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Experimental study of rock-sheds constructed with PE fibres and composite cushion against rockfall impacts

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ABSTRACT

To improve the impact resistance of rock-sheds, polyethylene (PE) fibres and expandable polyethylene (EPE) foams are proposed for structural construction. With PE fibres added into the matrix, the ductility and the impact resistance ability of concrete can be enhanced. Moreover, to reduce the dead load and impact load, EPE foam is utilized to replace some sand layers, forming a composite cushion. A series of large-scale rockfall impact experiments were carried out on four prototype models. Under a low- and medium-impact energy, compared to the traditional sand cushion, the composite cushion was more favoured to reduce the impact loading and was more suitable to resist multiple impacts. With the addition of fibres, the integrity of the concrete matrix was improved. The fibre concrete had a better energy dissipation capacity than that of the plain concrete. In addition, more cracks occurred in the plain concrete. When subjected to high energy, the reinforced concrete model was damaged with a large deformation and many fragments. However, the maximum deformation of the PE fibre-reinforced concrete model was very small, and almost no spalling or fragments were found. These results indicate that when constructed using PE fibres and EPE foams, the capability to resist the impact loading of rock-sheds can be significantly improved.

1. Introduction

As one of the most common hazards, rockfall is an extremely rapid process, and it is difficult to take evasive action. Due to the high risk of damage to infrastructure and the safety of peoples' lives, some necessary protective measures should be considered [1]. Currently, rock-sheds have been widely applied in small endangered zones. To improve protection against higher impact energy, a concrete slab is always covered with a cushion layer that acts as a shock absorber. Apart from dissipating the impact energy, the cushion layer can also distribute the impact contact stresses, decrease the peak loading, and increase the duration of the impact. All these functions favour the protection of the rock-sheds. Therefore, the capacity of rock-sheds to resist rockfall impacts depends on the properties of the structure itself and the cushion layer [2].

Unlike reinforced embankments, current research on rock-sheds is with respect to the impact performance, rather than the block trajectory control [1]. To improve the impact resistance of rock-sheds, prototype experiments are important and necessary. Some researchers have conducted several prototype experiments to study rock-shed structures by dropping a block of a certain weight and height on concrete slabs or cushion layers. Kishi et al. [3] carried out prototype impact tests by using two types of prestressed concrete (PC) rock-shed frames: inverted L frames and fully rigid frames. The results indicated that compared to the inverted L frames, the fully rigid frame could effectively disperse the sectional forces over the entire structure and had better resistance to impact loads. Zineddin and Krauthammer [4] designed rock-slabs with different amounts of steel reinforcement to investigate the dynamic response of reinforced concrete (RC) slabs. It was shown that the reinforcement quantities affected the slab failure modes. Mougin and Delhomme et al. [5–7] proposed a new rock-shed protection design with the concept of a structurally dissipating rock shed (SDR), which mainly utilized specially designed supports. These supports were made of steel and absorbed the impact energy through plastic damage deformation. Experiments were conducted on a one-third scale model of an actual SDR. Based on these experiments, the energy absorption effected by this type of RC slab and the punching damage of SDR was studied. Maegawa et al. [8] investigated the rockfall galleries constructed with concrete-filled tubular steel (CFT) beams. The test results showed that a CFT structure had great deformation and energy

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absorption capacity under impact loading. Konno et al. [9] designed a steel-concrete composite structure for a rockfall protection gallery. It was confirmed that this type of structure possessed high impact resistant capacity and ductility, retaining an impact-resistant safety margin greater than that of an RC/PC type rock-shed.

In addition to the stiff components of the impact resistance systems mentioned above, some other experimental campaigns have also been carried out on cushion layers. Calvetti et al. [10] performed four series of tests by letting a reinforced concrete boulder fall on absorbing soil strata. The influence of the soil's geometrical and mechanical properties was studied. Labiouse et al. [11] also conducted an experimental study to better understand the damping abilities of a soil cushion and to estimate the impact effect. In their experiments, different thicknesses of cushion layers and soil materials were considered. Kawahara and Muro [12] discussed the influence of sand density and cushion thickness on rockfall based on laboratory tests. Schellenberg et al. [13] designed special cushion systems consisting of high-tensile steel wire mesh and cellular glass. A thicker cushion layer can resist a higher impact energy. However, because of the relative high density of soil, thicker soil cushions lead to higher dead loads and less safety margins of rock-sheds under the impact loads. Kishi et al. [14] proposed a three-layered absorbing system, which was composed of an EPS (expanded polystyrene) layer, a reinforced concrete core slab and a sand cushion. In experimental research, the maximum transmitted impact force could be substantially reduced compared to a thick sand cushion.

