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Research Article

Influence of Mass Concentration on Microstructure and Pore Structure of Coal-Gangue-Based Green Cemented Filling Body

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In response to China's "double carbon" strategic goal, the problem of large emissions of coal gangue and low utilization rate of gangue cemented backfill with fly ash as admixture needs to be solved urgently. Based on this, this paper uses coal gangue powder as admixture and coal gangue as coarse and fine aggregate to prepare coal-gangue-based green cemented filling body (CGGCFB) with different mass concentrations (MC). The workability, mechanical properties, and microscopic pore structure (nuclear magnetic resonance and scanning electron microscope) were measured, respectively, to explore the effect of MC on the above mentioned properties. In terms of macroscopic properties, with the increase of MC from 80% to 82% and 84%, the slump of filling slurry decreased by 18.37% and 32.65%, the expansion decreased by 30% and 54.55%, and the bleeding rate decreased by 28.3% and 60.38%. The uniaxial compressive strength (UCS) of CGGCFB at different ages increased to varying degrees, and the maximum was 2.9 times of the original. In terms of microscopic pore structure characteristics, the total number of pores of CGGCFB decreases, the pore size changes from large to small, the shape tends to be uniform and circular, the force characteristics of the pores are improved, the complexity and tortuousness of the pore channels increase, and the inner surface of the pores becomes rough; the test results show that the performance of the backfill with a mass concentration of 82% is reasonable, and the utilization rate of coal gangue can be increased to 72%. The research results of this paper can further improve the utilization rate of coal gangue resources, and provide a theoretical reference for the research and application of coal gangue in mine filling.

1. Introduction

In September 2020, General Secretary Xi Jinping strategically proposed the "double carbon" goal of "reaching peak carbon emissions by 2035 and achieving carbon neutrality by 2060." As one of the most important basic resources accounting for more than 80% of China's energy reserve structure, coal will produce a large number of solid waste coal gangue in the mining process, accounting for about one-tenth of the total coal. At present, the total amount of coal gangue in China has reached more than 7 billion tons, while the annual comprehensive utilization rate is only about 500 million tons, resulting in a large number of waste of resources and pollution, so the rational use of coal gangue is particularly important. Coal-gangue-based green cement filling is the coal gangue, coal gangue powder, and cement and water in accordance with a certain proportion of the configuration of good fluidity, stability, and plasticity of the filling mixture, in the pump pressure or gravity under the action of transport to the mining area, in order to achieve safe coal mining technology means. It can effectively solve not only the pollution problem caused by the accumulation of coal gangue on the ground, but also can effectively control the pressure and surface subsidence in the mining area, and can truly realize the solid waste comprehensive utilization of coal gangue "zero emission" [1, 2], which promotes the green development of coal industry, and also responds to the carbon peak and carbon neutral target requirements in the 14th five-year plan. The coal gangue is currently used as a coarse and fine material. At present, the paste filling with coal gangue as coarse and fine aggregate is widely used in various mines, and a lot of research studies have been carried out by domestic and foreign scholars [3–9].

The filling body is prepared by mixing and curing the waste rock and tailings stripped from the open air on the surface with cement, natural sand, and various admixtures, which is used to refill the goaf of the mine. There are many factors affecting the performance of the filling body. In [10–13], the authors studied the working performance and uniaxial compressive strength of the mine filling paste with different mix ratios and coarse and fine aggregate types. Zhang et al. [10] mainly studied the effect of different water-cement ratios on the performance of iron ore tailings filling paste. Through testing its workability and strength, it was found that the optimal water-cement ratio was 0.4, but the general applicability was not known. Wang et al. [11] analyzed the change of strength by changing the particle size of coal gangue in rock glue gangue fly ash fillings, and found that the increase of coal gangue particle size would lead to the decrease of filling body strength. Jia and Feng [12] and Feng et al. [13] used waste concrete as fine aggregate and coarse aggregate, respectively, to replace coal gangue to prepare filling paste and studied the influence of waste concrete coarse and fine aggregate on the performance of filling paste from the perspective of working performance and uniaxial cubic compressive strength. In order to improve the mechanical properties of the mine filling paste, Ren et al. [5] used fly ash as an admixture to study the long-term stability of filling paste and the influence of the roof performance by drying shrinkage deformation. It was found that the addition of an appropriate amount of fly ash can enhance the mechanical strength of the filling paste. By changing the activation ratio of the admixture coal gangue powder and combining macroexperiments and microexperiments, Qiu et al. [14] analyzed the mechanism of the effect of activated coal gangue powder on the performance of the filling body. Qi et al. [9] measured the compressive strength, porosity, and resistivity of coal mine paste filling materials at different ages by experiments, studied the mineral composition and microstructure of 7 days, 14 days, and 28 days, and discussed the correlation between compressive strength, porosity, resistivity, and hydration process. Zhang et al. [15] studied the effect of the particle size distribution of different active auxiliary cementitious materials on the properties of coal-gangue-based filling materials. In the literature [16–21], the mix proportion optimization design of the filling paste with different substitution methods was performed. From these studies, it can be seen that the final mix proportion of the mine-filling paste prepared by different raw materials is also different, but the similar result is that the performance of various filling pastes is improved to varying degrees by higher mass concentrations. However, there are few studies on the macroperformance and microperformance effects of CGP as an admixture for mine filling. In this paper, based on the previous experiments, we innovatively use coal gangue as coarse and fine aggregates, and use coal gangue powder as cementing material instead of part of cement to prepare the mine filling paste with three different mass concentrations, and determine the slump, expansion, water secretion rate, and uniaxial cubic compressive strength of CGGCFB at different mass concentrations at different ages, and combine them with microtests to comprehensively analyze the change law of mine-filling paste performance to obtain the best mass concentration.

2. Physical and Chemical Properties of Filling Materials

In the process of preparing the mixing filler, the microshape of raw materials, the grading of coarse and fine aggregates, and the physical and chemical properties of the filling materials will affect the working performance and mechanical properties of the filler slurry. Therefore, it is of great significance to study the physical and chemical properties of cement, CGP, coarse and fine coal gangue aggregates, and other filling materials. This section takes CGGCFB filling raw materials as the research object, introduces the preparation process of CGP and coal gangue aggregate in detail, and analyzes the basic physical and chemical properties of cement, CGP, and coal gangue coarse and fine aggregates.

