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Applications of airtight concrete grouting to road tunnels*

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Abstract: Road tunnel excavation often traverses coal strata, which is at risk of firedamp explosion that usually results in disaster. Airtight concrete grouting is popularly used in this kind of tunnel project. Based on the essential theory of mechanics of fluids in porous media, the principle of improving concrete airtight property and its influential factors are investigated. The proportioning tests and monitoring method for airtight concrete are introduced, which is illustrated by a case study applied to the project of the Huayinshan Tunnel. It is proved by engineering practices that the achievement of this research work is beneficial to tunneling project across coal strata.

Keywords: road tunnel; airtight concrete; gas outburst preventing

If secondary lining concrete is not dense or its airtightness is low, the firedamp contained in the coal strata and H_2S and CO contained in rock strata will leak into the road tunnel by permeating through the secondary lining concrete supporting when a road tunnel goes across coal-bearing series strata containing firedamp or rock strata lodging harmful gas like H_2S and CO, which often cause explosion and intoxication casualty when the firedamp and gases accumulated to their threshold concentrations. That is disadvantageous to tunnel excavating and manipulation. So airtight concrete should be provided for the secondary lining to prevent the leakage of H_2S, CO and firedamp.

1. Compound proportion tests of airtight concrete

1.1 Mechanism for enhancing airtightness of concrete

Concrete is widely used in modern construction. It is a kind of man-made porous and heterogeneous material containing pores and cracks in different sizes and shapes. Most coagulative pores, capillary pores and air bubbles are ventilative passage ways. Besides these pores, concrete contained lots of interface cracks and sand slurries. They are connected to the meshwork to form larger air permeable passages.

Airtight concrete is mixed material blended with adscititious substance like silicon dioxide powder, powdered coal ash, high efficiency dehumidification material, and composite material airtight bumping mixture to adjust its microstructure. These additives ensure that the concrete after grouting is under a dense state, hence reduce the penetrability of gas and groundwater. Furthermore, they prevent the concrete strength from decreasing. Concrete with such additives can meet the working condition of airproof equipment. According to the Garman-Kozeng formula, the penetration coefficient K of cement and concrete is given by

$$K=C\varphi^3/(\tau\Sigma^2) \qquad (1)$$

where C is the Kozeng constant related to the cross section shape of the capillary tube; φ is the overall porosity; τ is the detour degree, i.e. the square ratio of the flow path length to the sample length; and Σ is the ratio of superficial area, i.e. the superficial area of pores divided by the volume of the porous material.

By Eq. (1), the penetrability through concrete has cubic nexus to overall porosity and inverse ratio nexus to the product of the detour degree and the square of superficial area in unit volume. The essential mechanism to enhance concrete denseness is to add additives and decrease the water quantity in the material so as to increase the density of concrete and decrease its porosity.

All normal adscititious substances have high water reducing capability. On the premise of well bumping property, reducing the ratio of water and cement in concrete can make the concrete homogeneous and dense, decrease its porosity, reduce the quantity of connective pores and capillary pores, and adjust the pore structure greatly.

Furthermore, the active component of concrete can react with the hydrated product of concrete, hydrated calcium aluminates and low sulfur $3CaO{\cdot}3Al_2O_3{\cdot}SrSO_4$.

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Calcium silicate gel is one of such products which packs and crams capillary pores and gelatinous pores. Its inflating enhances the density of concrete. There are some special airtight components which automatically seal micro pores.

1.2 Testing on compound proportion of airtight concrete

A suitably designed compound proportion test is prerequisite to ensuring the quality of airtight concrete. Through the test, various component effects on the concrete airtightness and the proper composition are determined.

1.2.1 Cement

In general condition, $525^{\#}$ and $425^{\#}$ normal silicate cements are selected instead of silicate cement mixture so as to prevent excessive cracks between cement slurry and aggregate surface caused by stratifying during concrete hardening. They restrain the formation of connected capillary tubes for water seeping.

