

Article

Correlation Analysis Between Pore Structure and Mechanical Strength of Mine Filling Materials Based on Low-Field NMR and Fractal Theory

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Abstract

Filling mining offers significant technical advantages in controlling rock mass movement and preventing disasters. Investigating the correlation between the macro- and micro-scale characteristics of filling materials will help optimize this process. The paper analyzes the variation patterns and mechanisms of the pore structure and mechanical strength characteristics of the filling body based on low-field nuclear magnetic resonance (NMR) technology and fractal theory, exploring the relationship between microstructure and macroscopic features. Results indicate that as the cement-to-sand ratio or mass concentration decreases, the total pore structure count in the filling material increases, predominantly consisting of micropores that account for over 76%. The complexity of total pores, micropores, mesopores, and macropores progressively decreases. Mechanical strength exhibits a positive correlation with both the cement-to-sand ratio and mass concentration. A reduced cement-to-sand ratio diminishes hydration products, lowering the cohesive strength of tailings particles. As mass concentration increases, the internal structure of the filling body becomes denser, enhancing its mechanical properties. An increase in pore number progressively improves pore connectivity, reducing fluid flow resistance. The porosity of the pore structure exhibits a strong correlation with fractal dimension, mechanical strength, and permeability coefficient, with a coefficient of determination ranging from 0.631 to 0.996. The strength prediction model constructed using mesopore porosity and material intrinsic characteristics also demonstrated excellent accuracy.

Keywords: mine filling material; pore structure; mechanical properties; fractal dimension; low-field NMR



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1. Introduction

Filling mining technology is a typical green mining technique capable of harmonizing with the mining environment. It offers distinct technical advantages in the control of rock mass movement and disaster prevention, subsidence mitigation, the treatment of waste rock and other solid wastes, and ecological conservation [1–4]. Analyzing the variation patterns and mechanisms of the pore structure and mechanical strength of filling materials, along

with examining the correlation between macro- and micro-scale characteristics, will help optimize the mechanical properties of filling materials. This will prevent surface subsidence and catastrophic events, providing crucial safeguards for safe mining operations [5–8].

The microporous structure characteristics are crucial factors determining the mechanical properties and permeability characteristics of filling materials [9,10]. Currently, the primary methods for examining the microstructure of filling materials include NMR technology, scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP), and X-ray diffraction (XRD) [11–14]. For example, Zhao, FW. [15] utilized NMR and SEM to examine the microstructural characteristics of lime-modified phosphogypsum cementitious backfill. Ouellet, S [14] employed MIP to evaluate the microstructural evolution of different silica-based cementitious backfill (CPB) specimens. The description of pore structure characteristics primarily encompasses porosity, pore size, and pore connectivity. For instance, Fridjonsson, EO [16] identified three distinct, reproducible peaks in the pore size distribution of cement paste backfill (CPB), which progressively shifted toward smaller pore sizes over hydration time and showed a positive correlation with sample permeability. Liu, Y [17] et al. classified pore structures based on pore size and dual T_2 cutoff values into either micropores, mesopores, and macropores or clay-bound, capillary-bound and mobile-fluid pores. Furthermore, fractal theory has been extensively applied to the quantitative characterization of pore structure complexity. By introducing the concept of fractal dimension, it compensates for the limitations of traditional pore structure parameters, thereby establishing a general relationship between porosity and fractal dimension [18–20]. For example, Zhao, K [20] et al. investigated the pore fractal characteristics of fiber-reinforced filling bodies, finding that the fractal dimension values for micropores ranged from 0.30 to 1.00, while those for mesopores and macropores fell within the range of 2.96 to 3.00. Deng, HW [21] employed fractal geometry to quantify the pore network of tailings cement tailing backfill (CTB). Subsequently, a predictive model for CTB uniaxial compressive strength was established using dual indicators: “harmless porosity” and “harmful pore fractal dimension.” Additionally, the slurry mix ratio (mass concentration, cement-to-sand ratio, etc.) [22,23], curing conditions (temperature, humidity, etc.) [24,25], and hydration time [26] are all critical factors influencing the formation of pore structure characteristics.

Filling materials are primarily used to support the surrounding rock mass in mining areas, thereby mitigating deformation and rockfall in the surrounding rock. Mechanical strength is one of their key performance indicators [27,28]. Current research on the mechanical strength characteristics of filling materials has mainly focused on uniaxial compressive strength, tensile strength, triaxial strength, shear strength, and other properties [29–32]. For example, Zheng, JR [33] investigated the development pattern of unconfined compressive strength (UCS) in cement-cemented filling materials using sulfide-bearing lead–zinc tailings. The study found that higher ordinary Portland cement (OPC) content resulted in higher UCS values. Under identical conditions, a finer tailings size reduced the UCS of the backfill at all ages; strength began to decline within short curing periods. Fall, M [34] investigated the effects of curing temperature and the synergistic interaction between temperature and CPB components on the primary mechanical properties of CPB (strength, elastic modulus, and stress–strain behavior). The study revealed that curing temperature significantly influences CPB mechanical properties, with the temperature effect jointly controlled by the cement-to-sand ratio, binder type, tailings mineralogy and curing time. Tu [35] found that under lateral confinement, the triaxial compressive strength of CTB is approximately twice that of uniaxial compressive strength, while its deformation capacity is about four times greater. When the grout fails, crack propagation occurs at the tips of internal pore structures, forming through cracks. This indicates a correlation between pore structure characteristics and mechanical strength. Addressing this phenomenon, Shao, XP [36] further reported

