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Formulation and performance of grouting materials for underwater shield tunnel construction in karst ground

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HIGHLIGHTS

- A new hardened cement-bentonite grouting material (HCBGM) for underwater karst cavern was proposed.
- Effects of compositions on performances of the HCBGM are investigated.
- Optimal formulation of HCBGM for karst cavern with groundwater flow was determined.
- The technique, cost and eco effectiveness of the HCBGM was verified by an field case study.

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ABSTRACT

Grouting is one of most important techniques for underwater tunnelling in karst ground which is actually difficult to be resolved due to the presence of underground water flow. This paper proposed a new grouting material to fill karst caverns when there is flowing underground water prior to shield tunnel construction. The grout uses bentonite and cement as the base material, and a curing agent were added to form excellent fluidity, stability and scour resistance. The effects of the composition and formulation on the performance of the grouting material, and the optimal formulations were determined through a series of laboratory experiments. The recommended parameters for the grout are a specific gravity for the bentonite slurry from 1.30 to 1.35, a cement content of 30%, a meta-aluminate content of 1.25% and a lignin content of 0.20%. The effectiveness of the hardened cement-bentonite grouting material (HCBGM) was checked by a field grouting application for a underwater shield tunneling in karst area, and the results illustrated that the proposed grouting material not only can fulfill the engineering requirements but also turns out cost effective and eco-friendly.

1. Introduction

Due to the rapidly increasing demands for city transportation construction, shield tunneling has been extensively used in the development of underground infrastructure [1–5]. Shield tunneling construction in karst regions is a common challenge, especially under the condition of underground water flow [6,7]. Geological hazards, such as shield sinking, water and mud inrush, tunnel face instability, ground collapse and soil liquefaction, can occur during tunnel construction in karst regions [8–11], therefore precautions are necessary to prevent heavy casualties and serious economic losses.

In engineering practice, there are many methods for the treatment of karst tunnels. One such treatment method is grouting which is an effective and widely used method to ensure the safety of tunnel construction [12–14]. There are also many materials to form the grout for grouting karst ground, including cement-based suspensions and chemical liquid, sand, artificial foams, polyurethane, and hot bitumen [15–18]. All these materials have been successfully used in karst treatment engineering, such as in the Blessberg tunnel of Deutsche Bahn [19], the longest railroad tunnel in South Korea [20], the Gavarres tunnel in Spain [21] and the Albula tunnel II in the Swiss Alps [22]. However, the above karst grouting materials mainly focus on the mountain tunnels, but few for shield tunnels, especially the suitability of using such grouting materials for underwater shield tunnel in karst ground is seldom reported in engineering. Under these conditions, the safety of shield construction in underwater karst cannot be guaranteed if grouting with an ordinary cement slurry due to its poor scour resistance, high bleeding ratio, poor stability and high cost. Although some engineers have found that chemical grouts can help

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mitigate these problems, the chemical materials are not only extremely expensive but also may result in water pollution. Moreover, chemical grouts show poor binding in moist environment as well as insufficient durability [23]. It is therefore of great engineering interest and necessity to find a new material which not only have superior performance to ensure the safety of shield tunnel construction but also be eco-friendly and less expensive.

In this study, a hardened cement-bentonite grouting materials (HCBGM) was proposed to serve as an anti-seepage and reinforcing treatment for karst ground with dynamic groundwater flow before tunnel excavation. The preparation of the new grouting material and the effects of composition and formulation on the grouting performance were investigated and optimized with the help of a series of laboratory experiments. The field performance of the HCBGM and its effectiveness were verified by a pertinent field case study.

2. Experiments approaches

2.1. Raw materials

Cement is always one of most important raw material for grouts. In this study, Nan-fang 42.5 Ordinary Portland cement produced in Xiangtan, Hunan, was used, which was produced according to the standards of Portland cement and ordinary Portland cement, China (GB175-99). The major chemical and physical properties of the used cement are listed in Table 1.

Bentonite, an absorbent aluminum phyllosilicate, is essentially impure clay consisting mostly of montmorillonite. In this study, a powdered, single-component, commercially available, sodium bentonite that was produced in Changsha, Hunan province, was used as the second major components for the grout. Table 2 presents the major chemical constituents and physical properties of the bentonite.