1.2.2 Aggregate material

Thin aggregate is constituted by river sands or filtered mechanical sands. The sands should be of stiff texture and well-graded. The maximum grain size of thick material is controlled at 40 mm diameter or so. After concrete mixture being grouted, the solid grains are under an unstable equilibrium state. They drop down because of gravity, by which the water is pushed upward. A series of aqueducts emerge. The upper grains drop down continuously and force the water to stay under and around them, which gives rise to the layer pores. Micro-pores form between the cement grains to shape connective meshwork. The bigger layer diameter of the thick aggregate material causes a larger quantity of pores, which results in a lower concrete water resistance.

So the effective measure to enhance concrete airtightness is to control sand diameter and use multi-grade grains in airtight concrete.

1.2.3 Cementing agents

The quantity of a cementing agent in airtight concrete should be not less than 300 kg m^{-3}. Such quantity ensures the proper proportion of cementing paste and thick aggregate materials, which makes concrete effective and keeps the texture from delaminating because of water seeping phenomena and prevents forming penetrating cracks between cement slurry and aggregate. When both silica powder and powdered coal are blended into concrete, they act synergically. A small quantity of silica powder can make the surface of powdered coal active and enhance the density of concrete further with a stable capacity. Meanwhile, the powdered coal has effect on the water retaining, hardening and shrinking of concrete mixture. It restrains the formation of pores and cracks. So compounding additive is more effective and reliable to enhance airtightness of concrete. It reduces the cement consumption while ensuring concrete airtightness. Thus the engineering cost is decreased.

1.2.4 Sands ratio

Sands ratio refers to the proportion of thick aggregate and thin aggregate in a concrete mixture. The overall surface and vacant size are larger with a larger sands ratio, which makes the concrete mixture dry and dense with low fluidness. Otherwise a small sands ratio affects the concrete mixture adhesion and water retaining capacity negatively regardless of the reduced overall surface of aggregate because there is no enough cementing paste layer around thick aggregate to act as lubricating medium. Resolution and water seeping phenomena will happen in this situation.

The optimum sands ratio is that the mixture acquires a maximum flow with a constant cementing paste consumption, and without resolution, water seeping and layer-building. Some relative test data showed that sands ratio should not be smaller than 0.35.

1.2.5 Water-cement ratio

The ratio of water to cement is the primary factor of controlling concrete denseness. Concrete airtightness is determined by the porosity of cementing paste firstly. The concrete penetration parameter K after hardening will decrease violently when the porosity of cementing paste capillary tubes exceeds 20 % to 30 %. It is testified that the ratio of water to cement should be controlled at about 0.55.

1.3 Test method of concrete airtightness

Concrete airtightness is mainly determined by the density of concrete related to the air medium character and penetrating pressure. The testing methods of concrete airtightness are nomally constant-voltage method and varying-voltage method. By constant-voltage method, the time that a ration of fluid penetrates into the concrete sample is measured under a constant working voltage. By varying-voltage method, the test sample is penetrated by a testing fluid under required pressure differential in required time interval. The fundamental principle of the test is based on Darcy Law. The flow state that the fluid passes through the test sample is viscous flow according to Darcy Law, which is the foundation to design the airtightness measure instrument. Constant-voltage method is adopted commonly to test concrete airtightness.

According to the simplified Darcy Law:

$$V = -\frac{K}{\mu}\cdot\frac{\partial p}{\partial x} = -\frac{K'}{\rho g}\cdot\frac{\partial p}{\partial x} \qquad (2)$$

$$K' = \frac{QG_A L}{A(p_1 - p_2)} \qquad (3)$$

where K' is the average air permeability coefficient given by Eq. (3); μ is the fluid viscosity; p_1 and p_2 are the test and atmosphere pressures, respectively; Q is the quantity of permeated gas divided by time; G_A is the weight of air divided by its volume; A is the air permeable area, i.e. the tested top surface area of the sample; and L is the thickness of the sample.