that moderate silica fume promotes calcium–silicate–hydrate formation in a ternary slurry, fills micro-voids, refines the pore network, and thereby enhances strength and durability. Additionally, factors such as tailings particle size, cement properties, cement-to-sand ratio, mass concentration, curing conditions, and additives [37–41] significantly influence the mechanical strength variations in the filling material.

In recent years, machine learning (ML) algorithms have also seen rapid development in predicting the pore structure and mechanical properties of grout. Qiu, JH [42] employed a population optimization algorithm combined with the CatBoost algorithm to study grout strength prediction, revealing that changes in micro-level pore structure are a key factor driving macro-level mechanical variations. Under adequate curing conditions and reasonable parameter ratios, lower pore volume in grout correlates with higher grout strength. Yin, SH [43] employed a Long Short-Term Memory (LSTM) prediction model optimized by a Genetic Algorithm (GA). Using cement content, solid content, waste rock content, and curing age as input variables, the model accurately predicted the trend of Unconfined Compressive Strength (UCS) ($R^2 > 0.996$). Niu Yonghui [44] constructed a yield stress prediction model for backfill slurry based on BOP-Stacking ensemble learning. Using 12 variables, including tailings, basic properties, and mix design parameters as the original dataset, the model accurately predicted the variation trend of backfill yield strength. Results indicate that the BOP-Stacking model significantly improved the R^2 values between predicted and actual values compared to individual models, with the highest improvement reaching 82.97%. This demonstrates that incorporating machine learning algorithms provides more comprehensive support for predicting the pore structure and mechanical properties of backfill materials.

In summary, this paper analyzes the effects of different cement-to-sand ratios on the porosity, fractal dimension, and connectivity of the pore structure in filling materials using nuclear magnetic resonance (NMR) technology and fractal theory. It identifies the variation characteristics of the mechanical strength of the filling materials and investigates their permeability coefficients. The correlations between pore structure, porosity, fractal dimension, mechanical strength, and permeability coefficient are explored, establishing an analytical model linking micro-pore structure to mechanical strength.

2. Methods and Theory

2.1. Raw Materials

Cement (from Anhui Conch Cement Co., Ltd., Wuhu, China), tailings (from a tin mine in Hechi, China), fly ash (from China Huadian Corporation Limited, Xiong'an New Area, China), and water were used as experimental raw materials. The tailings originated from a mine's filling station's whole tailings, where larger particles served as aggregate for structural support, while finer particles assisted cement in its cementitious function. The tailings primarily contained chemical components such as SiO_2 , CaCO_3 and $\text{Ca}(\text{SO}_4)(\text{H}_2\text{O})_2$, with a coefficient of uniformity C_u of 5.32 and a coefficient of curvature C_c of 1.25, exhibiting good particle size distribution. The cementitious material selected was Conch brand P.O. 42.5 ordinary Portland cement, primarily containing Ca_3SiO_5 , Ca_2SiO_4 , CaCO_3 , $\text{Ca}_2\text{FeAlO}_5$, and other chemical components. It exhibited a C_u of 6.30, a C_c of 1.15, and good particle size distribution. The fly ash used was solid waste from a coal-fired power plant, offering advantages such as low cost and good cementitious properties. The fly ash primarily contained chemical components such as SiO_2 , Al_2O_3 , and CaO , with a C_u value of 10.78 and a C_c value of 1.35, exhibiting good particle size distribution. Tap water from the laboratory was used for testing. The particle size distribution characteristics and XRD chemical composition test results of the experimental raw materials are shown in Figure 1 (Experimental Flow Chart).