2.1. Physical Properties of Coal Gangue. The gangue used in the test is from Daliu Tower coal mine in Shenmu, Shaanxi Province, which is crushed by a jaw crusher and screened by a vibrating screen machine. The particle size of a coarse aggregate is 20 mm~5 mm and that of the fine aggregate is 5 mm~0.075 mm. The coal gangue is ground by a ball mill for 120 min to powder, and the residue of 45 um sieve is 0%, reaching 600 mesh, and its physical parameters are shown in Table 1 below.

The crushed coarse aggregate of coal gangue conforms to the specification of “crushed stone or pebble particle gradation range,” and the gradation is good; the fine aggregate of coal gangue (coal gangue with particle size less than 5 mm) is poorly graded; according to the standard of sand for construction (GB/T14684-2022) [22], round sieve with aperture of 5 mm and 2.5 mm and square sieve with aperture of 1.25 mm, 0.630 mm, 0.315 mm, and 0.160 mm are used for manual screening, and the grading is adjusted according to the accumulated screening residue of each layer in the screening process and the upper and lower limits of Zone I sand in the specification. The specific coarse and fine aggregate gradation are shown in Figure 1.

2.2. Properties of Gel Materials. The cement used in the test was P·O42.5 ordinary portland cement produced by Shaanxi Xianyang Liquan Conch Cement Co., Ltd., without agglomeration, and its main properties are shown in Table 2.

2.3. Analysis of the Micromorphology of Coal Gangue Powder and Sand. The microstructure of CGGCFB was observed by SEM (scanning electron microscope), and the characteristics of CGGCFB were analyzed quantitatively. The microcosmic morphology of CGP and coal gangue sand is shown in Figures 2 and 3. CGP is mainly composed of ellipsoids, spheres, and some irregular flaky particles, which are more smooth and complete than the shape of fly ash [23]. As an admixture, CGP is relatively weak in changing the slurry

Table 1: Physical parameters of coal gangue.

Name	Water absorption (%)	Apparent density ($kg \cdot m^{-3}$)	Crushing index (%)
Coal gangue	4.38	2187.5	20.3

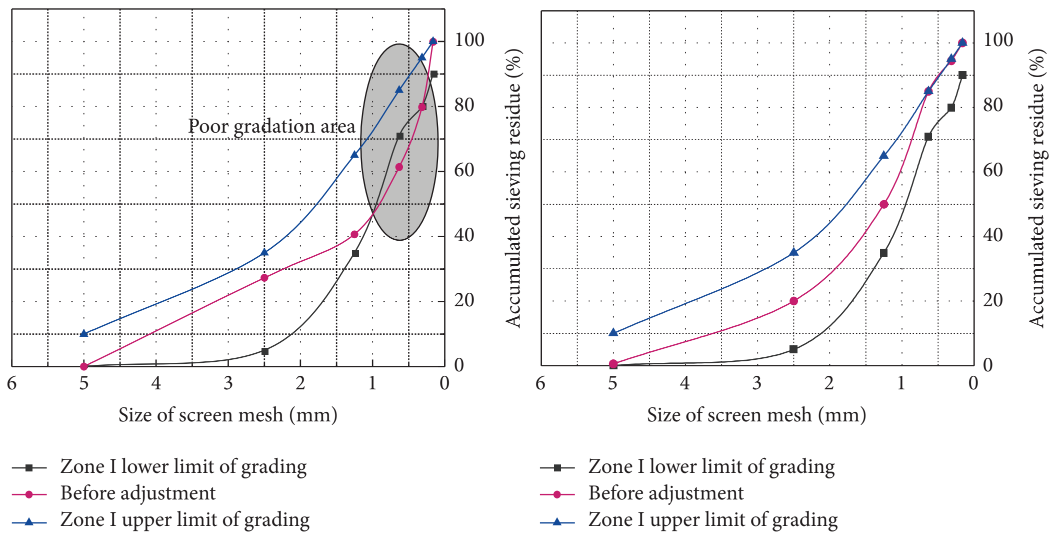

Figure 1: Grading curve of coal gangue sand.

Table 2: Index of P·O42.5 cement.

Setting time		Flexural strength (MPa)		Compressive strength (MPa)		Specific surface area (m^2/kg)	Fineness (%)	Burning loss (%)	MgO (%)	SO_3 (%)
Initial	Final	3 d	28 d	3 d	28 d					
160	250	4.5	7.9	26.3	42.5	347	3.6	2.8	2.3	2.5

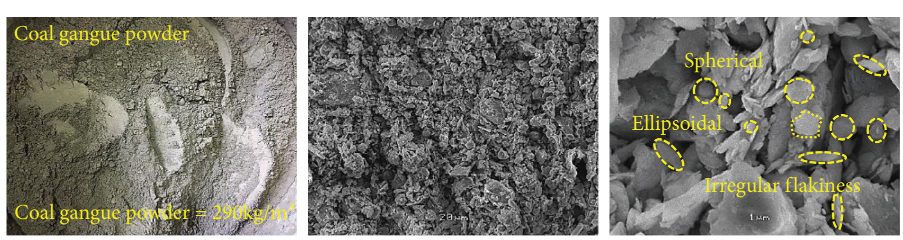

Figure 2: The morphology and microstructure of coal gangue powder.

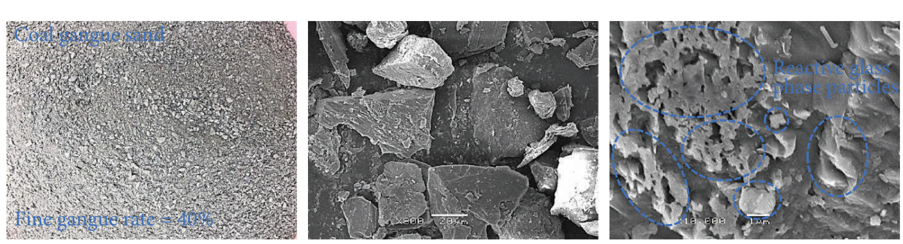

Figure 3: The morphology and microstructure of coal gangue sand.

workability; coal gangue sand is mainly composed of irregular massive particles of different sizes, and small particles of white glass phase are attached to the massive particles.

