Research Article

Ping Fu, Liwei Huang*, and Zhanqing Xing

Development and experimental research of a low-thermal asphalt material for grouting leakage blocking

<https://doi.org/10.1515/htmp-2020-0080>

received April 30, 2020; accepted July 14, 2020

Abstract: Tunnel water burst is among the common severe geological hazards in deep buried tunnel projects in China and throughout the world. Asphalt grouting is an effective method to block seepage channels in macroporous strata under the condition of flowing water, but it has defects such as a high heating temperature, complex high-temperature construction technology, and poor controllability during the grouting process. A type of “water-in-oil” low-thermal asphalt was developed in this study. It can cool and solidify and not be diluted when encountering water, and its construction temperature can be below 80°C. Experimental research on the physical and mechanical properties of the low-thermal asphalt leakage-blocking material was completed, including proportion experiments, fluidity, sensitivity to temperature, one- and two-dimensional indoor diffusion experiments, and impact experiments, which presented its physical and mechanical properties and can provide guidance for the application of the material in site projects.

Keywords: low-thermal asphalt, grouting leakage blocking, property experiment, impact experiment, simulation computation

1 Introduction

Long-distance deep buried tunnels usually encounter complex engineering geological environments, sometimes resulting in rock burst, water burst, geotherm, and other geological disasters that occur during project construction. For a long time, tunnel water burst has been among the common severe geological disasters in underground projects in China and throughout the world, particularly deep buried tunnels in water-rich areas [1,2]. For example, six water–sand mixture burst disasters of different scales occurred in the old Dana Tunnel of the Japanese Tokaido Shinkansen, with a total water burst of 1,50,000 m³/d. The maximal water burst in the diversion tunnel of the Jinping-II Hydropower Station in Sichuan, China, reached 2 m³/s, and the maximal hydraulic pressure was approximately 10 MPa. Water bursts during the construction of deep buried long tunnels typically pose great threats to the safety of workers and equipment, increase the economic costs of projects, and are likely to cause groundwater decline in a large area leading to severe secondary geological disasters. There are cases in which tunnel water bursts have resulted in severe consequences such as at the Huangshan and Geleshan tunnels in China.

Grouting, whose core is pertinent grouting materials, is the common technological method to solve the problem of tunnel water burst. Cement mortar, cement–water glass double liquid, (rapid coagulation) paste, polyurethane, and other common grouting materials have effective grouting effects in the blocking of macroporous strata with an opening of 30 cm and a flow velocity less than 0.5 m/s; mold bag grouting is usually applied in the blocking of leaking strata with the openings greater than 50 cm. However, there is no pertinent and effective grouting material for macroporous strata with an opening between 30 and 50 cm and a flow velocity greater than 0.5 m/s [3], and the most commonly applied method is to use a large amount of grouting material, making the grouting rate of the material greater than its flush rate to gradually decrease the leakage opening and leakage rate and finally build a complete blocking body. These

* **Corresponding author: Liwei Huang**, Engineering Safety Monitoring Center, China Institute of Water Resources and Hydropower Research, Beijing, 100044, China, e-mail: huanglw@iwhr.com

Ping Fu: Engineering Safety Monitoring Center, China Institute of Water Resources and Hydropower Research, Beijing, 100044, China, e-mail: fuping@iwhr.com

Zhanqing Xing: Engineering Safety Monitoring Center, China Institute of Water Resources and Hydropower Research, Beijing, 100044, China, e-mail: xingzhq@iwhr.com

materials include gravel, sawdust, soybean, cement bags, or other fibers, whose drawbacks include difficult construction, time consumption, wastage of material, and their difficulty to control—either the diffusion distance is limited or the channels and holes are likely to be blocked, such that it is difficult to guarantee the blocking effect. In addition, for good fluidity and groutability, the macroporous strata also require blocking grouting materials to ensure that the grouted slurry is not completely flushed away by water and has a certain impact strength and diffusion range over a short time [4]. The principles of asphalt grouting leakage blocking are that asphalt is sensitive to temperature and has good fluidity when heated to a liquid; its slurry does not have apparent particles and has good groutability; it does not dissolve in water, and its slurry will gradually cool and solidify when encountering water while not being diluted and dispersed by water, thus it has good grouting blocking performance.

There are cases in which hot asphalt grouting has been applied in leakage-blocking projects in China and throughout the world, for example, the Lower Baker dam in the United States, the Stewartville dam in Canada, the Bigge dam in Germany, and the upstream cofferdam of the Liujiaxia Hydropower Station and the diversion tunnel of the Huashan Hydropower Station in China [5,6]. At these sites, heated asphalt to a working temperature above 150°C was used to grout; thus, the temperature sensitivity of the asphalt was high, the grouting channels needed heat preservation, the construction included many processes, and the technology was complex. Moreover, the specific gravity of asphalt is low, and hence, it is likely to float on the surface of water, making the grouting process depth shallow and poor controllability, which limits the application of the asphalt grouting technology. As a result, asphalt leakage-blocking materials with a lower construction temperature (below 80°C) may be an effective method to solve the blocking of macroporous strata with a large opening and high flow velocity.