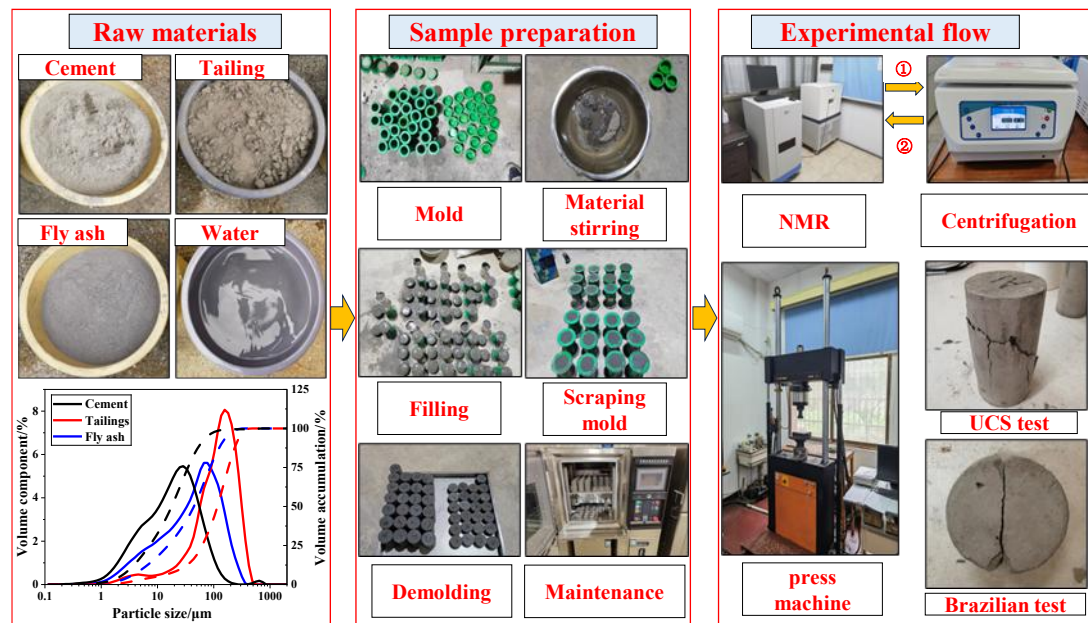


Figure 1. Test flowchart.

2.2. Specimen Preparation

Experimental designs involved grout mixtures with varying mass concentrations (68%, 70%) and cement-to-sand ratios (1/3, 1/4, 1/5, 1/6, 1/8) to observe their effects on the strength and pore structure characteristics of the filling material [45,46]. The material mix ratios are shown in Table 1. In accordance with the “Standard Test Methods for Properties of Ordinary Concrete Mix (GB/T 50080-2016)” [47], specimens were fabricated into cylindrical specimens measuring $\Phi 50 \text{ mm} \times 100 \text{ mm}$ and $\Phi 50 \text{ mm} \times 25 \text{ mm}$, designated as Groups A1 to A5 and Groups B1 to B5. Each group of specimens consists of 6 specimens, with 3 specimens each of the $\Phi 50 \text{ mm} \times 100 \text{ mm}$ and $\Phi 50 \text{ mm} \times 25 \text{ mm}$ specifications, totaling 60 specimens. During specimen preparation, the recovered tailings were dried and screened to remove excess impurities. Test molds were retrieved, thoroughly cleaned, dried, and coated with lubricant on their inner walls. According to the material ratios in Table 1, the required quantities of tailings, cement, and water were weighed. The weighed raw materials were thoroughly mixed, loaded into the molds, and then compacted. After scraping and demolding, the filled specimens were placed in a curing chamber for 28 days at 20 °C and 98% humidity, as shown in Figure 1.

Table 1. Design of test scheme for filling specimens.

Groups	Mass Concentration	Cement Tailings Ratio	Fly Ash	Cement Paste	Tailings Slurry	Water	Number
A1	68%	1/3	10%	14.50%	43.50%	32%	6
A2	68%	1/4	10%	11.60%	46.40%	32%	6
A3	68%	1/5	10%	9.67%	48.30%	32%	6
A4	68%	1/6	10%	8.29%	49.70%	32%	6
A5	68%	1/8	10%	6.44%	51.60%	32%	6
B1	70%	1/3	10%	15.00%	45.00%	30%	6
B2	70%	1/4	10%	12.00%	48.00%	30%	6
B3	70%	1/5	10%	10.00%	50.00%	30%	6
B4	70%	1/6	10%	8.57%	51.43%	30%	6
B5	70%	1/8	10%	6.67%	53.33%	30%	6

2.3. Experimental Test

Based on the test plan scheme, the testing of the filling material primarily included compressive strength, tensile strength, and pore structure distribution characteristics (obtained via NMR technology). According to the specimen preparation specifications,

$\Phi 50 \text{ mm} \times 100 \text{ mm}$ specimens were utilized for NMR testing and uniaxial compressive strength testing, while $\Phi 50 \text{ mm} \times 25 \text{ mm}$ specimens were employed for tensile strength testing.

Specimens that had reached the required curing age were removed from the curing chamber for NMR (Ain-iMR-150, Suzhou Nuomai Analytical Instruments Co., Ltd. Suzhou, China) testing. During the NMR testing process, specimens were first subjected to vacuum saturation treatment with a saturation vacuum pressure of 0.1 MPa for 24 h [21,48]. The CPMG sequence parameters for the NMR test were set as follows: echo time, 0.35 ms; echo number, 2048; wait time, 3000 ms; radio frequency delay, 0.08 ms; digital gain, 3; analog gain, 20; accumulation, 16. After the NMR test, the samples were subjected to centrifugation treatment using a TD-4 centrifuge (Changsha Xiangzhi Centrifuge Instrument Co., Ltd. Changsha, China). The centrifugation speed was set at 1000 rpm/min, the centrifugation time was 60 min, and the centrifugal force was approximately 672.5 g. This process separated free water from the internal pore structure of the filling material. The centrifuged sample was then subjected to another NMR test to obtain its T_2 cutoff value characteristics and permeability performance.