2.4. X-Ray Diffraction Pattern Analysis of Coal Gangue. The chemical composition of the hydration products in CGP determined by the XRD test is shown in Table 3. The test sample is less and equals to 350 mm. Figure 4 shows the XRD spectrum of CGP. It can be seen from the figure that the mineral composition of coal gangue is mainly composed of quartz, kaolinite, and calcium feldspar, and the chemical composition is mainly composed of SiO_2 and Al_2O_3. By combining the XRD diffraction spectrum and SEM results, it can be concluded that CGP after mechanical grinding has a certain degree of microactivity. Similarly, the gangue after mechanical crushing has pozzolanic activity. Active ions can be dissolved in the filling material to participate in the pozzolanic reaction [24], which can effectively improve the quality of the filling mixture.

3. Experimental Study

In this experiment, the effects of different mass concentrations on CGGCFB at different curing ages were studied when other factors were certain. The workability of CGGCFB was analyzed by measuring slump, expansion, and bleeding rate. The mechanical properties of CGGCFB were analyzed by measuring the compressive strength. Finally, the relationship between macroproperties and microproperties was analyzed by the nuclear magnetic resonance (NMR) test and the scanning electron microscope (SEM) test. The final mix proportion is determined by combining relevant scholars' research on coal gangue cemented filling [6–9] where the cement content is 190 kg/m³, the coal gangue powder content is 290 kg/m³, the fine gangue rate is 40%, and the mass concentration is 80%~84%; the calculation formula of mass concentration is as follows:

$$\rho_{\mathrm{mc}} = \frac{m_c + m_p + m_{\mathrm{fa}} + m_{\mathrm{ca}}}{m_{\mathrm{fb}}} \times 100\%, \quad (1)$$

where m_c refers to the quality of cement, m_p refers to the quality of coal gangue powder, m_{fa} refers to the quality of fine aggregate of coal gangue, m_{ca} refers to the quality of coarse aggregate of coal gangue, and m_{fb} refers to the quality of the slurry of the whole filling body.

The specific mix proportion of CGGCFB is shown in Table 4. According to GB/T50080-2016, the slump, expansion, and bleeding rate of each group of mixtures at different mass concentrations were measured, and then poured into a total of 48 cubic specimens with a size of 100 mm × 100 mm × 100 mm, of which the number of specimens for each concentration was 12; after solidification and demoulding, the specimens were cured at room temperature for 3 days, 7 days, 14 days, and 28 days, respectively, and three specimens were set up for each age group as a control. The cubic compressive strength and microscopic pore structure characteristics (NMR and SEM) were measured, and the specific test process was analyzed, as shown in Figure 5.

4. Test Results and Analysis

4.1. Effects of MC on the Workability of CGGCFB. The suitable workability of coal-gangue-based green cemented filling slurry (CGGCFS) determines the mechanical performance of CGGCFB, which can adequately support the roof of the mining area, effectively control the surface subsidence, and fully ensure the stability of the surrounding rock. On the contrary, the mechanical properties and quality of CGGCFB can also reflect the advantages of the suitable workability of CGGCFS. In this section, the influence of mass concentration on the working performance of CGGCFS and the mechanical properties of CGGCFB were studied. Based on the related research on macroscopic workability and mechanical properties, the internal reasons of the strength change of CGGCFB in different ages under different mass concentrations were revealed.

According to the test results, the variation law of filling slump, expansion, and bleeding rate with gradually increasing mass concentration is plotted as shown in Figure 6. From the figure, we can see that the workability of CGGCFS has different degrees of decreasing trend with the increase of mass concentration, and the decreasing trend of slump is slower and the decreasing degree of water secretion rate is larger under the requirement of meeting the specification.

It can be seen from Figure 6 that when the amount of other materials in CGGCFB is certain, as the mass concentration of the filling slurry becomes higher; the smaller the amount of water used, the smaller the slump and expansion, the higher the viscosity of the cemented filling slurry, and the poorer the fluidity and plasticity, and vice versa. The reason for this is that the increase in mass concentration is essentially a decrease in the amount of water consumption, which leads to an increase in the viscosity of the filling slurry, resulting in a decrease in the amount of slurry that acts as a lubricant inside it, an increase in the frictional resistance between the materials, and a weakening of the fluidity, which is reflected in a decrease in slump and expansion.

Under certain conditions of cement content, coal gangue powder content, and fine gangue rate, the higher the mass concentration of filling slurry, the smaller the water consumption, and the bleeding rate showed a downward trend. This is due to the fact that as the water consumption decreases, the viscosity of the slurry increases and no excessive water is analyzed inside the slurry. Therefore, under the premise of meeting the mechanical properties, the workability of the filling slurry is satisfied as much as possible to meet the requirements of slurry transmission.

4.2. MC Impact on UCS of CGGCFB. It can be seen from the formula in Section 3 that when the mass concentration of the filling body is large, the amount of cement, the amount of coarse and fine coal gangue aggregates, and the amount of coal gangue powder are relatively high, and the proportion

Table 3: Relative content of chemical composition of coal gangue.

Chemical composition	SiO_2	Fe_2O_3	Al_2O_3	CaO	Na_2O	MgO	K_2O	C, Ti, and other oxides
Relative content (%)	48.12	6.26	36.34	6.16	0.13	0.95	0.93	1.13

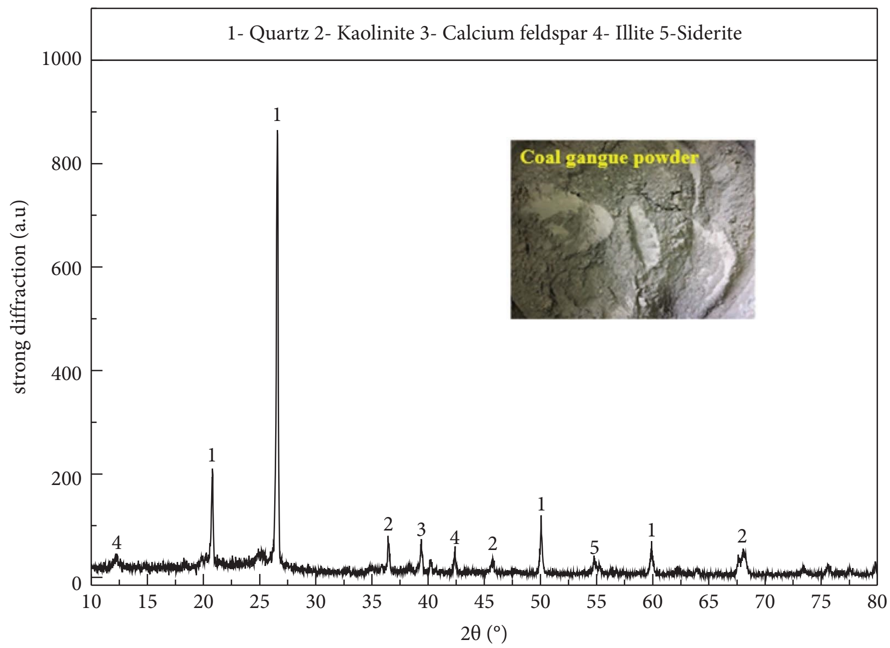

Figure 4: XRD diffraction map of coal gangue.