Jin *et al.* [7] found that in an existing tunnel using double-tunnel grouting protection method, a tunnel grouting method, and combining with shield method, can effectively reduce the double underground tunnel construction influence on existing tunnel and on the settlement and stress of the tunnel monitoring system, but the scope of this method is limited and can be applied only to tunnel grouting. Ping *et al.* [8] proposed a leakage plugging method with low-heat asphalt grouting, whose construction temperature is less than 80°C. When water is encountered, it cools and solidifies without dilution, and this method can be applied to the construction of leakage plugging in engineering.

However, this method has a poor effect on the leakage plugging of large-porosity strata with large openings and high velocity of flow. Lukajic *et al.* [9] proposed a method of asphalt seepage treatment for dam foundation. Under the condition of full load operation of the reservoir, hot asphalt injection and conventional cement grouting can effectively seal the main seepage area. However, this method needs to deal with high-speed and turbulent water flow, and the actual application cost is relatively high.

2 Low-thermal asphalt slurry

As a grouting sealing material, low-thermal asphalt slurry should have stable proportion, good fluidity, suitable temperature sensitivity, good diffusion performance, and impact resistance.

2.1 Slurry proportioning

2.1.1 Principle of low-thermal asphalt

Emulsified asphalt is a relatively stable “oil-in-water” multiphase dispersion system with asphalt as the dispersed phase and water as the dissolved phase. Under the effect of mechanical force, asphalt is dispersed as tiny particles (0.1–10 μm) uniformly in water, and a molecular-oriented arrangement and adsorption on surfaces or interfaces can be achieved by adding suitable emulsifiers to reduce the interfacial tension of the emulsion, such that a dispersion system is obtained [10]. Emulsified asphalt is liquid at room temperature. Using emulsifiers, two mutually dissolvable substances, asphalt and water, can dissolve and adsorb at the interface, converting the asphalt particles into single suspended units. The units have a natural instability [11,12], which is mainly presented in three forms: flocculation, agglomeration, and settlement. Flocculation is the re-aggregation of the asphalt particles in the emulsified asphalt. If mechanically strongly stirred, the asphalt particles can be separated again and then the asphalt will be in an “oil-in-water” state, that is, the asphalt particles are totally wrapped by water and the asphalt presents the properties of water—it will not solidify when encountering water (at low temperature) and is likely to be dispersed by water flow. With the continuous flocculation of emulsified asphalt, more

asphalt particles will aggregate, forming large asphalt particles. This is termed coalescence. Asphalt particles merge with each other, and the original state of asphalt is restored, such that the agglomerated asphalt particles cannot be separated by simply mechanically stirring. Then, the asphalt slurry is in a “water-in-oil” state, that is, the demulsified asphalt membrane wraps water inside it and presents the properties of asphalt. It will solidify when encountering water (at low temperature) and is unlikely to be dispersed, and the fluidity of the demulsified mixture is greatly improved because of the large amount of water. With the increase in agglomerated particles, the size of the asphalt particles gradually increases, and the asphalt particles settle because of gravity, such that the asphalt slurry can separate oil and water [13].

2.1.2 Low-thermal asphalt preparation

The “water-in-oil” state in the demulsification of emulsified asphalt not only has the properties of asphalt, i.e., it will not be dispersed but quickly solidify to obtain a certain impact strength when encountering water, but also has certain fluidity after demulsification and certain fluidity and groutability at high temperature (60–80°C); thus, it is suitable for blocking of grouting leakage in macroporous strata with large openings and high flow velocity [14,15].

According to the demulsification mechanism of emulsified asphalt, we selected methods such as adding cement, bentonite, polyurethane, and gravel, and heating to carry out the demulsification test of the emulsified asphalt. The results are presented in Table 1.

The ξ potential of cement is negative, and thus, it will produce a strong charge adsorption with cation emulsified asphalt after the emulsified asphalt is

added. At the same time, cement particles are strongly hydrophilic and will adsorb water in the emulsified asphalt onto its surface as the reacting water needed for hydration. The hydration of cement promotes the loss of the water phase in the emulsified asphalt and accelerates the demulsification of the emulsion and the aggregation of emulsion microdroplets. The hydration of cement emits heat and increases the local temperature of the mixture, promoting the demulsification and the aggregation of emulsion droplets. In addition, adding cement can apparently increase the proportion of the emulsified asphalt mixture and improve the impact strength, compressive strength, and other mechanical properties. According to the test results, the demulsification time of cement satisfies the requirement of grouting construction, and the properties of the mixture after demulsification satisfy the need for leakage blocking. Moreover, cement is easily obtained. Hence, we selected cement as the main demulsification material of the emulsified asphalt to prepare a low-thermal asphalt.