Mechanical tests included compressive strength tests and tensile strength tests. Among them, the tensile strength test was obtained through the Brazilian splitting test. The samples after NMR were dried and then subjected to uniaxial compressive strength tests to obtain the uniaxial strength (σ_c) and compressive modulus (E_c) of the filling body. Displacement control loading was adopted, with the rate set at 0.1 mm/min. The Brazilian splitting test yielded the tensile strength (σ_t) and tensile modulus (E_t) of the filling body. Displacement control loading was adopted, with the rate set at 0.1 mm/min. The specific process is shown in Figure 1.

2.4. Pore Structure Division, Fractal Dimension and Permeability Calculation

2.4.1. Pore Structure Division

NMR technology primarily analyzes the development of a sample's pore structure based on the response signals of hydrogen (H) atoms in the pore water within porous materials. It then derives the relaxation parameters of the porous material through inversion of the decaying signals. Typically, the pore radius of a porous medium is proportional to the T_2 relaxation time value; a longer relaxation time indicates larger pore diameters. The filling material was studied by Liu and Deng et al. [17,21], yielding ρ_2 (relaxation strength value) = 0.012 $\mu\text{m}/\text{ms}$ and F_S (pore shape factor) = 3. The specific pore radius calculation results are as follows:

$$r = 0.036T_2 \quad (1)$$

Based on Equation (1), the pore radius distribution characteristics within the filler material were calculated, and the pore structures were classified according to different pore sizes. According to the classification framework proposed by Jiang Z et al. [49], pores in porous media can be categorized into three size ranges based on their diameter: micropores ($r < 0.1 \mu\text{m}$), mesopores ($0.1 \mu\text{m} \leq r \leq 1.0 \mu\text{m}$), and macropores ($r > 1.0 \mu\text{m}$). The corresponding size ranges are illustrated in Figure 2a. It should be noted that this classification of pore structures is based on existing literature findings and has not been supplemented by other verification methods, potentially introducing certain limitations. The porosities of micropores, mesopores, and macropores are denoted as Φ_{mi} , Φ_{me} , and Φ_{ma} , respectively, while the total porosity is denoted as Φ_{total} .

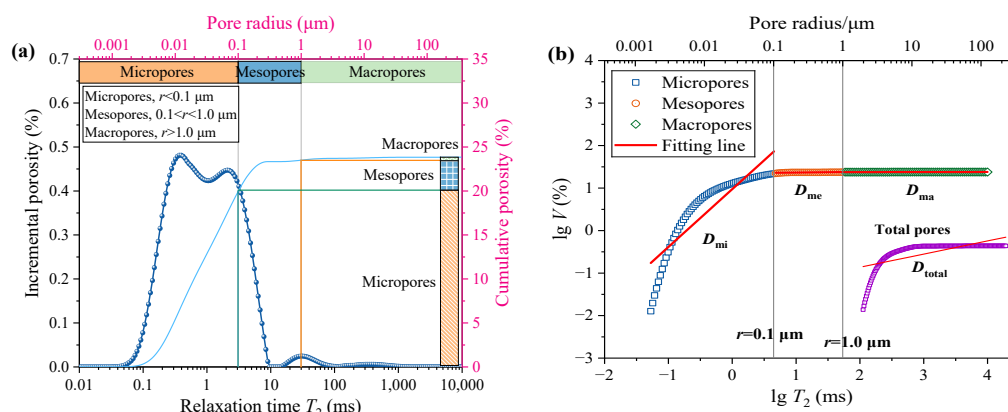


Figure 2. Pore structure division and fractal dimension calculation.

2.4.2. Fractal Dimension Calculation

The fractal dimension primarily reflects the complexity and homogeneity of the pore structure. Based on the principles of NMR technology, the calculation process of the fractal dimension can be described as follows:

$$\lg(V) = (3 - D_{NMR})\lg r + (D_{NMR} - 3)\lg r_{\max} \quad (2)$$

According to Equation (2), linear fitting was applied to each pore size region with a straight-line model to yield the slope $3 - D_{NMR}$. The fractal dimension D_{NMR} is then obtained by simple calculation, as shown in Figure 2b. For convenience of expression, the fractal dimensions of micropores, mesopores, macropores, and total pores are denoted as D_{mi} , D_{me} , D_{ma} and D_{total} , respectively.