Table 4: Mix proportion of CGGCFB performance test.

Number	Cement content (kg/m^3)	Content of coal gangue powder (kg/m^3)	Fine gangue rate (%)	Mass concentration (%)	Notes
*D*1	190	290	40	80	Effects of MC on the performance of CGGCFB
*D*2	190	290	40	82	
*D*3	190	290	40	84	

of water in the corresponding slurry is small, resulting in a decrease in the water-cement ratio, which affects the compressive strength of CGGCFB. According to the test results, the changing pattern of UCS of CGGCFB at different ages with the change of mass concentration can be drawn, as shown in Figure 7.

From the formula in Section 3, it is known that when the mass concentration of the filler is larger, the cement dosage, the coarse and fine aggregate admixture of coal gangue, and the coal gangue powder admixture are higher, and the proportion of water in the corresponding slurry is less, resulting in a lower water-cement ratio, which affects the compressive strength of CGGCFB. It can be seen from Figure 7 that under the condition of a certain curing age, with the increase in the mass concentration, the UCS of the CGGCFB shows a continuous increasing variation law, and when the mass concentration is between 80% and 82%, its influence on the early strength is greater than the influence on the later strength, and when the mass concentration is between 82% and 84%, its influence on the early strength is less than that on the later strength. The reason is that the filler with mass concentration between 80% and 82% has enough water to fully satisfy the hydration reaction of the cement at an early stage of hardening, and the hydration reaction is relatively intense, and the hydration reaction is basically completed at the later stage, and the influence of mass concentration on it is weakened; the filler with mass concentration between 82% and 84% has a larger mass concentration at the early stage of hardening, and some water will be stored by CGP, causing the hydration reaction not sufficient and violent enough; later, under the moist maintenance conditions, the cement continues to hydrate and the CGP carries out the corresponding microvolcanic ash reaction, which greatly enhances the strength of the filler;

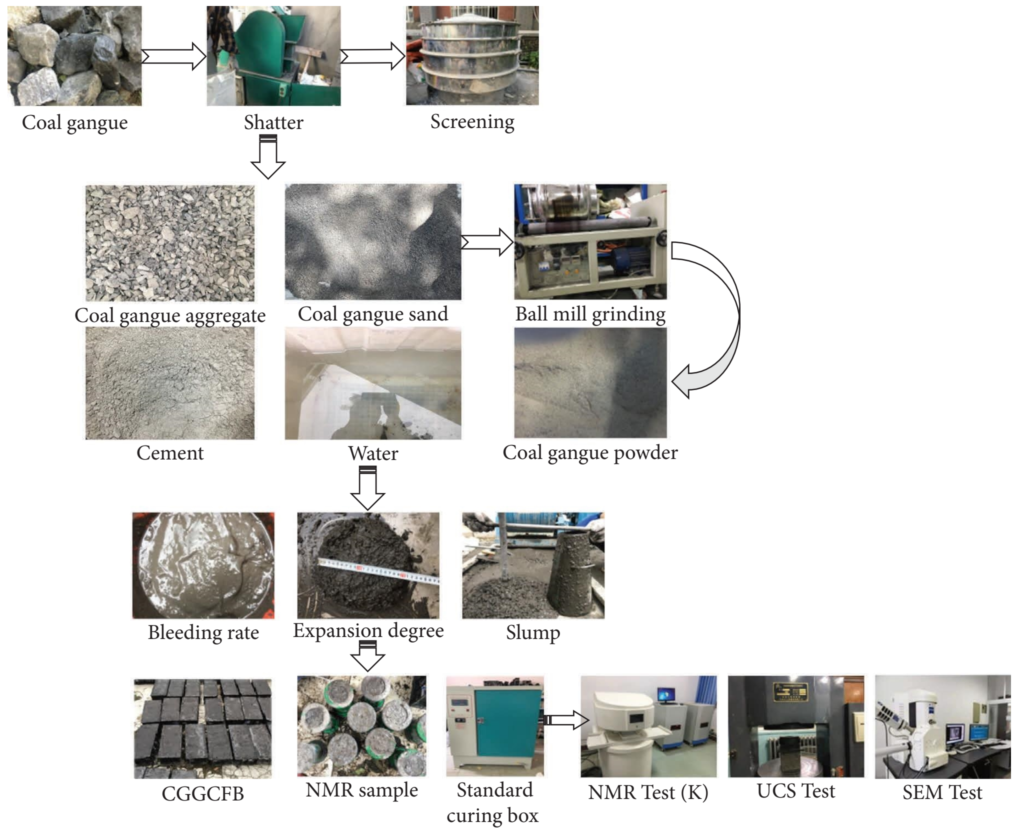

FIGURE 5: Test process.

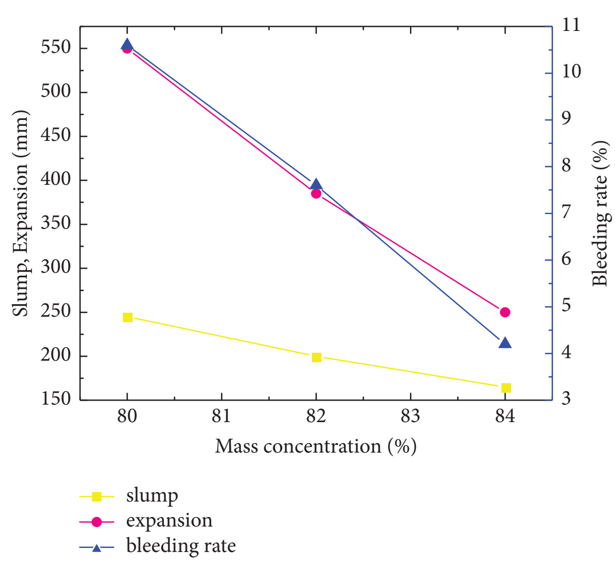

FIGURE 6: Working performance under different mass concentrations.

