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Mechanical performance and ultrasonic properties of cemented gangue backfill with admixture of fly ash

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ABSTRACT

Cemented gangue backfill (CGB) is prepared by mixing cement, coal gangue and water. Fly ash from the combustion of coal is commonly utilized as admixture to improve the mechanical performance and fluidity of CGB, as well as to reduce cost of preparing CGB. Uniaxial compressive strength (UCS) is one of the most commonly used indicators for evaluating the mechanical performance of CGB. Ultrasonic testing, which is a non-destructive measurement, can also be applied to determine the mechanical properties of cementitious materials such as CGB. So this paper investigates the UCS and ultrasonic pulse velocity (UPV) of CGB prepared at different fly ash dosage (19, 20 and 21 wt.%) and solid content (76.5, 77.5 and 78.5 wt.%), versus curing periods of 3–28 days. The UCS and UPV values of CGB increase with increasing fly ash dosage and solid content. In order to find out the correlation between the UCS and UPV values of CGB, different types (linear, logarithmic, exponential and power) of curve fitting are conducted on the CGB samples made at different solid content. An exponential relationship with the correlation coefficient of 0.959 appears to exist between the UCS and UPV for CGB samples. This obtained exponential relationship is validated to be available by performing the *t*- and *F*- tests. The results acquired by this paper are capable of providing guidance for utilizing UPV test to estimate the strength of underground CGB structures.

1. Introduction

Underground mining is a significant way to extract mineral resources from earth, but in the meantime, plenty of solid waste (e.g., waste rock, tailings and coal gangue) and underground mined-out voids are created [1]. The discharge of tailings and coal gangue on ground may contaminate the environment or even become a potential hazard (e.g., acid mine drainage and spontaneous combustion of coal gangue heap), and the underground voids can result in land surface subsidence [2]. The rock in coal mines is relatively softer than that in other types of mines such as metal mines, so the problem of ground subsidence for coal mines is more serious. For instance, ground subsidence around the abandoned coal mines has become a social problem in Korea, which may prevent the government to build infrastructures across the mining area [3]. In Turkey, large coal pillars are left to prevent land surface from subsiding, which is unfavorable to the mining operations and coal production [4]. In addition, ground subsidence induced by coal mining has also become a serious concern in many other countries, such as America, Australia and China [5–7]. However, the aforementioned problems can possibly be solved by the technology of mine backfill, which generally transports and places backfill materials (including waste materials) into underground openings to control strata movement and surface subsidence. As to metal mines, cemented paste backfill (CPB), which is a mixture of dewatered tailings, water and binder (2–7% by weight usually), is a recently developed material utilized for backfilling these mines [8–14]. In comparison with CPB, cemented gangue backfill (CGB), which is prepared by mixing coal gangue, binder and water, is developed as the backfill material for coal mines.

The CPB technology has been successfully employed in underground metal mine operations and is being increasingly and intensively employed all over the world [15–17], while the CGB technology is less used. Fig. 1 schematically demonstrates the role of CGB in controlling roof settlement and ground subsidence in a coal mine.

Once placed underground, the plastic CGB behind the hydraulic support is required to harden quickly (since the hydraulic support needs to advance rapidly to keep high production efficiency), for letting the hardened CGB structure to play its role of supporting

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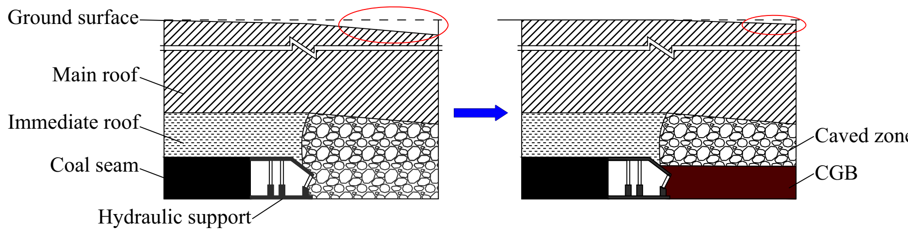

Fig. 1. Effect of CGB on controlling ground surface subsidence.

the soft overlying strata. Consequently, more binders are used for achieving higher strength in the CGB structure, and when necessary, some additives (such as hardening accelerating admixture) may also be added in. These operations will significantly increase the cost of preparing CGB mixtures, which somewhat limits the application of CGB technology for coal mine backfill. Nevertheless, with the increasing social concern on the problem of environmental pollution and ground subsidence induced by coal mining, the CGB technology that can both manage mine waste and control subsidence will be extensively utilized in future. As discussed above, mechanical performance is one of the most important parameters of a CGB structure. Triaxial compressive strength (TCS) and uniaxial compressive strength (UCS) are the two main criteria indicating the mechanical performance of a structure. In comparison with TCS test, UCS test is more convenient and cost saving, and can quickly determine the mechanical performance of a structure, such as rock [18], concrete [19], and CPB [20]. In addition, UCS test can also be incorporated into routine quality control programs at the mine [21]. As a kind of cementitious composites, CGB is similar with concrete and CPB in terms of mix matching, transporting and hardening. Hence, UCS test can also be applied for evaluating the mechanical performance of CGB.