2.4.3. Permeability Coefficient Calculation

Typically, pore structure characteristics encompass porosity, pore size, and pore connectivity. To understand the changes in pore connectivity in the filling material, this paper introduces the parameter permeability coefficient K to quantify this phenomenon. The permeability values of the filling material were calculated using the Coates model, as shown below:

$$K = \left(\frac{\Phi_{\text{total}}}{C} \right)^M \left(\frac{FFI}{BVI} \right)^N \quad (3)$$

In the equation, Φ_{total} represents the total porosity of the specimen, expressed as a percentage; FFI denotes the free water pore volume parameter; BVI denotes the bound water pore volume parameter; C , M , and N are model parameters with values of 10, 4, and 2, respectively. It should be noted that C , M , and N are empirical values, so K is an estimated value.

3. Analysis of Test Results

Based on the experimental design and procedure, the evolution characteristics of the void structure and the mechanical strength of the backfill material were obtained. The specific results are shown in Tables 2 and 3.

Table 2. Calculated results for porosity.

Groups	$\Phi_{\text{total}}\text{-AVE}/\%$	$\pm\text{SD}$	$\Phi_{\text{mi}}\text{-AVE}/\%$	$\pm\text{SD}$	$\Phi_{\text{me}}\text{-AVE}/\%$	$\pm\text{SD}$	$\Phi_{\text{ma}}\text{-AVE}/\%$	$\pm\text{SD}$
A1	17.528	0.310	16.009	0.054	1.344	0.199	0.175	0.030
A2	19.049	0.106	16.642	0.503	2.156	0.383	0.252	0.018
A3	20.440	0.143	17.000	0.339	3.183	0.392	0.258	0.030
A4	22.813	0.216	18.459	0.122	3.976	0.147	0.378	0.043
A5	25.054	0.271	19.910	0.196	4.642	0.082	0.503	0.013
B1	15.832	0.149	14.206	0.122	1.482	0.141	0.144	0.053
B2	17.159	0.270	14.598	0.224	2.280	0.179	0.281	0.019
B3	19.326	0.151	15.100	0.166	3.790	0.368	0.437	0.073
B4	20.475	0.171	15.779	0.212	4.259	0.322	0.437	0.042
B5	23.356	0.449	17.650	0.467	5.146	0.118	0.560	0.067

Table 3. Calculated results for strength and permeability coefficient.

Groups	$\sigma_c\text{-AVE}/\text{MPa}$	$\pm\text{SD}$	$E_c\text{-AVE}/\text{GPa}$	$\pm\text{SD}$	$\sigma_t\text{-AVE}/\text{MPa}$	$\pm\text{SD}$	$E_t\text{-AVE}/\text{GPa}$	$\pm\text{SD}$	K/mD	$\pm\text{SD}$
A1	8.322	0.421	1.715	0.121	1.458	0.301	0.257	0.041	9.926	0.325
A2	7.639	0.314	1.581	0.114	1.305	0.194	0.234	0.054	11.013	0.901
A3	4.613	0.523	1.308	0.152	0.815	0.203	0.165	0.032	13.248	0.326
A4	3.686	0.449	0.991	0.149	0.667	0.129	0.134	0.029	15.375	0.178
A5	2.108	0.090	0.535	0.030	0.356	0.123	0.115	0.010	16.903	0.040
B1	9.131	0.256	1.855	0.141	1.628	0.041	0.293	0.004	7.014	0.120
B2	8.126	0.156	1.631	0.104	1.415	0.114	0.245	0.001	9.670	0.210
B3	4.909	0.312	1.428	0.122	0.915	0.082	0.185	0.006	12.237	0.190
B4	3.871	0.267	1.029	0.129	0.757	0.119	0.153	0.009	13.320	0.156
B5	2.231	0.102	0.655	0.080	0.405	0.090	0.132	0.007	15.691	0.132

3.1. Evolution Characteristics of Pore Structure

3.1.1. T_2 Spectral Characteristics and Pore Distribution

As a non-destructive technique, NMR is widely used to monitor microstructural evolution in porous media, including rock, soil, backfill and concrete. According to the experimental design, T_2 spectrum characteristics and pore structure distributions of the filling material under saturated and centrifuged conditions were measured; the results are plotted in Figure 3.

It can be observed that at a constant mass concentration, the T_2 spectrum under saturated water conditions gradually transitions from a single main peak to a double main peak pattern as the cement-to-sand ratio increases. The relaxation time T_2 values corresponding to the main peaks show no significant change (range is less than 5%), while the corresponding porosity increments increase markedly. This indicates that increasing the cement-to-sand ratio reduces the number of pore structures within the material, as evidenced by the cumulative porosity values. When the cement sand ratio decreases from 1:3 to 1:8, the average Φ_{total} of Groups A1–A5 increases from 17.528% to 25.054%, while that of Groups B1–B5 increases from 15.832% to 23.356%, indicating a significant increase in pore count. The primary reasons are as follows: As the cement-to-sand ratio decreases, the cement content gradually diminishes while the tailings content increases. This reduction in cement hydration products prevents effective filling of voids between tailings particles, leading to the formation of numerous pore structures. At the same cement-to-sand ratio, a higher mass concentration results in a significant reduction in the number of pore structures. This occurs because an increase in mass concentration leads to higher cement and tailings content, creating a denser internal structure within the filling material. Simultaneously, the amount of cementitious product gradually increases. These products fill the original pore spaces, reducing the number of pore structures and decreasing pore diameters, thereby enhancing the overall density. Additionally, centrifugal force drives free water out of the filling body, resulting in a sharp decrease in hydrogen atom content and a corresponding reduction in detectable relaxation signals in NMR. Compared to the saturated state, the porosity component corresponding to the T_2 spectrum after centrifugation is significantly