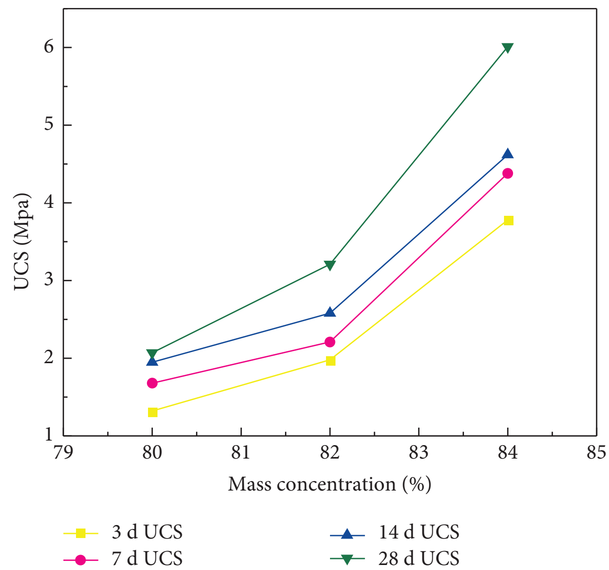

FIGURE 7: The relationship between UCS and mass concentration.

the larger the mass concentration, the smaller the water-cement ratio, and the higher the UCS of CGGCFB; therefore, under the condition of meeting the working performance of the filler slurry, the mass concentration of the cement should be increased as much as possible.

5. Effects of Mass Concentration on the Microstructure of CGGCFB

After the echo signal is obtained from the NMR test, the proportion of the fluid with different T_2 relaxation (transverse relaxation) times is calculated by mathematical inversion, that is, the NMR T_2 response spectrum. According to the NMR relaxation mechanism, the NMR signal with longer relaxation time on the T_2 response spectrum corresponds to the fluid in the larger pores of the filler, and the NMR signal with shorter relaxation time on the T_2 response spectrum corresponds to the fluid in the smaller pores of the filler [25]. Through the NMR test, the relationship between T_2 relaxation time and signal intensity of CGGCFB at three different mass concentrations (80%, 82%, and 84%) and different ages (3 days, 7 days, 14 days, and 28 days) can be obtained, as shown in Figure 8.

5.1. T_2 Spectrum Distribution. Under the condition of a certain mass concentration, the T_2 spectral distribution of CGGCFB at different ages is shown in Figure 8. Since the proportion of the peak area of the main peak is more than 85%, only the variation law of the distribution of the main peak with mass concentration and age is analyzed here. The T_2 distribution of fillings with different mass concentrations is mainly concentrated in 0.10~5.9 ms. It can be seen from Figure 8 that with the increase in curing time, the T_2 distributions of three different mass concentrations of CGGCFB shifted to the left as a whole. Among them, the T_2 distribution of 3~7 days shifted to the left faster than that of 7~14 days and 14~28 days, and the leftward shift of the T_2 spectrum distribution of CGGCFB could reflect its hydration reaction rate in each age. The displacement of the T_2 spectrum distribution shows that the cement not affected by CGP microaggregate effect has a faster hydration reaction speed in the early hardening stage of CGGCFB, and at this time, the generated hydration products form an initial network skeleton in the filling body, which fills the large gap of CGGCFB tightly, so that the left displacement speed is faster in 3~7 days; however, the T_2 spectrum peak area appears to increase first and then decrease because of the physical properties of the gangue itself, which contains pores, and with the growth of the maintenance time, the water absorption of coarse and fine aggregates of coal gangue gradually increases, and the peak area of the T_2 spectrum increases with the increase in age. The 14~28 days peak area decreases, which is because of the microaggregate effect of CGP, and the microvolcanic ash effect causes part of the intense hydration reaction of CGGCFB is postponed, so that the pores of the initially formed network skeleton and other pores inside the filler are further filled and compacted at a later stage. Therefore, in the process of practical application of the project, the more high-quality gangue is selected as the filling material to reduce the influence of the original properties of the material itself on the filling effect.

5.2. Analysis of Porosity and Pore Level Proportion. In addition to the size of the pore, the size of the filling body porosity and the proportion of various types of pore levels are also important factors affecting its mechanical properties. According to the classification of concrete pore grades by Academician Wu Zhongwei, they can be categorized as harmless pores (<20 nm), less harmful pores (20–50 nm), harmful pores (50–200 nm), and more harmful pores (>200 nm) [26, 27]. The pore-level proportion and pore-level volume distribution of CGGCFB at different mass concentrations and different ages are shown in Figure 9.

