

*Supporting Information*

**Optimization of Controlled Low-Strength Material from Multi-Component Coal-based Solid Waste**

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## **Experimental Section**

### **CLSM mixing program**

In the experiment, a cement mortar mixer (Shanghai INESA Scientific Instrument, JJ-15) was used to add all the solid materials except the water-reducing agent, and the solids were stirred for 1 min without adding water at this time. Next, the mixed water was divided into two parts. One part was mixed with the water-reducing agent and added to the solid-state mixture first, which was stirred for 1 min. Finally, all remaining water was added and then the mixture was mixed for 1 min. After standing for 1 min, the mixture was mixed for another 2 min.

### **Characterizations**

Scanning electron microscopy (SEM) images were recorded using ZEISS Gemini 300 at an accelerating voltage of 2–3 kV. The laser particle size analysis test was carried out with a rotational speed of 2500 r·min<sup>-1</sup>. The solvent was ethanol when testing cement and deionized water was used for other samples. Different refractive indices were selected according to different samples.

### **Performance tests**

To evaluate the various properties of the CLSM mixture, a series of tests were carried out:

(1) The flowability was performed according to ASTM D6103-17 (Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)) (ASTM 2017). The flowability was measured using a cylinder with a diameter of 75 mm and a height of 150 mm.

(2) The bleeding test and fresh density test conformed to GB/T 50080-2016 (Standard for Test Method of Performance on Ordinary Fresh Concrete) (GB/T 2016). The freshly mixed CLSM was placed in a 1 L volumetric cylinder and covered with a layer of plastic wrap to ensure that the drained water did not evaporate. The excreted water content of the mixture was measured after 1 h and every 15 min thereafter until no more bleeding and the amount of bleeding was recorded. The bleeding was the ratio of all overflow water to the water added to the CLSM.

(3) The test of compressive strength was carried out following GB/T 50081-2019 (Standard for Test Method of Concrete Physical and Mechanical Properties) (GB/T 2019). A universal pressure testing machine was used to load the CLSM specimen with a constant displacement rate of  $0.5 \text{ mm}\cdot\text{min}^{-1}$ , and the stress and displacement properties were recorded every 1 s until the specimen failed. For each curing time and specimen, the compressive strength test was performed three times, and only the average maximum strength was considered.

(4) Test pieces were tested for density, porosity, and absorption under the ASTM D6023-2016 (Standard Test Method for Density (Unit Weight), Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material (CLSM)) (ASTM 2016).

Determination of fresh density: After the flowability was measured by CLSM, it was added to a 1 L graduated cylinder for measurement. The formula is as follows:

$$D_1 = \frac{M_2 - M_1}{V_1} \quad (1)$$

where  $D_1$  refers to the freshly mixed density of CLSM ( $\text{kg}\cdot\text{m}^{-3}$ ),  $M_1$  is the mass of the measuring cylinder (kg),  $M_2$  is the total mass of CLSM and the measuring cylinder (kg),  $V_1$  is the volume of CLSM in the measuring cylinder ( $\text{m}^3$ ).

Determination of dry density, absorption, and porosity: After curing for 28 d, the samples were dried in an oven at  $110 \text{ }^\circ\text{C}$  for not less than 24 h, weighed after cooling, and dried to constant weight. The mass  $M_a$  of the dried sample was specified (kg).

At room temperature, the samples were put in water for no less than 48 h, until the mass increase value of the test sample every 24 h was less than 0.5% of the maximum value. After removing moisture from the surface of the sample with a towel and drying the surface of the sample, the mass of the sample after immersion was designated as  $M_b$  (kg).

In a suitable container, the test block was immersed in tap water and boiled for 5 h. It was allowed to cool for no less than 14 h by natural heat dissipation, and the final temperature was  $20\text{--}25 \text{ }^\circ\text{C}$ . After removing the moisture from the surface with a towel and measuring the mass of the sample, the mass of the immersed and boiled

surface-dried test block was  $M_c$  (kg).

Afterward, the sample was suspended with a metal wire in the test block and was put into a graduated cylinder with tap water. The volume of water rising was collected, which was the sample volume  $V_2$  ( $\text{m}^3$ ).

The formula is as follows:

$$D_2 = \frac{M_a}{V_2} \quad (2)$$

$$A\% = \frac{M_b - M_a}{M_a} \times 100 \quad (3)$$

$$P\% = \frac{M_c - M_a}{V_2 \times \rho_w} \times 100 \quad (4)$$

where  $D_2$  refers to dry density ( $\text{kg}\cdot\text{m}^{-3}$ ),  $A\%$  stands for absorption rate,  $P\%$  stands for porosity, and  $\rho_w$  is the density of water ( $1000 \text{ kg}\cdot\text{m}^{-3}$ ).

(5) The leaching experiment of metal ions is carried out according to the method in HJ 557-2010 (Solid waste-Extraction procedure for leaching toxicity-Horizontal vibration method) (HJ 2010).

Deionized water was used as a leaching agent to simulate the process of leaching harmful components into the environment when the waste was leached by groundwater. After curing for 28 days, the sample was broken and all the sample particles passed through the screen with a diameter of 3 mm. The sample with a weight of 100 g was weighed and placed in a 2 L extraction bottle with a liquid-solid ratio of 10:1 to add deionized water. The bottle was fixed on a horizontal oscillator with a frequency of  $110 \pm 10 \text{ min}^{-1}$  and an amplitude of 40 mm. After 8 h of oscillating at room temperature, the liquid was left to stand for 16 h and then tested by  $0.45 \text{ }\mu\text{m}$  microporous filter membrane.

## References

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