As a type of non-destructive testing (NDT) method, ultrasonic technique is frequently used to estimate the strength of rock [22] and concrete [23–25], by measuring the ultrasonic pulse velocity (UPV) through these media. Yasar and Erdogan [26] have established a correlation between the ultrasonic properties and compressive strength of carbonate rocks. Ulucan et al. [27] have correlated the compressive strength of concrete with its UPV. As to CPB, Diezd'Aux [28] and Galaa et al. [29] have obtained various UPV values through CPB samples with different binder dosage (3–5 wt.%), but they have not used the UPV testing results to evaluate the strength of CPB. Consequently, Yilmaz et al. [30] have conducted a study to take advantage of the UPV measurement to predict the strength of CPB samples.

Although CGB is a kind of cement-based materials like concrete and CPB, it is still different from concrete and CPB in terms of the aggregate used. Therefore, the previously obtained connections between UPV and strength in concrete and CPB cannot be used directly for CGB. To date, there are no studies having reported the usage of UPV test to assess the mechanical performance of CGB, not to mention having established the correlation between the strength and UPV of CGB.

As a type of industrial by-product, fly ash can be added into CGB to improve its performance (stability and fluidity) as well as to lower the binder costs by partially replacing the cement [31,32]. In the present study, fly ash is used as a mineral admixture in CGB. The CGB samples studied are prepared at different fly ash dosages and water-to-cement ratios and subjected to UPV and UCS tests over 3–28 days of curing period. Effects of fly ash dosages and solid content on the UCS and UPV values of CGBs versus curing time are investigated. Relationship between the UCS and UPV values of CGB samples are established in an attempt to apply the UPV measurement to predict the strength of CGB.

2. Materials and methods

2.1. Coal gangue and fly ash

The coal gangue and fly ash samples used in this study are respectively obtained from a coal mine in the northwest of China and a power plant near the mine. The chemical properties of the coal gangue and fly ash samples are shown in Table 1. Fig. 2 presents the X-ray diffraction (XRD) testing results for the coal gangue and fly ash. According to the data from Table 1 and Fig. 2, contents of Al_2O_3 and SiO_2 contained in the coal gangue are respectively 23.43 wt.% and 41.68 wt.%, indicating that the coal gangue samples used in this test can be classified as argillaceous rocks (with Al_2O_3 of 15–30 wt.% and SiO_2 40–60 wt.%), which are suitable to make CGB mixtures. In addition, SiO_2 content in the fly ash is high (56.89 wt.%), which provides activity for the fly ash to participate in hydration. Table 2 and Fig. 3 give the particle size composition of the fly ash samples. Content of the fly ash with particle size smaller than 74 μm is determined to be 46.49 wt.%. It should be noted that for preparing CGB mixtures, the coal gangue should be crushed until the maximum particle size is smaller than 15 mm.

2.2. Preparation of CGB samples with admixture of fly ash

According to the mix proportion shown in Table 3, a total number of 60 CGB samples (there are 5 kinds of mixes, and each mix is in triplicate and cured for 4 kinds of periods) with admixture of different fly ash contents are prepared. The required amount of coal gangue, fly ash, cement and water are mixed and homogenized in a mixer (as shown in Fig. 4a) until obtaining the desired CGB mixtures. Afterwards, the produced CGB mixes are poured into curing cubes of 7 × 7 × 7 cm in length × width × height to form cubic samples. These samples are then cured in HSBY-60B standard curing chamber (Fig. 4b) at temperature of 20 ± 1 °C and for periods of 3, 7, 14 and 28 days.

2.3. UPV and UCS tests

After the specific curing periods (3, 7, 14 and 28 days), the CGB samples are subjected to the UPV tests according to ASTM C 597 [33]. By taking advantage of the ultrasonic pulse method, the

Table 1
Chemical composition of the coal gangue and fly ash used in the tests.

Chemical component	Al_2O_3	SiO_2	S	K_2O	CaO	TiO_2	Fe_2O_3	Total
Coal gangue (wt.%)	23.43	41.86	3.70	0.82	23.74	1.36	5.09	100
Fly ash (wt.%)	31.89	56.89	0.66	1.39	1.84	1.95	5.38	100