2.1.3 Basic properties of the low-thermal asphalt slurry

The properties of the low-thermal asphalt should satisfy the following: the demulsification time should be suitable and controllable, the mixture formed after demulsification should be in the “water-in-oil” state and have good fluidity, and the viscosity and resistance to water dispersion as well as sufficient mechanical properties such as strength should be obtained. Therefore, we conducted a large number of multicomponent proportioning experiments and obtained the low-thermal asphalt proportion that satisfied the aforementioned requirements. The proportion and performance indicators are presented in Table 2.

Table 1: Results of the demulsification test of emulsified asphalt

Demulsification method	Demulsification time/s	Demulsification effect	Remark
Add cement 30%	284	Water in oil, good fluidity	Test is at room temperature; stirring is at low speed
Add bentonite 20%	162	Water in oil, poor fluidity	
Add polyurethane 3%	38	Mixture is generally gelatinous, poor fluidity	
Add gravel 100%	1,842	Separation of oil and water, poor fluidity of the mixture	
Heating 90°C	>3,000	Separation of oil and water, poor fluidity	

Note: the emulsifier was a slow-breaking, slow-setting cation type; the asphalt was no. 90 hydraulic asphalt; the cement was P.O42.5; the paraffin was industrial paraffin; the water was tap water.

2.2 Fluidity of low-thermal asphalt slurry

2.2.1 Fluidity

The flow of low-thermal asphalt is similar to the high-plasticity liquid. The most important factors in the diffusion distance of low-thermal asphalt in strata are the grouting pressure and temperature. In a groundwater-rich environment, the surface of low-thermal asphalt slurry is cooled, but because of the high specific heat and low thermal conductivity of the asphalt, its internal temperature decreases at a slow rate and remains rather high for several minutes after grouting, thus maintaining its fluidity. If we impose moderate pushing pressure (grouting pressure) to the asphalt mixture, the fluid internal asphalt will push the whole surface condensation shell, resulting in the flow outward and is likely to break through the condensation shell on the surface of the asphalt mixture, forming a new flow front and diffuse forward, until the yield strength of the asphalt slurry is greater than the pushing force of the grouting pressure resulting from the temperature decrease. The change in the fluidity of the low-thermal asphalt slurry with temperature is shown in Figure 1.

2.2.2 Rheological property

Low-thermal asphalt that contains cement particles is a typical Bingham fluid whose rheological property can be expressed by equation (1) as follows:

$$\tau = \tau_B(t) + \eta(t) \times \frac{dv}{dr}, \quad (1)$$

where $\tau_B(t)$ is the time-varying shear yield strength and $\eta(t)$ is the plastic viscosity coefficient of the Bingham fluid.

2.2.3 Test method

Suppose that the slurry is in the incompressible laminar state, and there is no slip at the capillary wall. During

steady flow, the shear stress and the pressure of the differential unit and the gravity of the slurry should satisfy the force equilibrium as follows:

$$\frac{\partial p}{\partial x} dx \cdot \pi r^2 + \gamma \pi r^2 = \tau \cdot (2\pi r) dx. \quad (2)$$

On the surface of a capillary with radius r , its shear stress is equal to yield stress τ_0 . Then, the part within radius r does not flow (solid state) because of $\tau < \tau_0$, thus forming a velocity distribution termed plug flow as shown in Figures 2 and 3.

The dimension of the core of the flow is the radius r_0 of the liquid cylindrical surface in which the shear stress is equal to τ_0 .

$$\tau_0 = \frac{r_0}{2} \left(\frac{\partial p}{\partial x} + \gamma \right). \quad (3)$$

From equations (1)–(3), the shear strength and viscosity formula of the slurry can be derived as follows:

$$\gamma = \eta \cdot x + \frac{4}{3} \tau_0, \quad (4)$$

where $x = \frac{4Q}{\pi R^3}$ and $\gamma = \frac{\gamma R}{2L} \left(L + L_1 - \frac{Q^2}{\pi^2 g R^4} \right)$.

In this formula, R is the radius of the capillary (m); L and L_1 are the length of the capillary and the height of the slurry on the stirring sink, respectively (m); Q is the volume flow of the capillary within unit time (m^3/s); τ_0 is the yield strength of the slurry (Pa); η is the plastic viscosity of the slurry ($\text{Pa} \cdot \text{s}$); and g and γ are the gravitational acceleration and the specific weight of the slurry, respectively.