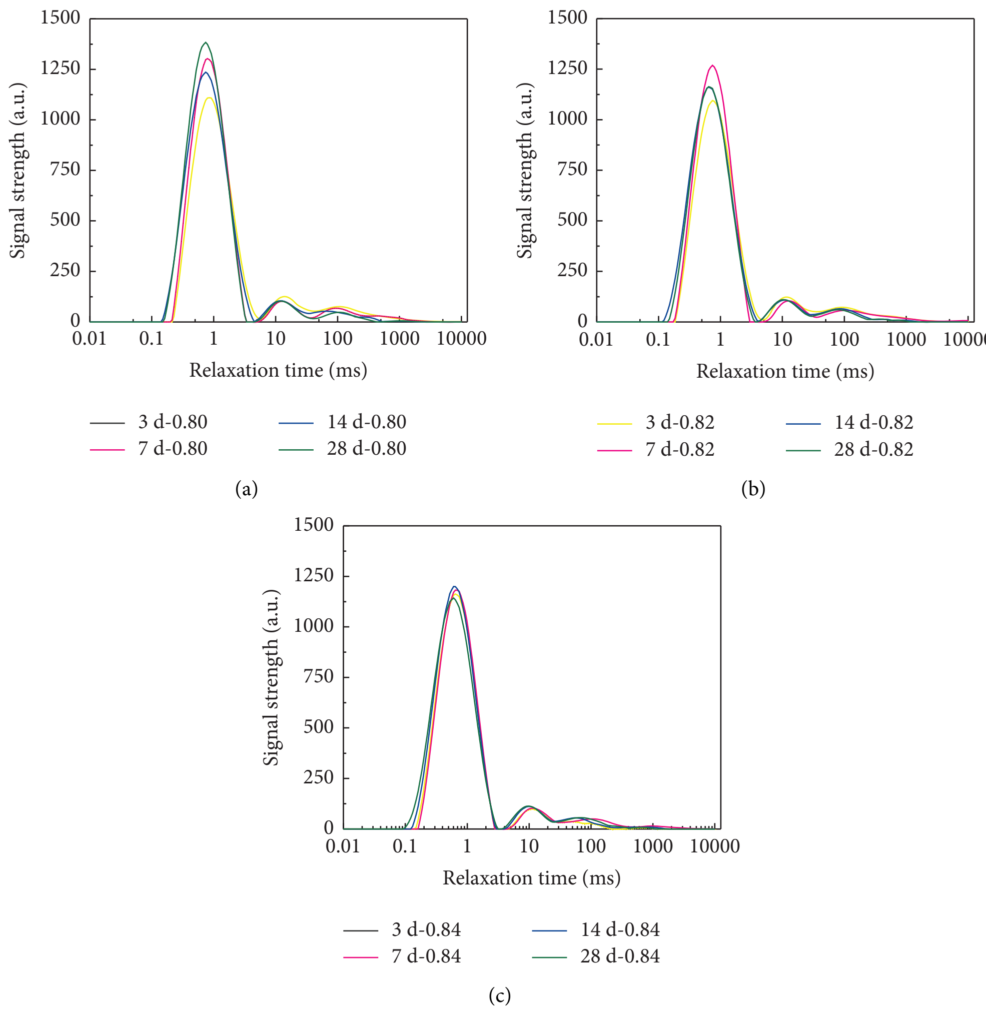

FIGURE 8: T_2 spectrum distribution curves of CGGCFB at different ages: (a) mass concentration 80%, (b) mass concentration 82%, and (c) mass concentration 84%.

As can be seen from Figure 9, the porosity of each specimen gradually becomes smaller with the increase of age and mass concentration; in terms of the percentage of hole classes, the harmless class holes gradually increase with the increase of age and mass concentration, and the harmless hole classes of most specimens account for more than 80% of the total pores. In the aspect of pore volume, the total pore volume decreases with the increase in age and mass concentration. At 80% and 82% mass concentrations, the pore volume of harmless holes first increases and then decreases with the growth of age, while the pore volume of less harmful holes, harmful holes, and multiharmful holes decreases with the growth of age; and at 84% mass concentration, the pore volume of harmless, less harmful, harmful, and multiharmful holes decreases with the increase in age. From the perspective of the proportion of pore-level classification and pore volume, the microscopic reasons why the UCS of CGGCFB gradually increase with the increase in age and mass concentration were fully revealed.

5.3. Pore Fluids. There is a limit value on the T_2 spectral distribution, that is, the T_2 cutoff value (T_{2cv}). When the T_2 relaxation time $>T_2$cv, it is a movable fluid, and when the T_2 relaxation time $<T_2$cv, it is a bound fluid, which is an important index reflecting the pore size of the filling body. In this paper, T_2cv = 10 ms, the free fluid saturation and bound fluid saturation of CGGCFB at different ages and different mass concentrations are shown in Figure 10.

As can be seen from Figure 10, the bound fluid saturation of CGGCFB at different ages and mass concentrations is much larger than that of the free fluid saturation; moreover, the bound fluid saturation gradually increases and the free fluid saturation gradually decreases as the age increases. The bound fluid saturation and free fluid saturation of CGGCFB with a mass concentration of 84% are relatively stable with age, which indicates that the internal pore structure of CGGCFB is relatively stable, which in turn reflects that its mechanical properties are relatively stable; the smaller the mass concentration, the greater the variation of the relative values between the free and bound fluid

