Ultrasonics 92 (2019) 79–92

Contents lists available at ScienceDirect

Ultrasonics

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

Aggregate gradation effects on dilatancy behavior and acoustic characteristic of cemented rockfill

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ARTICLE INFO

Keywords:
Cemented rockfill
Gradation
Dilatancy
Ultrasonic
Acoustic emission

ABSTRACT

Investigating the effect of the aggregate gradation on the material properties of cemented rockfill is significant for the green mining, economic benefit and engineering safety. Consequently, the ultrasonic test, uniaxial compression experiment and acoustic emission (AE) monitor on cemented rockfill were carried out, for which the aggregate satisfied Talbot gradation. The dilatancy behavior and AE characteristic of cemented rockfill under load were investigated. The damage in the internal structure under compression was revealed by the deformation and AE signals of cemented rockfill. The effect of the Talbot index on the ultrasonic pulse velocity (UPV) and the strength parameters such as stress of dilatancy onset and uniaxial compressive strength (UCS) of cemented rockfill was analyzed. The mechanical properties of cemented rockfill materials were evaluated by the establishment of the relation between the UPV and the strength parameter. The results show that The difference between the stress of dilatancy onset and the UCS, the deformation performance and the activity of AE signals during dilatancy are positive correlated with the Talbot index of aggregate in cemented rockfill. The relation between the UPV and the strength parameters (stress of dilatancy onset and UCS) of cemented rockfill can be characterized by the positive linearity, and the UPV is also suitable for characterizing the stress of dilatancy onset of cemented rockfill material. The cubic polynomial is more suitable for describing the relations between the parameters of strength and UPV and the Talbot index of aggregate than the quadratic polynomial, and the Talbot index with optimal aggregate gradation reflected the maximum strength of cemented rockfill material should be around 0.45–0.47.

1. Introduction

Cemented rockfill is a kind of filling materials, a relatively new green material, typically uses waste rock, construction waste and other waste solid materials to crush and screen, then bonds with cementing materials and water to form [2,16,46,63]. The filling mining with cemented rockfill is a green mining technology, not only solves the waste of land resources and the pollution of water resources caused by the waste rocks in stope, but also effectively decreases the strata movement and surface subsidence during underground mining [19,56,54,55,71,88,89,87,93]. Therefore, it creates great benefits in terms of economy, environment and engineering safety.

During mining and subsequent service, the backfill structure must remain stable. Consequently, its mechanical stability is the most important quality criterion of material properties [14,31,69]. At present, the researches about the cemented filling materials mainly focus on the selection and proportioning of cementing materials and the influencing factors on its mechanical properties [66,72]. Therefore, lots of scholars studied the effects of the type and content of cementing material on the mechanical properties of cemented filling materials [1,25,62,29,30,32,82]. Due to the influence of hydration condition on the bonding process of cementing material, some researches discussed the relations between the factors such as hydration temperature, curing temperature and curing time and the mechanical properties of cemented filling materials [18,33,37,39,40,61,64,84]. In addition, other researchers found that some additives such as alkaline mineral, wood, consolidation agent, fiber and nanomaterials can promote the hydration process of cementing material. So these additive materials were appropriately mixed in the cemented filling materials to improve its mechanical properties [17,47,20,21,23,35,65,48,51,50,49]. However, the

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https://doi.org/10.1016/j.ultras.2018.09.008
Received 8 May 2018; Received in revised form 2 September 2018; Accepted 19 September 2018

Nomenclature

List of symbols

AE	acoustic emission
c	peak point
cc	initial point of elastic deformation
cd	dilatancy onset
ci	terminal point of elastic deformation
D	damage area
d	the size of particles
$d_{\max}$	the maximum size of particles
m	mass of cementing material
M	the mass of the particles sizes below or equal to d ratio to the mass M_t of total particles mass, $M = M_t\left(\frac{d}{d_{\max}}\right)^n$
M_t	the total mass of particles
$M_{d_1}^{d_2}$	the mass of particles size in the interval $[d_1, d_2]$, $M_{d_1}^{d_2} = \left[\left(\frac{d_2}{d_{\max}}\right)^n - \left(\frac{d_1}{d_{\max}}\right)^n\right] M_t$
n	Talbot index
o	initial point of pore compaction
P	ratio $P = \frac{M}{M_t} = \left(\frac{d}{d_{\max}}\right)^n$
UCS	uniaxial compressive strength
UPV	ultrasonic pulse velocity
v	content of distilled water
XRD	X-ray diffraction
ε_1	axial strain
ε_3	circumferential strain
ε_v	volumetric strain
σ_1	axial stress
σ_{1c}	uniaxial compressive strength
σ_{1cd}	stress of dilatancy onset

above contributions on the cemented filling materials mainly focus on the strength characteristics, the dilatancy behavior is rarely investigated. In fact, from the once and again disasters in geotechnical engineering, it is easy to find that the cracks have fully developed in the internal structure of geotechnical materials before peak strength, that is, the dilatancy [75,77]. The unstable propagation of cracks in the dilatancy stage brings great hidden dangers to the engineering. As a result, it is important to explore the dilatancy behavior of cemented rockfill materials to improve the stability of backfill [53].