We tested the low-thermal asphalt with different parameters more than two times and used a graphical method or regression analysis to solve the rheological parameters τ_0 and η of the low-thermal asphalt.

2.2.4 Test device and method

We developed a set of vacuum decompression capillaries to measure the viscosity, including (1) a device to

Table 2: Proportion and performance indicators of low-thermal asphalt

No.	120°C hot asphalt/g	Emulsified asphalt/g	Emulsifier/g	Cement/g	Paraffin/g	80°C hot water/mL	Proportion	80°C apparent viscosity/Pa s	Compressive strength/MPa			Remark
									1 day	7 day	28 day	
1	100	100	—	25	5	—	1.06	5.17	1.26	2.06	2.62	
2	100	—	3	40	5	120	1.11	0.76	2.64	3.89	7.06	
3	—	100	—	30	—	—	1.12	22.76	1.32	2.37	5.21	80°C

Figure 1: Change in apparent viscosity of low-thermal asphalt with temperature.

Figure 2: Equilibrium of differential unit.

Figure 3: Velocity distribution (moving upward).

provide negative pressure in a vacuum pump; (2) flow channels for asphalt that are capillaries with different

radii and lengths; (3) pressure measurement devices including a vacuum meter at the interface of the vacuum pump and a vacuum meter plugged into the rubber plug of the collecting glass bottle; (4) a collecting device, i.e., a glass bottle with a rubber plug on which three holes were drilled for the vacuum meter, the capillary, and the vacuum pump, and the collecting bottle was placed on an electronic scale to record its instant weight difference during the experiment; and (5) an asphalt insulation device, a temperature-controllable heating device, and a plexiglass board sink.

The low-thermal asphalt slurry flows upward in the capillary as shown in Figure 4.

We placed 15 cm × 15 cm × 30 cm low-thermal asphalt samples into the temperature-controllable thermostatic sink, created negative pressure using the vacuum pump, and measured the different weights of asphalt that were sucked into the collecting bottle under different pressures, such that the rheological parameters of the low-thermal asphalt at different temperatures could be determined.

2.2.5 Rheological parameter

According to the aforementioned test device design and according to the described test method, the rheological parameter test is carried out for the selected three typical proportions of low heat asphalt slurry. The results are shown in Figure 5.

This figure shows that the plastic viscosity and yield strength of the three low-heat asphalt ratios decrease with the increasing temperature.

Figure 4: Vacuum decompression capillary device to measure viscosity.

2.3 Temperature sensitivity test of the low-thermal asphalt

2.3.1 Test device

The performance of the asphalt was closely related to temperature. We designed $15\text{ cm} \times 15\text{ cm} \times 10\text{ cm}$ low-thermal asphalt samples, placed them into a thermostatic water bath, and tested the change in their temperature fields with time at different temperatures. We developed a set of temperature field acquisition devices that consisted of a transmitter, temperature sensor, switching power supply, RS485 acquisition module, and acquisition software.

2.3.2 Test results and analysis

We used the 2# low-thermal asphalt slurry for the test. The results are shown in Figures 6 and 7.

The temperature sensitivity of low-thermal asphalt is the main factor affecting its plugging effect. Figure 6 shows the temperature decay process of low-thermal asphalt samples at 200 and 600 s, indicating that the temperature of most volumes of low-thermal asphalt will drop below 40°C in 600 s, and its flow diffusion performance will be greatly weakened, but at the same time, it also improves the energy of low-thermal asphalt to resist the impact of water flow.

2.4 Slurry diffusion experiment

Compared to the high-moisture cement suspension colloid slurry, low-thermal asphalt slurry has a totally different diffusion form. During the diffusion of the cement slurry, cement particles gradually settle when flowing and form blocking at a certain distance from the drill hole after a period of time, thus gradually filling all the pores from those farther away to those nearby. When

Figure 5: Rheological parameters of low-thermal asphalt at different temperature.

Figure 6: Temperature field distribution of low-thermal asphalt sample at 200 and 600 s.

low-thermal asphalt diffuses, it will form an apparent diffusion front and diffuse from nearby to far away. With the continuous perfusion, low-thermal asphalt agglomerates and constantly spreads out and is adsorbed on the surface of seepage channels after cooling. With the continuous thickening of the asphalt adsorption layer, seepage channels are continuously narrowed until they are completely blocked. The pores through which low-thermal asphalt diffuses are completely filled with asphalt, forming a dense blockage; therefore, seepage and leakage blocking is accomplished.

2.4.1 One-dimensional grouting experiment

2.4.1.1 Experimental model

We designed and fabricated one-dimensional (1D) experiment model using PVC tube and filled it with gravel layers of different proportions and porosities. The sizes of the gravels were 2–5, 5–10, 10–20, 20–50, and 2–50 mm. We conducted low-thermal asphalt grouting experiments under different pressure conditions when there was no water or full water inside the model, respectively. The layout of the model is shown in Figure 7.