2. Engineering examples

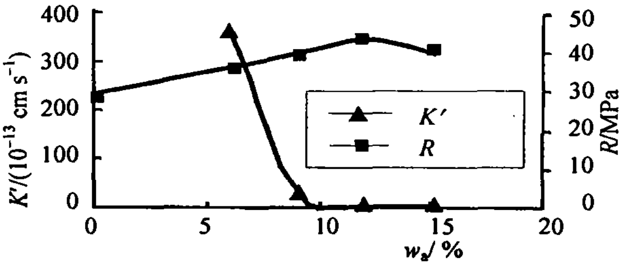
The Huayin tunnel was selected as the subject to be tested, which was one of the longest road tunnels in

China. The geological condition in the tunnel region was complex. The main geological problem was that the tunnel had to pass through coal-bearing series strata, coal goaf, karst rock region and huge fault zone, where flooding from karst cave, gas, hydrogen sulfite and oil gas layer were the primary geological risks. There was a large quantity of gas in the Permian coal-bearing series strata to be tunneled. Furthermore, there existed many cracks containing gas. The tunnel was located under coal goaf and coalmine tunnels. By survey data, at the east and west points where the tunnel met coal strata, the gas pressures were 1.44 MPa and 1.87 MPa, the gas contents were 8.94 $m^3 t^{-1}$ and 9.14 $m^3 t^{-1}$, and the maximum gas emission rates were 11.04 $m^3 min^{-1}$ and 17.68 $m^3 min^{-1}$, respectively. So the coal strata and cracks that contained gas were one of the rigorous engineering geological problems in this tunnel project.

The engineering situation of this tunnel required airtight grouting concrete as the material for the secondary lining (including the inverted arch) and road surfaced (including cable duct) concrete.

Here the air permeability coefficient was less than 1×10^{-19} cm s^{-1}. The waterproof straps were used in construction slots, deformation slots and shrink slots. Secondary lining was arranged while earlier supporting deformation was stable.

According to the test in-situ, concrete strength (*R*) and permeability coefficient *K'* for different blended additive consumption of airtight bumping materials were obtained as shown in Fig. 1.



The mass ratio of cement: sand: detritus: water=1: 2.75: 2.95:0.52

Fig. 1. Relations of the concrete permeability coefficient *K'*, the strength of concrete *R* and the airtight additive consumption expressed as the mass fraction w_a

A series of compound proportion tests were conducted in order to find the optimum proportion for good performance, easy practice and low cost. HG series airtight bumping additive was selected to replace 10 % cement. Its penetration coefficient was 8×10^{-12} mm s^{-1}.

Its strength was raised by 20 % of that of normal concrete and its consumption was reduced by 15 %. The compound proportion and test results in the Huayin tunnel are shown in Table 1. The airtight concrete with higher designed strength fed the request of airtightness according to the test data in-situ.

Table 1. Compounds proportion of airtight concrete applied to the Huayin Tunnel and according test results

S_d /MPa	K_d /(10^{-11}cm s^{-1})	Designed compound proportion				*R*	Consumption/kg per cubic meter cement					S_{28} /MPa	K_{28} /(10^{-12}cm s^{-1})
		cement	sand	detritus	additive		cement	sand	detritus	water	H-G		
20	1	1	3.11	3.24	0.1	0.55	303	961	988	142	31	26.9	0.88
25	1	1	2.74	2.86	0.1	0.55	337	940	967	148	34	31.4	0.82

Note: S_d denotes the designed strength; K_d is the designed permeability coefficient; *R* is the water- cement ratio; H-G represents the H-G airtight bumping material; S_{28} is the strength in-situ after 28 days; and K_{28} is the air permeability coefficient after 28 days.

3. Conclusion

From the research work described above, the airtightness in secondary lining can be improved by the following accesses.

a) To decrease the water-cement ratio and reduce the quantity of capillary pores in order to increase the water-reducing ratio, and use the activated component which improves the hydration degree and productivity of hydrated C-S-H gel. Reducing hydrated contracting is instrumental in preventing contracting cracks.

b) To apply waterproof straps to secondary lining for construction slots and shrink slots.

c) To measure the horizontal shrinking parameter and displacement of the earlier supporting of the arch top and provide secondary lining while the surrounding rocks movement is stable. These measures can bear excessive deformation and pressure upon the secondary lining that have bad affect on the airtightness of concrete.

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