Construction and Building Materials 172 (2018) 660–669

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mechanical properties and constitutive equations of crumb rubber mortars

Wei-Jie Song [a,b], Wei-Guo Qiao [a,b,*], Xu-Xu Yang [a,b], Deng-Ge Lin [a,b], Yan-Zhi Li [a,b]

[a] *Shandong Provincial Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology, Qingdao 266590, China*
[b] *College of Civil Engineering and Architecture, Shandong University of Science and Technology, Qingdao 266590, China*

HIGHLIGHTS

- A series of triaxial tests were implemented to exam the mechanical behavior of crumb rubber mortars.
- The necessity of incorporating the influence of the damage threshold into the damage evolution model was discussed.
- A damage constitutive model of crumb rubber mortars was established.

ARTICLE INFO

Article history:
Received 4 November 2017
Received in revised form 14 March 2018
Accepted 29 March 2018

Keywords:
Crumb rubber mortars
Damage threshold
Microcosmic element strength
Constitutive model
Strain softening

ABSTRACT

There will be a lot of pollution in the process of production and degradation of rubber. It is imperative to recycle rubber in order to build a green and saving environment. A new kind of mortar with rubber particles is an effective way to reuse the used rubber products. The crumb rubber mortar effectively resist external stress through its own deformation. Therefore, it is of practical significance to study the strength behavior of crumb rubber mortar. The stress-strain curves of crumb rubber mortars with 5 different rubber contents under a triaxial stress condition are obtained through laboratory testing. The internal variation law of the elastic modulus, Poisson's ratio and damage variable are analyzed, and the necessity of incorporating the influence of the damage threshold into the damage evolution model is discussed. According to a rock damage model based on Lemaitre's strain equivalence theory and the introduction of the damage threshold based on the traditional Weibull random distribution, the damage constitutive model of crumb rubber mortars under the influence of the damage threshold is established by considering two factors. The method of determining the model parameters is presented. The model can describe the entire process of strain softening and deformation of crumb rubber mortars for various levels of rubber content or confining pressure. The model can also fully reflect the linear elastic deformation characteristics of rock under small deformations and the nonlinear mechanical behavior after the peak strength is exceeded. The model is particularly suitable for describing the complex stress states in the field of underground engineering, and it provides a reference for the design of supporting structures. Finally, by comparing the measured results of three-axis compression tests of crumb rubber mortars with various rubber contents, the rationality of the model is verified.

1. Introduction

With the rapid development of the global transportation industry, the number of used automobile tires has increased dramatically. Rubber, the main component of tires, features a strong thermal degradation resistance; thus, the efficient recycling of waste rubber has become a scientific and engineering challenge that requires urgent solution [1,2]. In 2015, countries at the Paris Climate Conference agreed on an energy consumption and carbon emission reduction strategy and advocated policies to conserve resources and protect the environment. At present, the civil engineering materials industry is focused on the efficient use of renewable materials and has advocated for green development. To effectively improve the physical and mechanical properties of mortars and improve its ductility and compressive deformation capacity, rubber particles can be effectively combined with cement and sand to form crumb rubber mortars. In this way, resources can

---

* Corresponding author at: Shandong Provincial Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology, Qingdao 266590, China.

E-mail address: Qiaowg1@163.com (W.-G. Qiao).

https://doi.org/10.1016/j.conbuildmat.2018.03.263
0950-0618/

be recycled to promote the sustainable development of nature, the economy and society in general. Therefore, it is necessary to systematically study the mechanical properties of crumb rubber mortars [3–5].