Figure 7: Design and image of the 1D experiment model.

The gravels were classified by size and then filled the model. Prior to grouting, we conducted a hydraulic conductivity experiment to the model filled with gravel. When the gravel amount and the volume to be filled were the same (in a medium-dense state), the permeability coefficient of the gravels with the same size were slightly different. Different sizes of the permeability coefficient of the gravels are presented in Table 3.

2.4.1.2 Diffusion process

2# proportioning was mainly adopted in the proportioning of the low-thermal asphalt grouting material. Grout was placed into the prefabricated 1D model through a connected special screw pump and pipeline. The temperature of the low-thermal asphalt was 80°C. We measured the range of the completely filled area after the diffusion of the asphalt slurry. After the low-thermal asphalt slurry solidified for 7 days, we broke the PVC tube and obtained the diffusion distance of the asphalt and the condition of the concretion, as shown in Figures 8 and 9.

The larger the grain size of sands in the experiment, the diffusion radius of the slurry in the model filled with water and no water increases with the increase of pressure, and the larger the grain size, the farther the slurry diffuses. With the increase of pressure, the diffusion distance of slurry in

Table 3: Test results for the permeability coefficient of the model before grouting

Gradation/mm	2–5	5–10	10–20	20–50	2–50
Permeability coefficient/cm/s	0.025	0.240	0.550	1.125	0.160

the sand with a particle size of 10–20 mm increases more than that in the sand with a particle size of 2–50 mm.

2.4.1.3 Mechanical performance test of the concretion

In the solidified grouting concretion, we obtained $4\text{ cm} \times 4\text{ cm} \times 16\text{ cm}$ test samples by cutting and grinding and conducted mechanical performance tests in different instars. The results are presented in Table 4.

The 28 day compressive strength of the asphaltic calculus is greater than 2 MPa, and the larger the grain size of sands, the higher the strength; its deformation modulus and permeability coefficient have similar trends.

2.4.2 Two-dimensional grouting experiment

2.4.2.1 Two-dimensional experiment model design

We used a $1.5\text{ m} \times 1.5\text{ m} \times 1.0\text{ m}$ steel model. After presetting the grouting pipe, we filled the model with gravel of different gradations and set a steel plate on the top. Through the jack, different applied stress was simulated. The experimental model is shown in Figure 10.

2.4.2.2 Low-thermal asphalt grouting experiment

The model was filled with gravels of the same gradation and size as in the 1D experiment to simulate real strata, and its compactness and hydraulic conductivity before grouting were also the same. Fill water was input through the inlet to maintain the saturation state of the ravel layers, and the pressure was applied to the steel plate of the model with the jack to simulate low-thermal asphalt grouting at different depths. The experimental results are shown in Figure 11.

2.5 Impact experiment

2.5.1 Experiment model

To test the seepage and leakage blocking adaptability of the low-thermal asphalt slurry in the block stone overhead strata under different boundary conditions and flow velocity conditions, we fabricated an experimental model on the premise of satisfying similar requirements, as shown in Figure 12. The block stones were mainly cobblestones with a diameter of 200–500 mm and were randomly thrown into the model. A different flow velocity was achieved using the pipe at the end.

2.5.2 Impact experiment

We selected two common leakage-blocking materials, low-thermal asphalt and cement–water glass, to conduct the impact experiment. During the experiment, the leakage-blocking effect and the retention of the slurry were tested, and the result is presented in Table 5.

Figure 8: 1D experiment model after grouting low-thermal asphalt.

Table 4: Mechanical performance of asphalt concretions in the 1D experiment model

Gradation/mm	Without water				With water			
	Compressive strength/MPa		28 day modulus of deformation/MPa	28 day hydraulic conductivity/cm/s	Compressive strength/MPa		28 day modulus of deformation/MPa	28 day hydraulic conductivity/cm/s
	3 days	28 days			3 days	28 days		
2–5	2.14	2.37	5.05	1.2×10^{-5}	1.69	2.46	5.64	3.5×10^{-5}
5–10	2.45	3.45	7.70	7.1×10^{-6}	2.18	3.15	6.53	1.7×10^{-5}
10–20	2.84	3.6	5.15	3.2×10^{-6}	2.65	3.05	7.24	1.9×10^{-5}
20–50	3.62	4.81	12.90	4.8×10^{-6}	2.98	3.34	9.45	9.6×10^{-6}
2–50	3.12	4.39	12.10	5.4×10^{-6}	2.68	3.29	10.20	2.5×10^{-5}

Figure 9: Diffusion distance of low-thermal asphalt slurry in the 1D experiment model: (a) gravel model not filled with water and (b) gravel model filled with water.