reduced and primarily exhibits a single peak distribution. This indicates that free water in relatively larger pores has been expelled from the filling material. Overall, the relaxation times corresponding to the main peak in both saturated and centrifuged states range approximately from 0.04~10 ms, corresponding to pore sizes between 0.00144~0.36 μm . This corresponds to the distribution range of micropores and mesopores.

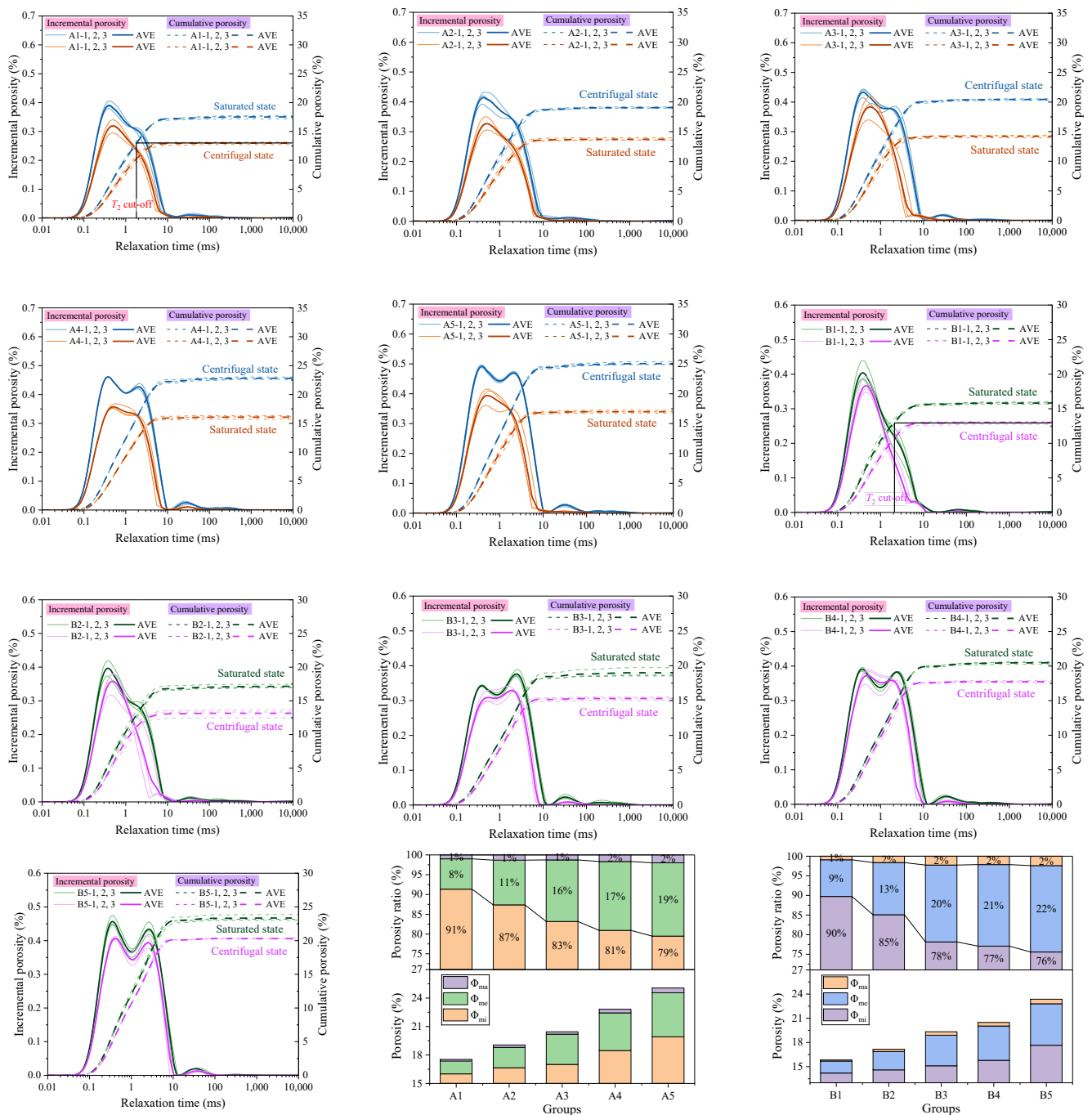


Figure 3. NMR T_2 spectra and pore structure distribution.

