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Effect of particles with different mechanical properties on the energy dissipation properties of concrete

Song Lu [a,*], Jin-Yu Xu [a,b], Er-Lei Bai [a], Xin Luo [c]

[a] *Department of Airfield and Building Engineering, Air Force Engineering University, Xi'an 710038, China*
[b] *College of Mechanics and Civil Architecture, Northwest Polytechnic University, Xi'an 710072, China*
[c] *Construction Engineering Planning & Design Institute, Logistic Support Department, Central Military Commission, People's Republic of China, Beijing 100036, China*

HIGHLIGHTS

- Flexible particles concrete and rigid particles concrete are prepared.
- Energy dissipation characteristics of different particles concrete are studied.
- Φ100 mm SHPB apparatus was improved by using the pulse shaper technique.
- As a new material, the development prospect has been discussed.

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ABSTRACT

Expanded polystyrene concrete (flexible particles concrete) and alumina hollow ball concrete (rigid particles concrete) with volume content of 0%, 10%, 20%, 30%, 40% and 50% were prepared. In this paper, energy dissipation characteristics of different types of particles concrete were investigated, while the mechanism was analyzed. Impact compression experiments were carried out by a Φ100 mm split Hopkinson pressure bar (SHPB) apparatus which was improved by pulse shaping technique. Main conclusions are as follows: As for flexible particles concrete, the adding of flexible particles with volume content of 20% can effectively improve specific energy absorption and energy absorption of concrete, and the rigid particles concrete achieve the best energy absorption performance at the volume content of 40%. Through the analysis of fracture morphologies, the damage degree of the ordinary concrete and particles concrete increase as the incident energy change rate increases. The energy absorption performance of flexible particles concrete with volume content of 20% is better, compared with rigid particles concrete with volume content of 40%.Therefore, with volume content of 20%, the flexible particles concrete has characteristics of the most excellent energy dissipation and a wide development prospect in engineering application.

1. Introduction

Concrete is one of the largest inorganic construction materials in the world, which is widely used in civil defense projects. Aiming at weakening explosion wave and absorbing the explosion energy, stratified structure is a common form of civil defense project. The design of the distribution layer is the key technology, in which the materials should possess many important characteristics, namely excellent energy absorption property. A large number of studies have shown that, importing intentionally a large number of pores into concrete in some way will contribute to the energy absorption property [1–3].

There are various means of incorporating pores in the matrix (e. g, bottom ash aggregates [4], carbon felts [5] and binder gel [6]). According to the mechanical properties of particles, particles can be divided into flexible particles and rigid particles. Expanded polystyrene (EPS) is a kind of lightweight polymer material with horniness close-cell structure and strong deformation capacity, which shows a long yield plateau under the compression [7,8], indicating that EPS is a kind of typical flexible particle material. In recent years, an increasing number of experimental research works [9–13] have been carried out on the performance of concrete added with EPS. The preparation technology of EPS concrete was studied [14], while the influence of particle size on the mechanical performance of EPS concrete was also explored [15–19]. In addition, some researchers tried to study on the energy absorption performance of EPS concrete under quasi-static or low-velocity impact

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* Corresponding author.
E-mail address: lusong647@163.com (S. Lu).

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loads [20,21]. However, these researches mainly focus on the preparation technology, deformation ability and compressive strength of EPS concrete under quasi-static loading [22–24]. Limited research has been carried out on the mechanical behaviors of EPS concrete under high strain rate loading. Alumina hollow ball [25] is a kind of typical rigid particle material, which has many advantages of large internal space structure, thin shell, and excellent physical and chemical properties. Currently, researches on alumina hollow ball concrete mainly focus on the preparation method and quasi-static performance [26–28]. The study conducted by Li et al. [26] introduced a scientific way to prepare reinforced porous concrete added with alumina hollow ball. Moreover, Su, et al. [27] investigated the effect of amount of alumina hollow ball on the properties of porous ceramics, including microcellular structure, thermal property and compressive strength. Furthermore, Maria, et al. [28] analyzed the influence of hollow sphere size and matrix strength on the quasi-static performance of alumina hollow ball composites. Since concrete is a typical rate-sensitive material, its mechanical behavior and failure mechanism change significantly as the loading rate increases [29]. As a result, it is significant to research on the mechanical performance of particles concrete under impact loading. Particles concrete possess a large amount of hole-like structure which will deform or crush under impact loading. The particles added into concrete matrix will reduce the brittleness and improve the energy absorption [30]. Flexible particles can be extruded, leading to deformation, such as expanded polystyrene (EPS), while rigid particles such as alumina hollow ball, will crush because of extrusion. Hence, it is necessary to study on the influence of particles with different mechanical properties on the dynamic and static mechanical properties of concrete. Not only will the study help to the performance optimization of particles concrete, but also guide the design of the distribution layer in a better way. Moreover, it will promote the development of civil defense project.