The modifier is made in-door, which contains an accelerator and water-reducing agent. The content of such modifier meets the relative technical requirements set by the Chinese government (GB 8076-2008). Meta-aluminate was used as a setting accelerator to short the setting time of the grout while Lignin was used as a water-reducing agent to improve the mobility of the grout.

The above materials forms a hardened cement-bentonite grouting materials (HCBGM) which is used in this study. Because HCBGM has the advantage of a controllable diffusion distance, HCBGM which consequently can reduce the total amount of raw material required. As a result, the engineering cost of HCBGM is obviously lower than that of a cement slurry.

2.2. Testing program

Generally, grouting material for karst in the presence of dynamic groundwater scouring needs good fluidity and stability, a low bleeding rate, sufficient compressive strength as well as lower hydraulic conductivity and better scour resistance. In this study, based on the evaluation of the consulting, design and construction units, the recommended parameters for the grouting material include a fluidity between 120 cm and 170 cm, an initial setting time of more than 30 min, and a retention rate of more than 75% with a flow velocity of approximately 0.2 m/s. After the 28-d standard curing period, the compressive strength should be more than 1 MPa, and the hydraulic conductivity should be less than 10^{-5} cm/s. The influence of the amount of each components on the performance of HCBGM was intended to be investigated by an analysis with each factor determined by the Orthogonal table L16 (4^4), as shown in Table 3.

The HCBGM can be prepared with the following steps HCBGM. At first, the bentonite is immersed in the water stirring for approximately 15 min, and adjusted to the desired specific gravity (A). Second, cement (B) is added to the bentonite slurry in the proper proportion, and the mixture was stirred with a stirrer for approximately 5 min to form cement-bentonite grout. Finally, proper proportion of meta-aluminate (C) and lignin (D) were added to the cement-bentonite and the mixture was stirred with a stirrer for approximately 5 min to form the HCBGM. A schematic of the HCBGM preparation process is shown in Fig. 1.

The grouting material samples were prepared with various formulations, and the setting time, fluidity, bleeding rate, bulk shrinkage rate, scour resistance, hydraulic conductivity and compressive strength of each sample were measured. Then, the effects of composition and formulation on the performance of the grouting material were analyzed.

2.3. Testing methods

The fluidity and setting time of the grouting material have a strong influence on its pumpability and groutability. Experiments was carried out to investigate the effects of each factor on the fluidity and setting times of HCBGM compared with those of control pastes. A Vicat apparatus was used for these experiments to evaluate the setting time of the HCBGM according to the Chinese Standard GB/T 1346-2011. The fluidity of the HCBGM was determined following the Chinese Standard GB 8077-2000. First, each HCBGM sample was prepared and put into a conical mold (with a top diameter of 36 mm, bottom diameter of 60 mm and height of 60 mm).

Table 1
The major chemical and physical properties of Portland cement.

Chemical constituents	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	SO_3	Loss on ignition
Content/%	22.7	7.7	4.7	2.7	56.8	2.7	2.3
Physical properties	Initial set	Final set	28-Day compressive strength				
Test results	155 min	235 min	46.3 MPa				

Table 3
Factor level of HCBGM.

Factor level	A:Specific gravity of bentonite slurry	B:Cement content (%)	C:Meta-aluminate content (%)	D:Lignin Content (%)
1	1.20	20	0.5	0.0
2	1.25	30	1.0	0.2
3	1.30	40	1.5	0.3
4	1.35	50	2.0	0.5

Table 2
The major chemical constituents and physical properties of the bentonite.

Chemical constituents	SiO_2	Al_2O_3	Fe_2O_3	MgO	Ti_2O_3	CaO	Na_2O	Loss on ignition
Content/%	63.58	15.42	4.61	1.58	0.56	0.74	1.00	9.11
Physical properties	Blue absorption power		Colloid index		Expansion ratio	Colloid ratio		mud-making rate
Test results	18–29 (g/100 g)		63%		>10	100%		>16 m^3/t