Crumb rubber mortars have been widely used in the fields of building construction, road construction and underground engineering. In particular, crumb rubber mortars can be introduced into highways, high-speed railways, and airport pavements. Furthermore, crumb rubber mortars have been used as a structural material to enhance the dynamic performance and seismic performance of concrete structures [6,7]. Scholars worldwide have conducted substantial experimental research on the mechanical properties and durability of crumb rubber mortars and have achieved a series of valuable results [8–10]. For example, Li et al. used various content and sizes of rubber particles filling high-strength concrete (RHSC) to conduct mechanical experimental research [11]. The results showed that adding rubber powder can reduce the strength of high-strength concrete, increase energy absorption capacity, reduce brittleness, and increase the ductility of high-strength concrete. Shen et al. used scanning electron microscope (SEM) to observe polymer–rubber aggregate-modified porous concrete [12]. Their study found that the interfacial transition zones between the rubber and cement slurry were enhanced by the polymer and that the polymer films in the cement hydrate and rubber particles lay in a staggered distribution, increasing the flexibility of the crumb rubber concrete (CRC). By changing the volume ratio of the rubber particles in crumb rubber mortars, Khaloo et al. found that the brittle behavior of rubber granule concrete decreases as the rubber content increases and that its strength and tangential elastic modulus are greatly reduced [13]. Liu et al. studied the fatigue properties of standard crumb rubber mortar samples with 60 different rubber contents [14]. The results showed that under certain stress levels, the fatigue life and dynamic strain of crumb rubber mortars are higher than that of ordinary concrete. Li et al. conducted uniaxial compression tests on rubber concrete (RC) with various rubber volume contents and particle sizes [15]. A uniaxial compression constitutive model of low volume RC was established and optimized. Zhang et al. used acrylic acid (ACA) and polyethylene glycol (PEG) to treat rubber particles [16]. The results showed that relative to unmodified RC, the compressive and flexural strengths of modified rubberized concrete (MRC) with 10% rubber particle content can be increased by 25.9% and 26.4%, respectively. Su et al. used concrete particles of various particle sizes in concrete instead of 20% of natural fine aggregate in volume [17]. The results showed that rubber aggregates with smaller or continuously graded size have relatively high strengths and low water permeabilities. Feng et al. conducted uniaxial compression tests on CRC [18]. The experimental results showed that the uniaxial compressive strength of CRC decreases as the colloidal rubber content increases, and a formula for the estimation of CRC strength was also proposed. Osório et al. [19,20] analyzed the effect of rubber content on the mechanical properties and porosity of cement mortars and focused on the interrelation of strength/porosity in the rubberized cement and mortars. Through SEM micrographs of the fractured surface of the rubberized cement mortar, spheroidal and irregular porous morphologies were clearly observed.

By analyzing the above documents, research on RC focuses on strength, brittleness and durability. Research on the mechanical properties and constitutive model of crumb rubber mortars is relatively limited and confined to uniaxial compression at present. However, in the field of underground engineering, crumb rubber mortars as a support structure are often placed under a triaxial stress state. Therefore, to determine whether crumb rubber mortars can be used as a structural material, it is important to determine the stress-strain relation of crumb rubber mortars under the triaxial stress state.

In this paper, a series of triaxial tests have been carried out to exam the strength and deformation behavior of crumb rubber mortars with 5 different rubber proportions. The necessity of incorporating the influence of the damage threshold into the damage evolution model has been discussed. Moreover, a constitutive model of triaxial compression for crumb rubber mortars has been proposed that can be used to predict their stress-strain response. And the method for determining parameters of the constitutive model is also described. Through comparison with the experimental results, the rationality of the model was verified. This study is intended to promote the application of crumb rubber mortars in underground engineering stabilization.

2. Experimental study of physical mechanics

2.1. Materials and mixing ratio

The chemical composition and physical and mechanical properties of P.O42.5-grade Portland cement produced in Ji'nan are shown in Tables 1 and 2. The fine aggregate includes sand and rubber particles. The sand used is local river sand, with a maximum particle size of 5 mm and a continuous gradation. The particle size of the rubber is 6–8 mm, and the apparent density is 1200 g/cm^3. Recycled used rubber products were pre-treated, including sorting, removal of impurities, cutting, cleaning, drying and other processing procedures. In the end, rubber particles with pure color, uniform particles, and qualified technical indicators were selected as test materials. Additives include a water reducer and binders. The water reducer is naphthalene-reducing superplasticizer DC-WR1 with a water-reducing rate of 15%–25%, with the appearance of yellowish brown powder. The binder adopted DC-W10 polyacrylate emulsion. The test water is ordinary tap water. The specific experimental materials are shown in Fig. 1.

A mixing ratio of M-0% is used as the control group, the ratio of water to cement (W/C) is 0.35, and the ratio of sand to cement (S/C)

Table 1
Chemical composition of P.O42.5-grade ordinary Portland cement.

CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	Na_2O	K_2O	Ignition Loss
63.57	20.97	5.21	5.03	2.18	1.31	0.35	0.13	1.25

Table 2
Physical and mechanical properties of P.O42.5-grade ordinary Portland cement.

Specific surface area (cm^2/g)	Density (g/cm^3)	Setting time		Compressive strength (MPa)	Flexural strength (MPa)
		Initial (min)	Final (min)		
3450 ± 50	3.00 ± 0.02	120 ± 5	310 ± 10	48.5 ± 2.0	9.2 ± 0.5