analysis of tunnel fire-retardant coatings under elevated temperature

Temperature (℃)	Interface maximum Heat flux (W/m^2)	Interface change temperature (℃)	Internal average temperature(℃)
600	952.19	247	406
800	1272.26	320	540

Conclusions

The analysis indicates that when temperature of tunnel fire resistance layer is 400℃, the thermal efficiency of both the lightweight aggregate concrete fire resistance layer and the fire-retardant coatings is similar. When temperature on tunnel fire resistance layer reaches 600℃ and 800℃, the change of temperature in thermal contact interface and internal average temperature are also similar for both the materials. With the increase of temperature, heat flux of both the materials increases with insignificantly different levels. All above indicates that lightweight aggregate concrete shows great potential to be used as fire resistance layer in tunnel. Moreover, it is considered that the thermal performance of lightweight aggregate concrete fire resistance layer could be further improved by increasing its thickness in the practical construction. Lightweight aggregate concrete has similar thermal performance to the fire-retardant coatings commonly used. However, the former is more environmentally friendly, and can be constructed in an easier and more economical way. Therefore, the research on the application of lightweight aggregate concrete in tunnel fire resistance layer is much relevant to the civil engineering today.

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