By examining the pore structure distribution characteristics diagram, it is evident that the filling material primarily consists of Φ_{mi} , followed by Φ_{me} , with the least amount being Φ_{ma} . The Φ_{mi} values for the fillings in Groups A1 to A5 were 16.009%, 16.641%, 16.999%, 18.459%, and 19.909%, respectively, and their porosity ratio exceeded 76%, each exceeding 79%. The Φ_{mi} values for the fillings in Groups B1–B5 were 14.206%, 14.598%, 15.100%, 15.779%, and 17.650%, respectively, and their porosity ratio exceeded 76%. Φ_{total} ,

Φ_{mi} , Φ_{me} , and Φ_{ma} all inversely correlate with the cement-to-sand ratio. As the cement-to-sand ratio decreases, the quantity of hydration products generated by cement hydration diminishes, while the usage of tailings gradually increases. This facilitates the formation of pore structures, leading to an increase in their number. As mass concentration increases, Φ_{total} and Φ_{mi} gradually decrease, resulting in a denser internal structure of the filler and reduced pore space.

When the material's Φ_{total} increases, Φ_{mi} , Φ_{me} , and Φ_{ma} also gradually increase. As the cement-to-sand ratio decreases, the proportion of Φ_{mi} in both Group A and Group B fillings gradually diminishes, while the proportions of Φ_{me} and Φ_{ma} progressively increase. At cement-to-sand ratios ranging from 1/3 to 1/8, the Φ_{mi} proportion in Group A fillings decreased from 91% to 79%, the Φ_{me} proportion increased from 8% to 19%, and the Φ_{ma} proportion rose from 1% to 2%. For Group B fillings, the Φ_{mi} proportion decreased from 90% to 76%, while the Φ_{me} proportion increased from 9% to 22% and the Φ_{ma} proportion rose from 1% to 2%. The reduced cement-to-sand ratio led to a gradual decrease in cementitious products, and the increasing tailings content resulted in a greater number of larger pore structures.

3.1.2. Fractal Dimension of Pore Structure

The fractal dimension of pores serves as a primary indicator for describing the homogeneity and complexity of pore structures. Generally, a higher fractal dimension indicates greater complexity in the pore structure. Based on the fractal dimension calculation formula, the values of D_{total} , D_{mi} , D_{me} and D_{ma} were obtained for fillings with different cement-to-sand ratios, as shown in Table 4, and fractal dimension fitting coefficients are all higher than 0.8.

Table 4. The calculation result of fractal dimension.

Fractal Dimension	D_{total} -AVE	$\pm SD$	D_{mi} -AVE	$\pm SD$	D_{me} -AVE	$\pm SD$	D_{ma} -AVE	$\pm SD$
Group A1	2.883	0.004	2.345	0.006	2.990	0.002	2.997	0.002
Group A2	2.872	0.004	2.253	0.023	2.960	0.006	2.997	0.001
Group A3	2.868	0.010	2.217	0.005	2.949	0.008	2.996	0.001
Group A4	2.864	0.001	2.180	0.001	2.940	0.002	2.995	0.000
Group A5	2.855	0.001	2.161	0.011	2.934	0.002	2.994	0.001
Group B1	2.841	0.004	2.268	0.005	2.982	0.003	2.999	0.001
Group B2	2.812	0.021	2.203	0.005	2.966	0.006	2.997	0.002
Group B3	2.807	0.004	2.180	0.011	2.948	0.006	2.996	0.002
Group B4	2.753	0.002	2.165	0.002	2.920	0.001	2.993	0.001
Group B5	2.746	0.006	2.147	0.002	2.914	0.002	2.992	0.001

It can be observed that D_{total} ranges from 2.855 to 2.883, D_{mi} from 2.161 to 2.345, D_{me} from 2.934 to 2.990, and D_{ma} from 2.994 to 2.997. As the cement-to-sand ratio decreases, D_{total} , D_{mi} , D_{me} and D_{ma} all decrease gradually, indicating reduced homogeneity and complexity of the total pores, mesopores, and macropores within the fillings. For Group B fillings, D_{total} ranged from 2.746 to 2.841, D_{mi} from 2.147 to 2.268, D_{me} from 2.914 to 2.982, and D_{ma} from 2.992 to 2.999. D_{total} , D_{mi} , D_{me} and D_{ma} all showed positive correlations with the cement-to-sand ratio. As mass concentration increased, D_{total} , D_{mi} , D_{me} and D_{ma} generally exhibited a decreasing trend, indicating that a reduction in pore structure quantity promotes the formation of a more homogeneous internal structure within the filling material.

3.2. The Evolution Characteristics of the Mechanical Strength of Filling Materials

Mechanical strength is one of the key characteristics of filling materials. According to the experimental design, the mechanical strength properties (σ_c , E_c , σ_t , E_t) of filling materials with different cement-to-sand ratios were obtained, as shown in Figure 4.