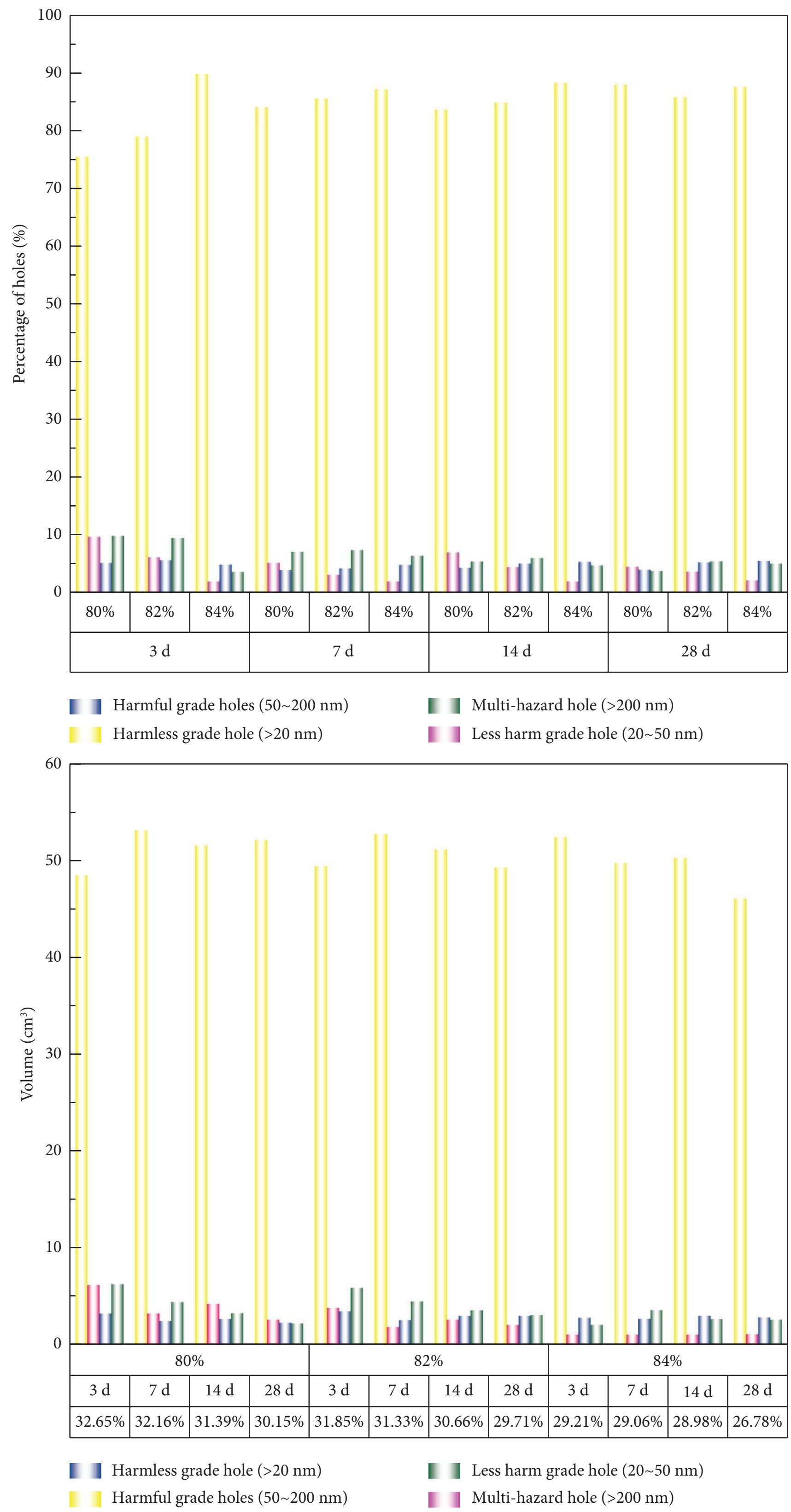

Figure 9: Proportion and distribution of pore size of CGGCFB at different ages and different mass concentrations.

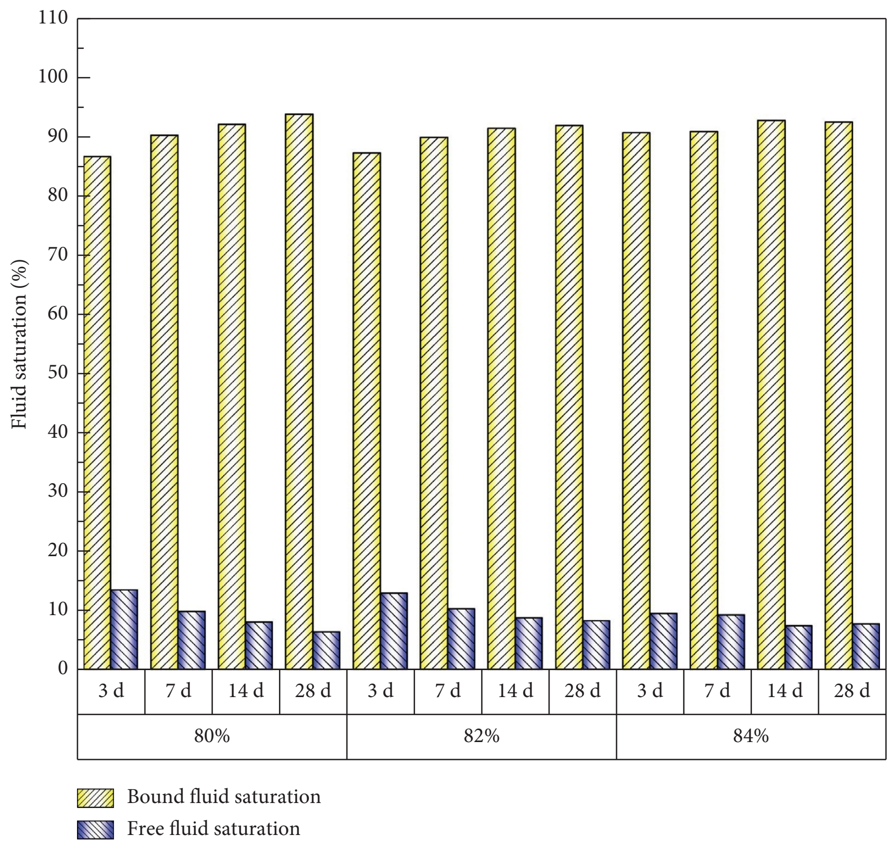

FIGURE 10: Free fluid saturation and bound fluid saturation of CGGCFB at different ages and mass concentrations.

saturation within the filling, and the more significant the difference. The larger the mass concentration, the smaller the variation of the relative value between the free fluid saturation and the bound fluid saturation within the filling, the weaker the difference, and the mechanical properties are relatively stable. The greater saturation of bound fluid in the specimen represents more small pores ; the greater saturation of free fluid represents more large pores. Then, the larger the mass concentration, the more the number of large pores and small pores in CGGCFB, which is relatively balanced, and the number of large pores in its internal structure changing to small pores is relatively small, and the evolution of pore structure is weak. The smaller the mass concentration, the more the macropore structure in CGGCFB needs to be improved, and the number of macropores changing to small pores is relatively large, and the pore structure evolves dramatically.

The hardened CGGCFB can be approximately regarded as a two-phase medium material composed of a solid matrix and pore fluid. This subsection will discuss the pore fluid characteristics of CGGCFB. According to equation (2), the variation law of internal nuclear magnetic porosity (K_{Coates}) of CGGCFB at different ages and different mass concentrations is shown in Figure 11.

$$K_{\text{Coates}} = \left(\frac{\phi}{C_2}\right)^{m_2} \times \left(\frac{\text{FFI}}{\text{BVI}}\right)^{n_2}, \qquad (2)$$

where Φ stands for total porosity %, FFI stands for movable fluid saturation %, BVI is irreducible fluid saturation %, and m_2, n_2, and c_2 are model parameters, which can be obtained through experiments, and default values 4, 2, and 10 are used in this paper.

