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Laboratory test on foamed concrete-rock joints in direct shear

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HIGHLIGHTS

- Compressive properties of foamed concrete with different dry densities were studied.
- Three failure types of foamed concrete-rock joins in direct shear were identified.
- The bond-slip behaviors of foamed concrete-rock joints were investigated.
- A model of the foamed concrete-rock interface for practical purpose was proposed.

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ABSTRACT

Foamed concrete has been widely used in tunnels where foamed concrete-rock joints are usually encountered. However, few studies have been conducted on the mechanical properties of the joint. To investigate the shear behaviors of the joint, compressive properties of foamed concrete were first studied by compression tests, and a series of direct shear tests under constant normal load condition were then conducted. Three failure types were identified during the tests: interface failure, foamed concrete failure and the mixed type. Both the normal stress and dry density of the foamed concrete can significantly influence the shear behaviors of the joint, but have little effect on the friction coefficient of the joint. Based on the results, a model was proposed for the joint, which can successfully describe the shear behaviors of the joint. The model can easily be implemented in numerical codes, and then be used to investigate the mechanical behaviors of tunnels in practical cases.

1. Introduction

Foamed concrete is defined as a light cellular concrete that can be classified as a lightweight concrete (density of 400–1850 kg/m^3) [1]. Owing to its high porosity, foamed concrete offers distinctive properties, including low density, low thermal conductivity, and excellent shock-absorbing abilities. Therefore, in practice, foamed concrete has been widely used in civil engineering areas [2]. For example, it has been used for sound barriers, fire walls, foundations, building panels, mine plugs, roadway crash barriers, and geotechnical fill applications [3–5]. In recent decades, a large number of tunnels have been built around the world. Foamed concrete is characterized by its desirable adhesive capability in the tunnel lining, low cost, and easily availability in engineering construction sites. Therefore, the foamed concrete has been used extensively in tunnels.

In Canada, cement-based foam has been widespread used for tunnel annulus grouting [5]. Foamed concrete has been used as the isolation material between the shotcrete layer and final lining to absorb seismic deformation in the Galongla tunnel in China [6]. Tian et al. [7], Wang et al. [8] and Xu et al. [9] proposed that the use of foamed concrete as tunnel lining to sustain large rock deformation in areas with high geo-stress. Huo et al. [10] investigated the damping effect of the foamed concrete cushioning layer in crossing a high-speed railway tunnel, and the results demonstrated that the foamed concrete layer can significantly protect the tunnel lining. Zhao et al. [11] proposed a foamed cement-based material as the sacrificial tunnel lining structure cladding under internal blasting loading. Choi and Ma [12] proposed lightweight foamed concrete/mortar for facilitating tunnel drainage, and this composite lining was successfully implemented in a two-lane road tunnel in South Korea. When used as tunnel lining, the foamed concrete layer is usually installed between the rock and tunnel lining. Therefore, the interactions between the rock and foamed concrete layer can significantly influence the static and dynamic tunnel behaviors, and studying foamed concrete-rock interactions is of great significance.

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Generally, the strength and stiffness of the rock are much larger than those of foamed concrete, and the interactions are mainly dominated by the foamed concrete and foamed concrete-rock joint. Therefore, to gain a better understanding of foamed concrete-rock interactions, the mechanical properties of the foamed concrete and shear behaviors of the foamed concrete-rock joint must be examined comprehensively. In conventional studies, the mechanical properties of concrete or rock are usually obtained from compression and tension tests, while the shear behaviors of a joint are generally investigated though direct shear tests in the laboratory. Similar to foamed concrete-rock joints, various direct shear tests have been conducted on rock and shotcrete-rock joints with a range of geometries and stress boundary conditions. Shear tests are generally conducted under two major boundary conditions: direct shear tests under constant normal load (CNL) [13–16] and direct shear tests under constant normal stiffness (CNS) [17–19]. In general, shear properties of a joint are influenced by numerous factors, such as initial adhesion [20], surface morphology [14], mechanical properties of rock and concrete, normal stress [15], temperature [16]. For a bonded joint, the shear strength is a combination of adhesion and friction contributions, and generally expressed by the Mohr-Coulomb failure criterion. Based on test results and this criterion, several mechanical models for rock and rock-concrete joints [21–23] have also been proposed.

