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Blast mitigation effect of the foamed cement-base sacrificial cladding for tunnel structures

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HIGHLIGHTS

- A foamed cement-based material is proposed as the sacrificial cladding of tunnels.
- We invent an instrument to test impact mitigation effects of the proposed material.
- A 3D numerical model is used to validate blast mitigation effect on tunnel lining.
- The feasibility of the material as the sacrificial cladding of tunnels is verified.

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ABSTRACT

A foamed cement-base material is proposed as the sacrificial cladding of tunnel lining structures to provide the blast mitigation effect. An experimental investigation on responses of the foamed cement-base material specimen with different ingredient proportions to impulse loads is conducted. Two main ingredients of specimens, i.e. the expandable polystyrene (EPS) particles and cement matrix, contribute to the buffer action significantly. Finite element numerical analysis of the composite concrete tunnel lining is performed to assess the blast mitigation effects attributed by the proposed foamed cement-base sacrificial cladding. Dynamic responses caused by blasting loads are mitigated effectively by the proposed foamed cement-base sacrificial cladding with the optimized thickness.

1. Introduction

Anti-blast design of underground structures, such as tunnels and subway stations, has been gaining more and more extensive interest. Various protection technologies are explored to prevent the severe damage caused by blast waves to underground structures and personnel. The underground structures with low critical damping tend to reach considerable vibration amplitude even under the moderate impulse. Improvement of energy dissipation capability enables vibration amplitude reduction effectively. The concept of sacrificial cladding design is a good solution [1,2], in which the sacrificial cladding adhesive to the skin of the structural member is capable of dissipating or absorbing the blast energy and contributes to the blast mitigation effects on underground structures.

In terms of blast mitigation, different types of protective layers as the sacrificial cladding to absorb energy have been explored. A few researchers have explored the protective abilities of some types of materials as the sacrificial cladding. Guruprasad and Mukherjee [1] proposed layered mild steel plates employed to dissipate or absorb the blast energy, and studied the impulse distributions and energy absorptions in plastic deformation of the mild steel plates. Hanssen et al. [2] suggested aluminum foam panels as the sacrificial cladding. Ma and Ye [3] investigated the energy absorption capacity of the double-layer foam cladding under blast load based on a rigid-perfectly plastic-locking foam model. Afterwards, Ma and Ye [4] proposed an analytical Load-Cladding-Structure (LCS) model to predict the maximum deflection of the foamed sacrificial cladding and the maximum blast load for a particular configuration of the foam cladding and

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the protected structure. Theobald and Nurick [5] studied the responses of tube-core claddings under blast loads by means of experimental blast tests, and found that panel crush distance increases with increasing impulse and decreases with an increasing number of tubes in the panel core. Palanivelu et al. [6] studied crushing and energy absorption performance of different geometrical shapes of small-scale glass/polyester composite tubes under quasi-static loading conditions, and found that the corresponding energy absorption of the special geometrical shapes were better than the standard square and hexagonal geometrical shapes. Tarlochan et al. [7] conducted quasi-static compression experimental investigation of composite sandwich cladding structures fabricated from glass fiber, polystyrene foam and epoxy resin. Hadjadj and Sadot [8] described the mechanism of shock and blast wave mitigation in aqueous foam material. Britan et al. [9] researched shock wave propagation through wet particulate foam material and gave the main parameters controlling the shock wave mitigation.

In this paper a new foamed cement-base composite functional material, made from cement, lightweight aggregate expandable polystyrene (EPS) particles and reinforcement polypropylene fiber, is proposed to the sacrificial cladding serving as the energy-absorbing and load-distributing system. Compared to metallic foam and aqueous foam material, this foamed cement-base material is characterized by desirable adhesive capability to the tunnel lining, low cost and easily availability in engineering construction sites. The knowledge of the foamed cement-base material performance under shock and blast waves is required to guide the design of the foamed cement-base sacrificial cladding in tunnel lining structures. In this paper, an experimental investigation on the responses of the foamed cement-base material specimen subjected to impulse loads is conducted. The effects of the proportions of each material ingredient and compression ratio on the impact resistance are studied. Furthermore, the influence of the material ingredients content on the compressive ability and energy absorb performance of the foamed cement-base material, which yield the basis of the foamed cement-base sacrificial cladding design for tunnel structures, are obtained by dimensionless analysis. Finally, the FE model of full-scale composite reinforced concrete tunnel lining is established, in which the proposed foamed cement-base material is employed as the sacrificial cladding of the tunnel lining, and parametric analysis of the numerical model subjected to internal blast loadings is performed to assess the blast mitigation effects caused by the foamed cement-base material.