The cemented rockfill is a porous medium material composed of three parts of aggregate, cementing materials and pores [41]. The cementing materials have a great influence on the mechanical properties of cemented filling material [83]. However, the type, amount and obtaining method of cementing materials in actual projects are constrained by engineering conditions and engineering economic benefits [57]. For the control of pores in the backfills, it mainly depends on the filling technology in the stope and the contact difficulty between the cemented rockfill and the goaf roof [59]. At present, the cemented rockfill with the ratios of 1:2 to 1:12 are generally applied in engineering, which the ratio is the mass ratio of cementing material to aggregate [58]. That is, the aggregate accounts for at least 66% of cemented rockfill. Thus, the effect of the aggregate on the mechanical properties of cemented rockfill can't be ignored, especially for the physical and chemical properties of the aggregate and its spatial distribution in the backfills [85]. Kesimal et al. [45], Fall et al. [26] and Benzaazoua et al. [8] systematically studied the influences of the type and content of aggregate on the strength characteristics of cemented filling materials, including the early strength, late strength and long-term strength. Table 1 is the main material composition of several kinds of aggregate given by Benzaazoua et al. [8]. It believed that the strength of cemented paste backfill is negatively related to the content of sulfur in the aggregate. And it pointed out that the solid waste containing high sulfide must be desulfurized. Ke et al. [42] discussed the effect of the fineness of aggregate on the transportability and strength of cemented paste backfill. It considered that the increase in the fineness of aggregate is detrimental to the workability of cemented filling material, and its fluidity is negatively correlated with the particle fineness. However, the increase of fineness can improve the strength characteristic of cemented filling material. In contrast, Fall et al. [28] obtained the results that the medium fineness of aggregate is more conducive to the strength of cemented paste backfill. When the fine particle content reaches 35–55%, its strength remains essentially constant or begins to decrease with the decrease or increase of particle fineness. Consequently, in the effect of the aggregate distribution on the mechanical properties of cemented filling materials, the difficulty in quantifying the particle size distribution and the diversity of test conditions cause the huge differences in research results [86,4,60].

At this point, the effect of the spatial distribution of aggregate on the material properties of cemented filling material is gradually valued. Börgesson et al. [9] considered that the particle size distribution of aggregate seriously affects the homogeneity of cemented filling material, which resulted in the difference on its mechanical properties. Gautam et al. [36], Kesimal et al. [44], Sari and Pasamehmetoglu [68], and Bosiljkov [10] obtained the optimal distribution of particles in cemented filling material through experiments. As the results, the strength of cemented filling material with the optimal gradation is at least 10% higher than ungraded or other graded cemented filling material. It also improves the resistances of frost and salt [52], and with lower water requirement in cemented filling material production process [91,90]. It can be seen that the optimization on the particle size distribution of aggregate can improve the pore structure of backfill [43]. It enhances the strength characteristics of cemented rockfill by strengthening the interlaced framework structure of backfill. However, the aggregate with multiple particle sizes easily construct a high-dimensional parameter space, which greatly effects on the material properties of cemented rockfill. For example, for the aggregate with six particle size intervals of (0-d_1), (d_1-d_2), (d_2-d_3), (d_3-d_4), (d_4-d_5), and (d_5-d_6), it is necessary to seek the optimal value of the strength parameters of cemented rockfill in the six-dimensional space $[Y_1{:}Y_2{:}Y_3{:}Y_4{:}Y_5{:}Y_6]$, which easily results in the curse of dimensionality [74]. Therefore, the suitable gradation function of particle size to characterize the aggregate distribution should be established, and the optimization on the distribution of particles in high-dimensional space can be obtained according to that universal function. It is really significant both in theory

Table 1
Material composition of aggregate by total dry weight (wt.%) [8].

Sample	S	Ca	Si	Al	Mg	Fe	Cu (ppm)	Zn (ppm)	Pyrite
A1	32.2	1.07	10.12	2.630	0.21	26.8	1870	45,600	60.6
A2	24.4	0.99	15.7	4.870	0.35	20.6	0.24	2.1	42.4
B	15.9	1.44	15.3	4.065	2.695	20.7	1108	1795	29.8
C	5.2	1.17	26.29	5.640	0.57	5.13	30	149	9.75