3 Simulation computation of low-thermal asphalt leakage blocking

For grouting leakage blocking in macroporous strata, the slurry flows into the flowing water strata via drill holes

under the effect of pressure, and first resists the flush of water flow without the limit of the upper wall. Then, it settles down and gradually diffuses to the surrounding area, during which it is in a free diffusion period. When the slurry settles and diffuses to the upper wall of the porous channels, it is limited by the upper wall and will diffuse in pores under grouting pressure, forming an

Figure 10: Design and image of the 2D experiment model.

Figure 11: Graphs of the minimal diffusion distance of low-thermal asphalt in models with different gravel sizes in the 2D experiment: (a) strata pressure, 80 kPa; (b) strata pressure, 160 kPa; (c) strata pressure, 320 kPa; (d) strata pressure, 640 kPa.

apparent diffusion front. During leakage blocking with grouting slurry, the process from resisting the flush of water flow to gradually diffusing to the required radius is considered the pore diffusion stage [11] as shown in Figure 13. Based on this diffusion method, we built grouting leakage-blocking models suitable for different

strata, compiling a computation program and simulating the process of leakage-blocking grouting.

In real leakage-blocking projects, the effect of leakage blocking has a close relation with the opening of pores, the water flow velocity, and the shear yield strength of the slurry and its increased rate. The shear yield strength of

Table 5: Impact experimental results for typical materials

Flow velocity/ m/s	Low-thermal asphalt				Cement–water glass			
	Smooth underlying surface		2–5 mm gravel		Smooth underlying surface		2–5 mm gravel	
	Blocking percentage/%	Retention percentage/%	Blocking percentage/%	Retention percentage/%	Blocking percentage/%	Retention percentage/%	Blocking percentage/%	Retention percentage/%
0.2	100	100	100	100	100	75	100	81
0.5	100	100	100	100	100	62	100	68
1.0	100	100	100	100	95	48	100	64
1.2	100	100	100	100	88	34	92	43
1.5	100	92	100	98	62	28	68	32
2.0	100	71	100	82	37	11	38	13
2.5	70	52	73	58	10	5	12	10
3.0	42	18	43	19	—	—	—	—

Figure 12: Image of the impact experimental model.

the slurry has an approximate power-function relation with time as follows:

$$\tau = \tau_0 e^{\alpha t}, \quad (6)$$

where τ is the shear yield strength, τ_0 is the original shear yield strength, α is the time coefficient, and t is the time.

The result of the plugging effect of different muds and different strata is shown in Figure 14. According to the physical and mechanical performance of the low-thermal asphalt grouting material, presented in Table 6, we completed a simulation computation of the strata leakage-blocking effect (slurry retention percentage as the assessment indicator) for different strata (mainly the opening) and different flow velocities. Suppose that the leakage blocking is effective if the retention percentage

of the slurry $>30\%$, and the leakage blocking is efficient and reliable if the retention percentage of slurry $>60\%$.

Slurry retention rate is one of the important indexes to evaluate the plugging effect. Figure 14 shows the gap opening and the flow rate of the low-thermal asphalt slurry when the plugging effect is effective and reliable. Obviously, for the same flow rate, the larger the opening is, the smaller the slurry retention rate is, that is to say, the opening corresponding to the 30% slurry retention curve is greater than that corresponding to the 60% slurry retention curve. Similarly, if the opening is lower than the same, the larger the flow rate is, the smaller the slurry retention rate is. That is to say, the flow rate corresponding to the 30% slurry retention rate curve is greater than that corresponding to the 60% slurry retention rate curve.

Figure 13: Diffusion method of the slurry in wide pores: (a) free diffusion period and (b) pore diffusion stage.

Figure 14: Leakage-blocking effect of different slurries and different strata.

4 Results

We conducted indoor proportioning, fluidity, temperature sensitivity, diffusion performance, and impact experiments of low-thermal asphalt slurry with regard to low-thermal asphalt grouting material, together with the simulation computation of leakage blocking. The results are as follows:

- (1) The fluidity of 2# low-thermal asphalt characterized by apparent viscosity is better than that of the other two types of low-thermal asphalt. Its apparent viscosity is approximately $0.75 \text{ Pa} \cdot \text{s}$ at 80°C and less than $10 \text{ Pa} \cdot \text{s}$ at 60°C .
- (2) With a decrease in temperature, the plastic viscosity, yield strength, and other rheological parameters of low-thermal asphalt quickly increase. The fluidity of 2# low-thermal asphalt characterized by rheological parameters is also better than that of other two types of low-thermal asphalt. At 80°C , the plastic viscosity of the 2# low-thermal asphalt is less than $100 \text{ mPa} \cdot \text{s}$, and the yield strength is less than 32 Pa . At 60°C , the plastic viscosity of the 2# low-thermal asphalt is approximately $1,200 \text{ mPa} \cdot \text{s}$, and the yield strength is approximately 55 Pa .
- (3) Asphalt has poor thermal conductivity and slow temperature diffusion. The outside of slurry which is in direct contact with water, cools quickly, and thus, the temperature of its central part is always higher than its surrounding part, and the farther from the boundary, the more slowly the temperature decreases. At 200 s , the 70°C region comprise most of

the inside of the asphalt, but after 600 s , the 40°C region becomes the main part.