It can be seen from Figure 11 that under a certain mass concentration, with the increase of the curing age, the permeability shows a sharp decrease trend; as the mass concentration increases, the decreasing trend with the age slows down. The smaller the mass concentration, the more significant the degree of permeability change with age. The reason is that the cementation and precipitation of hydration products lead to the decrease of pore channels of CGGCFB, the increase of pore tortuosity, and the increase of surface roughness inside the pores, resulting in a significant decrease in permeability. At a higher mass concentration, due to the obvious reaction at a lower mass concentration, the NMR permeability of CGGCFB with mass concentrations of 82% and 84% showed a decreased lag and a decrease in the decrease range, and this phenomenon was most obvious at a mass concentration of 84%. In addition, the permeability at the age of 28 days increases slightly when the mass concentration is 82%. The reason is that, with the increase of the mass concentration, the number of large pores changing into small pores decreases, and the relative changes of bound fluid saturation and free fluid saturation of CGGCFB are smaller than their changes at 80% of the mass concentration, which is the result of a small increase in nuclear magnetic permeability.

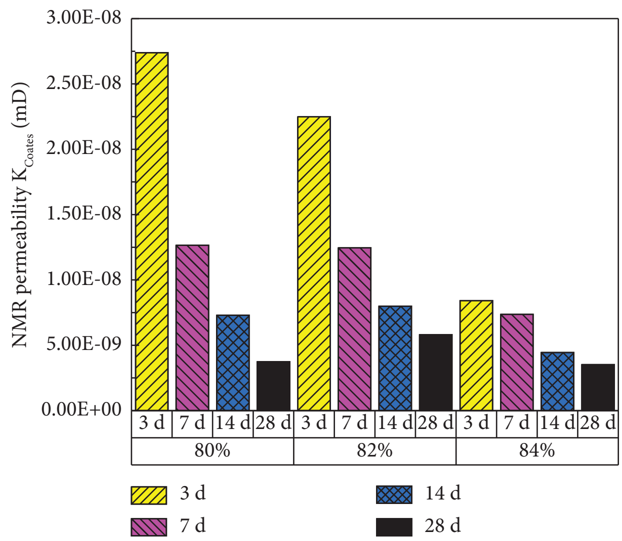

Figure 11: Internal nuclear magnetic permeability of CGGCFB at different ages and mass concentrations (K_{Coates}).

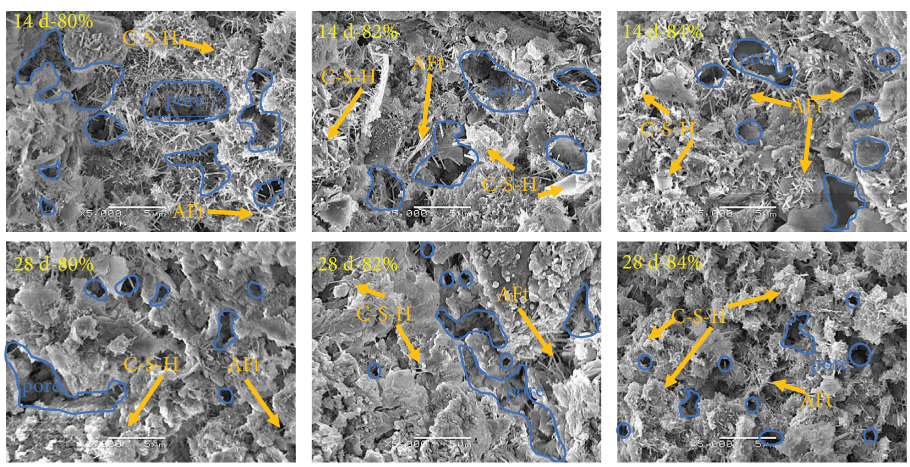

Figure 12: Microstructure of CGGCFB with different mass concentrations at different ages.

Figure 12 shows the microstructural changes and hydration products of CGGCFB with different mass concentrations at different ages. The red graphs with different shapes represent the number, size, and shape of pores, as well as the change law of pore channels with mass concentration and age. The longitudinal comparison shows that, with the same mass concentration and with the increase of curing age, the change rule of pore characteristics is the same as mentioned above, and it can be seen from Figure 12 that the shape of the hydration product AFt is similar to the petal shape when the curing age is 14 days, and its shape is needle column when the curing age is 28 days.

6. Conclusions

By combining experiment with theory and taking mass concentration as the main factor and starting point, this paper explores its influence on the macroscopic working performance, mechanical properties, microscopic pore structure characteristics, and pore fluid characteristics of CGGCFB at different ages, reveals the internal relationship between the mechanical properties and the microscopic pore structure of CGGCFB at different mass concentrations at different ages, and mainly draws the following conclusions:

(1) The main mineral composition of coal gangue is quartz, kaolinite, and anorthite. The chemical composition of coal gangue is mainly SiO_2 and Al_2O_3, which has higher water absorption than natural aggregates, is close to the crushing index of type II gravel, and has high stability, which meets the requirements of the filling aggregate. It can be concluded from XRD, SEM, and chemical composition of coal gangue that ordinary CGP has certain microactivity.

(2) Under certain conditions of other variables, with the increase of the mass concentration of the filling slurry from 80% to 84%, the slump is 245mm, 200mm, and 165mm, respectively, which decreases

by 18.38% and 32.65%; the expansion degree is 550mm, 385mm, and 250mm, respectively, reducing by 30% and 54.55%; the bleeding rates are 10.6%, 7.6%, and 4.2%, respectively, which decreases by 28.3% and 60.38%; the working performance of CGGCFB has been improved. The influence of MC on the UCS of CGGCFB is mainly because the change of water consumption leads to the change of the water cement ratio, which is the only factor directly related to water. The more water is used in the filling body when the filling slurry is stirred fully and evenly, the smaller the mass concentration, , and the rich water forms bubbles or channels in the filling body. After the filling body hardens, it will leave voids and cause the strength of the filling body to decrease and vice versa.

(3) The pore characteristics of CGGCFB were analyzed in detail based on NMR and SEM, and the pore size, pore volume, and pore fluid of CGGCFB were greatly improved. At the same curing age, with the increase in mass concentration, the number of pores decreases, the pore size decreases, and the shape tends to be uniformly circular, . The pore stress characteristics are improved, the complexity and tortuousness of pore channels increase, and the internal surface of the pores becomes rough.

(4) Based on the working and mechanical properties of CGGCFB and the change law of micropore structure, it is more reasonable when the mass concentration is 82%, and according to this mixing ratio, the comprehensive utilization rate of coal gangue is increased to 72%.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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