There are no coarse and fine aggregates in foamed concrete. Consequently, the mechanical properties of foamed concrete differ significantly from those of normal concrete [24], lightweight concrete [25–26], and the rock. Moreover, these properties are influenced by various factors such as porosity [27–29], materials and mix proportions [30,31], and specimen size [32]. As a result, the shear behaviors of the foamed concrete-rock joint may differ significantly from those of rock joints or normal concrete-rock joints. However, few studies have been conducted on foamed concrete-rock joints. Therefore, the aim of this study is to investigate the shear behaviors of foamed concrete-rock joints. In order to achieve this goal, compression tests were first carried out on foamed concrete to study its mechanical properties. Following this, a series of direct shear tests were conducted on foamed concrete-rock joints under the CNL condition. Finally, a model was established for the foamed concrete-rock interface, which can easily be implemented in numerical codes. This model can be used to investigate the mechanical behaviors of tunnels in practical cases where foamed concrete-rock joints are encountered.

2. Test samples and specifications

2.1. Constituent materials and mix proportions of foamed concrete

The main constituent materials are the cement, water, and foaming agent.

Table 1
Foaming performance of foaming agent.

Expansion ratio	Half-life (min)	Foam density (kg/m^3)	Foam diameter (μm)		
			5 min	30 min	60 min
30	60	33.8	390	480	580

(1) Cement: the cement used in this study is ordinary Portland cement, classified as 425# according to the Chinese standard [33]. The 28-day standard compressive strength is larger than 42.5 MPa.
(2) Water: common tap water.
(3) Foaming agent: one type of commercial composite foaming agent was selected from the Hua-tai Building Materials Development Co., Ltd, Henan province, China. It is a synthetic foaming agent, whose specifications are given in Table 1. Expansion ratio: the foaming-agent to the foam volume ratio is approximately 30. Half-life: half of the foam will dissipate in 60 min. Foam diameter: the foam diameter increases with time, and the diameters at different times are given in Table 1.

No standard method exists for proportioning foamed concrete. In this study, the foamed concrete was designed according to the dry density. The mix proportion of the foamed concrete was determined using the method proposed by Tan et al. [34]. Three dry densities applicable to the tunnel lining were selected, and the mix proportions are given in Table 2.

2.2. Foamed concrete production method

First, the cement and water were mixed in a blender, and the foam was manufactured simultaneously. Thereafter, the foam was put into the slurry, and mixed for 2–3 min at a high-speed of 60–120 r/min. When the cement slurry and foam were mixed evenly, the foam slurry was poured into molds. The specimens were removed from the molds after 24 h for casting and then cured for 28 days in the standard curing room.

2.3. Preparation of test samples

2.3.1. Foamed concrete samples for compression tests

First, cubic foamed concrete samples (300 mm × 300 mm × 300 mm) were prepared according the above procedure. After curing for 28 days, the samples were cored using a 50-mm inner diameter diamond drill bit. Then standard cylindrical samples (Ø50 mm × 100 mm) were obtained. The size of test samples was determined to comply with the laboratory test equipment.

2.3.2. Foamed concrete-rock joint samples

The rock samples consist mainly of sandstone. The uniaxial compressive strength of the rock is approximately 99.3 MPa, while the elastic modulus is approximately 10.6×10^3 MPa.

The rock piece was shaped into a cubic rock sample (150 mm × 150 mm × 75 mm), and the size was determined to comply with the laboratory test equipment, and it meets the requirements of the ISRM suggested method [36]. For a foamed concrete layer used as tunnel lining, the roughness of the rock surface is influenced by various factors such as the excavation method, in-situ stress and rock mass, so it lies within a wide range in practical cases. For simplicity, numerous direct shear tests have been conducted on concrete-rock joints with small roughnesses [14–16]. If a tunnel is excavated using a tunnel boring machine or a thin shotcrete layer exists, the roughness of the foamed concrete-rock joint will

Table 2
Mix proportions for different dry densities of foamed concrete.

Number	Dry density (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Foaming agent (kg/m^3)
1	250	208.33	93.75	1.47
2	550	458.33	206.25	1.14
3	750	625.00	281.25	0.93