- (4) When the grouting pressure is 1.2 MPa , the diffusion distance of slurry in a $2\text{--}5 \text{ mm}$ gravel layer is approximately $20\text{--}40 \text{ cm}$, and the diffusion distance of slurry in a $2\text{--}50 \text{ mm}$ gravel layer can reach $80\text{--}120 \text{ cm}$. In a gravel layer consisting of $20\text{--}50 \text{ mm}$ granules with larger pores, the diffusion distance of slurry can reach 150 cm .
- (5) For the same grouting pressure, the diffusion distance of the slurry without water is longer than the diffusion distance under a saturation condition, with a maximal 30% increase. The diffusion distance of low-thermal asphalt in strata with a different depth condition is obviously affected. At a depth of 25 m (where the strata pressure is 600 kPa), the diffusion distance of slurry decreases by more than 20% .
- (6) The test results of the compressive strength, hydraulic conductivity, and other mechanical parameters of the low-thermal asphalt slurry concretion indicate that the strength of low-thermal asphalt concretion can reach $2\text{--}5 \text{ MPa}$, and the hydraulic conductivity is less than $5 \times 10^{-5} \text{ cm/s}$.
- (7) For strata with a flow velocity less than 2 m/s , the blocking percentage is 100% when using low-thermal asphalt slurry for blocking, and thus, the blocking efficiency is high.
- (8) The simulation computation of leakage blocking indicates that, in medium-opening leakage strata (50 mm), low-thermal asphalt is effective in blocking when the water flow velocity is 1.2 m/s and is efficient and reliable in leakage-blocking grouting when the water flow velocity is 1.0 m/s .

Table 6: Performance indicators of the low-thermal asphalt leakage-blocking material

Leakage-blocking material	Original yield strength/ Pa	Time coefficient	Remark
Low-thermal asphalt	32	0.05	80°C construction temperature

- (9) The test results are consistent with the numerical simulation calculation results, which further clarifies the applicability and superiority of the low-thermal asphalt grouting material in plugging grouting under dynamic water conditions.

5 Discussion

The results showed that the low-thermal asphalt grouting was a highly effective method to block seepage channels in macroporous strata under flowing water conditions.

- (1) The fluidity of low-heat asphalt varies with the change of temperature, and it still has good fluidity.
- (2) Low-thermal asphalt grouting has good diffusion ability, and its diffusion distance is mainly related to the gradation of particles in the sand and gravel layers. Generally, the leakage channel of large hole is larger than 1 cm (the smaller channel can be blocked with cement-based grouting material), which is suitable for grouting pumping and slurry diffusion in the formation. The diffusion distance of low-heat asphalt slurry is also related to the grouting pressure, the condition of rich water in the stratum, and the additional stress in overburden. The diffusion distance increases with the increase of the grouting pressure. Higher grouting pressure can be used to obtain larger slurry diffusion distance in small particle formation.
- (3) Low heat asphalt is a kind of grouting material with good impermeability, which can meet the impermeability requirements of general engineering. But its elastic modulus is only 5–10 MPa, which is obviously too soft. In addition, asphalt has inherent creep characteristics. Composite grouting with cement-based grouting materials can make up for the low strength of asphalt concrete with low calorific value.
- (4) Compared with cement–sodium silicate slurry, low-heat asphalt grout has higher retention rate and better water-blocking effect.

6 Conclusion

Macroporous leakage stratum is a problem that deeply buried long tunnels and other underground projects are often confronted with. Low-thermal asphalt makes use of the property of asphalt, i.e., “liquid that is easy to flow

when heated and solid when encountering water and cooling,” it has good adaptability to leakage blocking in macro-porous strata, reliable blocking effect, and high blocking efficiency; and it has important engineering application value.