C60 ordinary concrete was adopted as a matrix, while EPS or alumina hollow ball were incorporated in the matrix by replacing certain volumes of sand and stone by simultaneously maintaining constant volume ratio between sand and stone at each step. In the laboratory test, EPS concrete or alumina hollow ball concrete with volume content of 0%, 10%, 20%, 30%, 40% and 50% were prepared. Impact compression experiments were carried out by a Φ100 mm split Hopkinson pressure bar (SHPB) apparatus, which was improved by pulse shaping technique, achieving mechanical parameters under the condition of different strain rates. Thereby, the energy dissipation properties were analyzed on the basis of the contrast between EPS concrete and alumina hollow ball concrete.

2. Basic situation of test

The raw materials of C60 ordinary concrete mainly include: cement, fly ash, sand, stone, superplasticizer, silica fume and water.

The basic property of each composition is listed as follows: 42.5R ordinary Portland cement; grade I fly ash (low calcium); medium sand: fineness modulus is 2.78, grading qualified, density is 2.63 g/cm^3, bulk density is 1.50 kg/L, silt content is 1.1%; stone: particle size is $5 \sim 20$ mm, density is 2.70 g/cm^3, bulk density is 1.62 kg/L, silt content is 0.2%; superplasticizer: water reducing rate is 20%; silica fume: average particle size is $0.1 \sim 0.15$ μm, specific surface area is $15 \sim 27$ m^2/ g, SiO_2 content is $85\% \sim 95\%$.

With the quality of 386 kg cement, 214 kg fly ash, 30 kg silicon ash, 6 kg super plasticizer, 184 kg water, 599 kg sand and 1070 kg stone per 1 m^3, the mixture ratio of C60 ordinary concrete can be represented.

As the representative of flexible particle, EPS should be mixed into the concrete by following steps to improve concrete adhesion with cement paste and prevent segregation and layering: first, mix fly ash, silicon ash, admixture, part of cement and water together to form a mortar with low water-cement ratio (30 s); second, add EPS (30 s); third, the rest of the water and cement, and mix for 30 s, after which add sand, stone (120 s), mix into uniform mixture.

Alumina hollow ball was used as representative of rigid particles with basic characteristics of follows: four groups of particle size (0.2–1.0 mm, 1.0–2.0 mm, 2.0–3.0 mm, 3.0 mm–5.0 mm), $Al_2O_3 > 99\%$, compressive strength at room temperature > 8 MPa. The following mixing sequence of alumina hollow ball concrete was required: 1) firstly mix superplasticizer and water into a solution identified as F in advance. 2) Mix fly ash, silica fume and half of the cement together into a mixing ash (30 s). 3) Add 3/4 of F solution, and then form a mixing mortar (30 s). 4) Add the sand, the stone, a quarter of F solution and half of the cement, mix for 120 s. 5) Pour the mixture out from the machine, sprinkle alumina hollow balls by manual mixing.

According to the requirements of the test, fresh concrete was poured into the mould. Previously, the bonding of mixture and mould should be prevented by cleaning up the mould with a layer of mineral oil coated on the inner surface, while the water loss of surface can be prevented by wrapping the mould with plastic. After 28 d standard curing ($T = 20 + 2$ °C, relative humidity RH > 95%), the cylindrical specimens were used in the dynamic compression tests, which should subject to grinding processing to control its width and surface flatness with the size of Φ95 x 50 mm, as shown in Fig. 1.

3. Impact compression

3.1. Impact compression test method

SHPB [31,32] has become popular in being used for investigating materials under compression at high strain rates, such as ceramic [34], rock [35] and other nonmetallic materials. A 100-mm-diameter SHPB was used for testing, as shown in Fig. 2.

This apparatus consists of main body, energy source and measurement systems. Main body mainly contains launch tube, striker bar, incident bar, transmission bar and energy absorbing setup. The air compressor and pressure vessel are contained in energy source system. Measurement system contains velocity and dynamic strain measurement setup. The striker, incident and transmission bars are made of 48CrMoA and have Young's modulus of 210 GPa, density of 7850 kg/m^3, and wave velocity of 5172 m/s.

Beyond that, the propagation process of stress pulse in the SHPB apparatus can be described as follows: the impact of striker bar at the free end of incident bar generates an elastic strain wave, namely the incident pulse, which can propagate through the incident bar, then reaches the incident bar-specimen interface. While a part of the incident pulse is reflected back into the incident bar, the rest propagates through the specimen and generates the transmitted pulse in the transmitted bar.

3.2. The validity of test

In this paper, the test was validated by the stress equilibrium and nearly constant strain rate loading. Moreover, the pulse shaping technique [34,36] was applied to the SHPB apparatus to improve the accuracy of the testing of dynamic mechanical properties. In addition, the incident pulse was shaped from square to half-sine-like which can effectively reduce the dispersion effect [37],