In conclusion, currently, most research still remains in the study of structural types and traditional RC concrete. For rock-shed structural construction, although concrete has been widely used, its brittle property and weak tension strength restrict its utilization under dynamic loading. With the development of material science, some novel materials provide promising potentials in structural construction and could be applied to improve the impact resistance of rock-sheds. When subjected to impact loading, the impact resistance of rock-shed structures includes the performance before and after the damage. As the sudden collapse of rock-sheds should be avoided after damage, the excellent ductility of the structure is very important. Unfortunately, previous related research is very rare. To optimize the performance of concrete, especially in the stage of the post-cracking phase, fibre materials are added to the concrete matrix. Research suggests that the addition of fibre materials leads to substantially improved structural ductility, better hysteretic response under a cycle load, improved resistance of the concrete cover to spall, improved shear resistance, and an overall improved energy absorption capacity of the structure [15–19]. These excellent properties are very suitable for fibre concrete to be applied in impact resistant structures. Scholars have also conducted many studies on the dynamic properties of different types of fibre concrete. For example, Yoo et al. [20] investigated the effect of the reinforcement ratio on the flexural behaviour of fibre-reinforced concrete beams under impact loading. Semsi et al. [21] designed 10 different types of steel fibre concrete to identify the mechanical losses in terms of compressive strengths and splitting tensile strengths following the effects of impact. Wang et al. [22] studied the behaviour of coconut fibre reinforcement concrete under drop weight impact loading. They evaluated the effect of height on the maximum compressive stress and the damage pattern in the repeated impact test. Verma et al. [23] carried out some experiments to understand the low-energy impact response of ultra-high performance concrete panels with different fibre volumes, thicknesses of panels and impactor energies. Due to financial and technical restrictions, prototype experiments on fibre concrete are rare. Most present impact experiments are limited single components such as a beam or slab. The size of the testing specimen and impact energy are both relatively small. On the other hand, testing results can only reflect the dynamic response of a single structural component rather than a whole structure. Due to the corrosive nature and high cost of steel fibre, many other fibre materials, such as glass fibres and synthetic fibres were studied [24,25]. Among these fibres, polyethylene (PE) fibre not only can improve the ductility and the impact resistance ability of concrete but also has outstanding durable characteristics. However, little work has been conducted concerning the PE fibres mixed with concrete. Therefore, in this paper, large-scale rock-shed model experiments were conducted to investigate the superior characteristic of PE fibre reinforcement concrete under impact loading.

Apart from improving the performance of the structure itself, cushion layers can also be utilized. At present, the material involved in most cushion research is still sand soil. As another effective protection measure against rockfall, reinforced embankments have obtained technological developments. Though various experiments (including real-scale and small-scale) have been conducted to investigate the response of embankments to impact load, the materials used to act as an energy dissipater are still limited to soil, geotextile, gabion cages, geocells and recycled tires [26,27]. Therefore, there are rare researches on the cushioning materials with a low density and a perfect energy dissipation ability. Unlike sand soil, foams have some attractive features, such as low density and good energy absorption capabilities. From the packaging of goods to military devices, from civil to aerospace engineering, foams have been widely used [28,29]. In this paper, foam material is considered to replace some sand soil, forming a composite cushion layer to resist rockfall impact. At present, many studies are focused on the properties of foams. Krundaeva et al. [30] and Chen et al. [31] investigated the influence of the strain rate on the stress-strain curves of expanded polystyrene (EPS), considering different temperatures and densities. Ozturk et al. [32] obtained the stress–strain curves under multiple compressive loading and unloading. Fernandes et al. [28] and Ozturk et al. [33] performed guided drop tests to study the response characteristics of polymeric foams subjected to multiple dynamic loading. Currently, foam testing is limited to the laboratory. Large-scale experiments where foams act as a shock absorber are rare. Moreover, most research is on EPS material. When rockfall occurs frequently, rock-sheds will be subject to multiple rockfall impacts. Therefore, the durable ability to bear continuous impact loading is very important. EPS can dissipate large amounts of impact energy showing low reaction forces. However, after impact, EPS deforms permanently without elastic recovery. Its energy absorption capability is significantly decreased, and it cannot continue resisting multiple impacts. Thus, in the energy absorbing application where foam is loaded only once, EPS material is a good selection. In case of a subsequent impact, such as rockfall, EPS is not suitable. Therefore, when choosing a foam material to form composite layers, the characteristics of rockfall should be considered [34]. Besides EPS, there are several other types of foams with a low density and good cushion performance, such as expandable polyethylene (EPE), expanded polyolefin (EPO) and expanded polypropylene (EPP). Among these foams, the impact resistance performance of EPP is the best. However, its price is very high which has limited its wide application in engineering. The performance of EPO falls in between of EPE and EPS. And the price of the three types of foams is similar. With regard to cushioning performance, EPE is better than EPO and EPS. In summary, through the comparison of different foams, EPE is proposed to replace part sand soil to form a composite cushion layer. Currently, there is little research on the dynamic performance of EPE. According to the previous research by authors [35], for a first impact, the mechanical behaviour of EPE and EPS is quite similar. Nevertheless, because of its good resilience characteristics, EPE foam owns a perfect multi-impact protection property. More important, compared to EPS, EPE is environmentally friendly.

Given that the capacity of rock-sheds to resist impact loading can be improved, reinforcement materials and cushion materials are introduced to rock-shed structures and cushion layers respectively. In this paper, a fibre-reinforced concrete (FRC) rock-shed covered with composite cushion layers was designed, as well as three other types of rock-sheds. A series of large-scale rockfall impact experiments was carried on the four prototype models. Finally, the experimental results of the resisting behaviours of different models to rockfall impact were studied