- (1) Low-thermal asphalt has good fluidity and pumpability below 80°C and solidifies while not being dispersed when encountering water; thus, it is reliable and efficient for leakage-blocking grouting in macroporous leakage strata.
- (2) Low-thermal asphalt has low thermal conductivity, its internal temperature slowly decreases, and it can maintain a rather high temperature and certain fluidity within the first several minutes following grouting; thus, it has good groutability in pipes, holes, or stratum pores. Under the effect of grouting pressure, its diffusion distance can satisfy the requirement of grouting blocking.
- (3) Low-thermal asphalt material contains cement and other particles, and its specific weight is slightly heavier than water, which benefits the diffusion of slurry in pores. Meanwhile, the construction temperature of low-thermal asphalt is below 80°C such that a conventional screw pump can be used for grouting, and it still has certain pumpability at 60°C, which allows for simple and convenient construction equipment.
- (4) “Water-in-oil” low-thermal asphalt contains a large amount of water, has relatively low strength during later stages, and has relatively large creep property. Thus, in real construction, after larger leakage channels are blocked by low-thermal asphalt, reinforcement grouting with cement slurry should be implemented.

Acknowledgments: This research was supported by the National Thirteen-Five Key Scientific Research Project (No. 2016YFC0401805) and Thirteen-Five Key Scientific Research Project of China Institute of Water Resources and Hydropower Research (No. EM0145B462016).

References

- [1] Wei-quan, Z., Z. Jin-jie, F. Ping, and Y. Xiao-dong. Experimental study on grouting leakage-blocking with modified asphalt. *Railway Const. Technol.*, Vol. 2011, No. 9, 2011, pp. 43–46.
- [2] Ping, F., Z. Jin-jie, Z. Wei-quan, and Y. Xiao-dong. Study and application of fast-coagulating paste technology. *Water*

- Resources and Hydropower Engineering*, Vol. 36, No. 1, 2005, pp. 63–66.
- [3] Zhikuan, N., J. Jiahong, and W. Zhenxiang. Grouting work method with high-thermal asphalt to prevent water burst in New Yongchun tunnel. *Chinese Journal of Rock Mechanics and Engineering*, Vol. 23, 2004, pp. 5200–5206.
 - [4] Ziren, F., X. Wencheng, and S. Xinmin. Application of Grouting Work Method with High-thermal Asphalt in Treatment of Water Burst in Underground Projects. Proceedings of the Sixth Cross-strait Academic and Technical Symposium on Tunnel and Underground Engineering, 2007.
 - [5] Deli, Y. H. Discussion on the reasons for premature demulsification in the application of emulsified asphalt. *New Building Materials*, Vol. 4, 2008, pp. 80–82.
 - [6] Turkmen, S. Treatment of the Seepage Problems at the Kalecik Dam (Turkey). *Engineering Geology*, Vol. 68, No. 3, 2003, pp. 159–169.
 - [7] Jin, D., D. Yuan, X. Li, and H. Zheng. An in-tunnel grouting protection method for excavating twin tunnels beneath an existing tunnel. *Tunnelling & Underground Space Technology*, Vol. 71, No. 8, 2018, pp. 27–35.
 - [8] Ping, F., W. Chun, and Y. Xiaodong. Study on technology of grouting leakage-blocking with low-thermal asphalt. *Water Resources and Hydropower Engineering*, Vol. 12, 2013, pp. 63–67.
 - [9] Lukajic, B., G. S. Smith, and J. R. Deans. *Use of Asphalt in Treatment of Dam Foundation Leakage: Stewartville Dam*. ASCE Spring Convention, Denver, April, 1985.
 - [10] Jinsheng, Z., Z. Jinyan, X. Xiaoyu, and H. Xiuhong. *Asphalt Material*. Beijing: Chemical Industry Press, 2009.
 - [11] Ping, F., Z. WeiQuan, and Z. Jinjie. Study on model of grouting leakage-blocking with non-water reactive material. *Chinese Journal of Geotechnical Engineering*, Vol. 37, No. 8, 2015, pp. 1509–1516.
 - [12] Zhang, D. M., Z. K. Huang, and Z. Y. Yin. Predicting the grouting effect on leakage-induced tunnels and ground response in saturated soils. *Tunnelling & Underground Space Technology*. Vol. 65, No. 5, 2017, pp. 76–90.
 - [13] Ozcelik, M., and F. Tuzlu. Leakage analysis of Deriner Dam (Artvin-Turkey) using 3D modeling. *KSCE Journal of Civil Engineering*, Vol. 22, No. 4, 2017, pp. 1–7.
 - [14] Hui Y, Jun D, Chaoyang P, Dezeng Z, Gongyu S, Xinwang D, et al. Grouting technology of L type surface borehole applied to water disaster prevention in mine. *Coal Science & Technology*, Vol. 45, No. 4, 2017, pp. 171–175.
 - [15] WeiQuan, Z. Study and Application on Flowing Water Leakage-blocking Grouting Technology in Macro-porous Strata. Doctoral dissertation. China Institute of Water Resources and Hydropower Research, 2012.