2. Test specimen and experimental set-up

2.1. Foamed cement-base materials

Foamed material, a kind of economical porous medium, is easily shaped and with low density. It is composed of the internal pores and skeleton. When under the compression, it undergoes large deformation process with the almost constant stress. The advanced capabilities of absorbing energy, buffering impact, weakening oscillating and reducing stress amplitude enable the foamed material acting as blast mitigating and decompressing member in engineering. Herein, a composite foamed cement-base material is proposed to serve as the sacrificial cladding to protect the critical bearing structure.

The material for test specimen contains cementing ingredient, lightweight aggregate ingredient, reinforcing and toughening ingredient, etc. No.52.5P.II R portland cement with strength as 52.5 MPa specified in Chinese Specification "Common portland cement" [10] is employed as cementing ingredient. Expandable polystyrene (EPS) particles with 1.5 mm size mainly contributing to the blast mitigation effect are used as the lightweight aggregate. Commercially available polypropylene fiber acts as the reinforcing and toughening component.

Cement is a powdery hydraulicity inorganic gelled material, and becomes into slurry mixing with water. The EPS particles glue together by hardening of cement. The water cement ratio is controlled at 35% to make sure the mixture form under the half dry condition, so that closed porous materials develop, which permit the long plateau stress under loads and desirable energy-absorbing ability.

Expandable polystyrene (EPS) particles exhibit considerable compressibility, and are capable to produce the large recoverable elastic deformation. With good resilience and resistance under impact, the EPS acting as the main hybrid damping component is added into the cement.

Polypropylene fibers are added into the mixture of EPS and the cement slurry and twine between the EPS particle cementing surfaces. Polypropylene fibers are designed to improve the plastic yielding capability of the cladding material. In addition, emulsion powder employed as adhesive is also added to this cement-matrix composite material.

Test specimens are cylinders with diameter 15.6 cm and height 6 cm, shown as Fig. 1. The PVC plastic pipes with outer-diameter 16 cm and height 15 cm are used as the specimen moulds, shown as Fig. 2. A cut on the side of the PVC pipe enables it to be easily removed from the specimen when the curing of specimen finished.

All the specimens are compressed and formed in the moulds. Compression ratio, the density ratio of the specimens before and after compressing, is introduced to represent the compactability. Compression ratio of the specimens in this test varies from 65% to 90%. The details of the specimens are displayed in Table 1.

2.2. Experimental set-up

At present, Split Hopkinson Pressure Bar (SHPB) is performed extensively in higher strain rate impact tests of metal and metallic alloy materials. Uniform stress distribution is the basic assumption in SHPB. However, the proposed foamed cement-base material with low strength, large strain, low wave velocity, and specimen size limitation is unable to conform to the uniform stress distribution assumption. In SHPB, wave impedance of specimen bar and Hopkinson pressure bar mismatch seriously, and transmission signal is minimized. The proposed foamed cement-base material is not amenable to be tested by means of SHPB. A new experimental method and evaluation standard are designed to fully study the resistance of the foamed cement-base composite functional material to impact loadings.

The schematic representation of the small-scale blast test set-up is shown in Fig. 3. The test set-up mainly includes 5 components: atmosphere cannon, steel marbles, specimen, pressure system, and protective cage.

Air compressor can offer the atmosphere cannon gas with certain pressure. By controlling the solenoid valve, the compressed gas inside the atmosphere cannon

Fig. 1. Test specimens.

Fig. 2. The moulds of the test specimens.