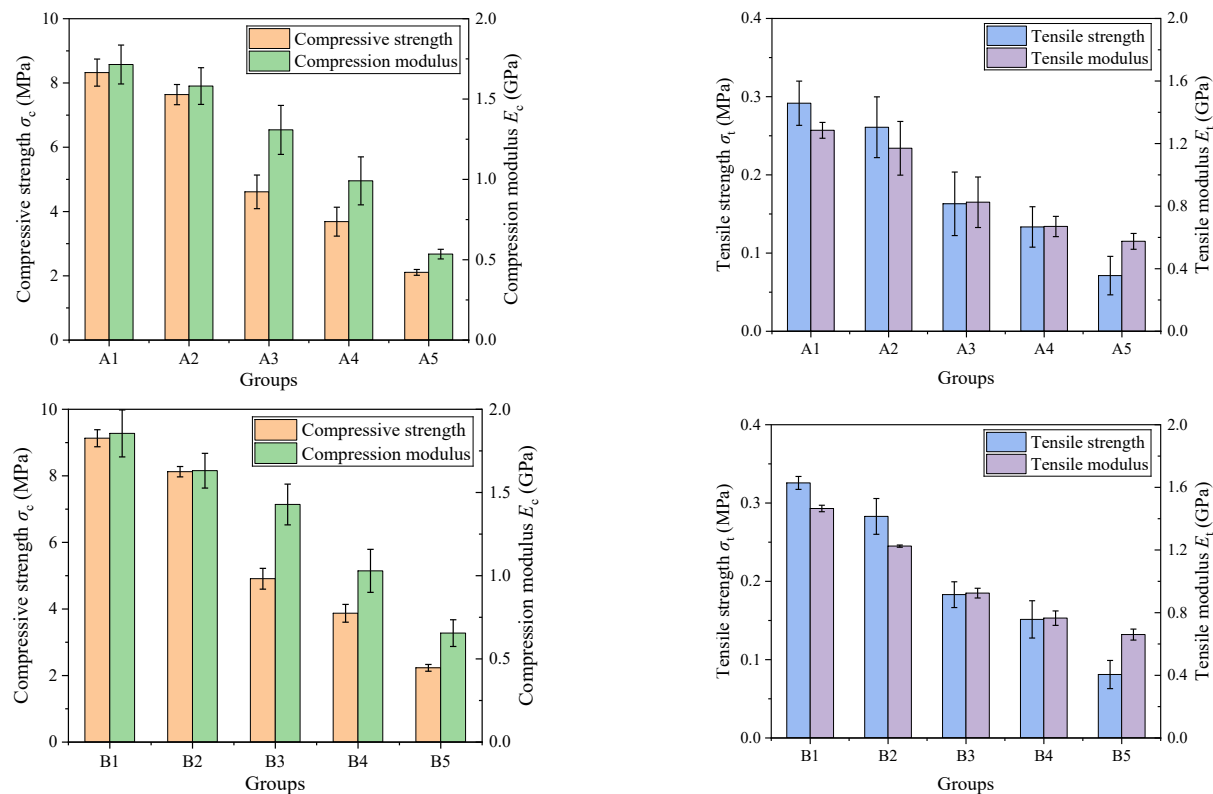


Figure 4. Evolution characteristics of the mechanical strength of backfill materials.

As shown in Figure 4, as the cement-to-sand ratio decreases, σ_c , E_c , σ_t and E_t all gradually decrease. For Groups A1 to A5, σ_c ranges from 2.107 to 8.321 MPa, E_c from 0.535 to 1.715 GPa, σ_t from 0.356 to 1.458 MPa, and E_t from 0.115 to 0.257 GPa. For Groups B1 to B5, σ_c ranges from 2.231 to 9.131 MPa, E_c from 0.655 to 1.885 GPa, σ_t from 0.405 to 1.628 MPa, and E_t from 0.132 to 0.293 GPa. As the cement-to-sand ratio decreases, cement usage gradually declines while tailings content increases. The hydration products generated by cement fail to effectively fill the voids between tailings particles, leading to a gradual reduction in the bonding strength between tailings. This, in turn, affects the material's σ_c , E_c , σ_t and E_t . Furthermore, an increase in Φ_{total} accelerates this process. As the number of pores increases, the solid skeleton area gradually decreases, leading to a reduction in the pressure the material can withstand under load. Simultaneously, the increased number of pore structures also increases the number of pore tip expansions, further deteriorating the material's strength. As mass concentration increases, the formation of hydration products from cement hydration progressively rises. This leads to a denser internal structure within the filling material, with gradually enhanced bonding strength between particles. Under load conditions, the number of pore tip expansions decreases, resulting in increased filling strength. The consistent trend in strength and modulus changes indicates that both reflect alterations in the material's internal structural integrity and micro-mechanical properties.

3.3. Multi-Scale Characteristic Analysis of Filling Materials

3.3.1. Porosity Fractal Dimension Correlation

The correlation characteristics between the pores of the filling material and the fractal dimension are shown in Figure 5. It can be observed that there is a good correlation between the porosity of the pore structure and its fractal dimension. The coefficient of determination for Group A fillings is higher than 0.777, while that for Group B fillings is higher than 0.631.

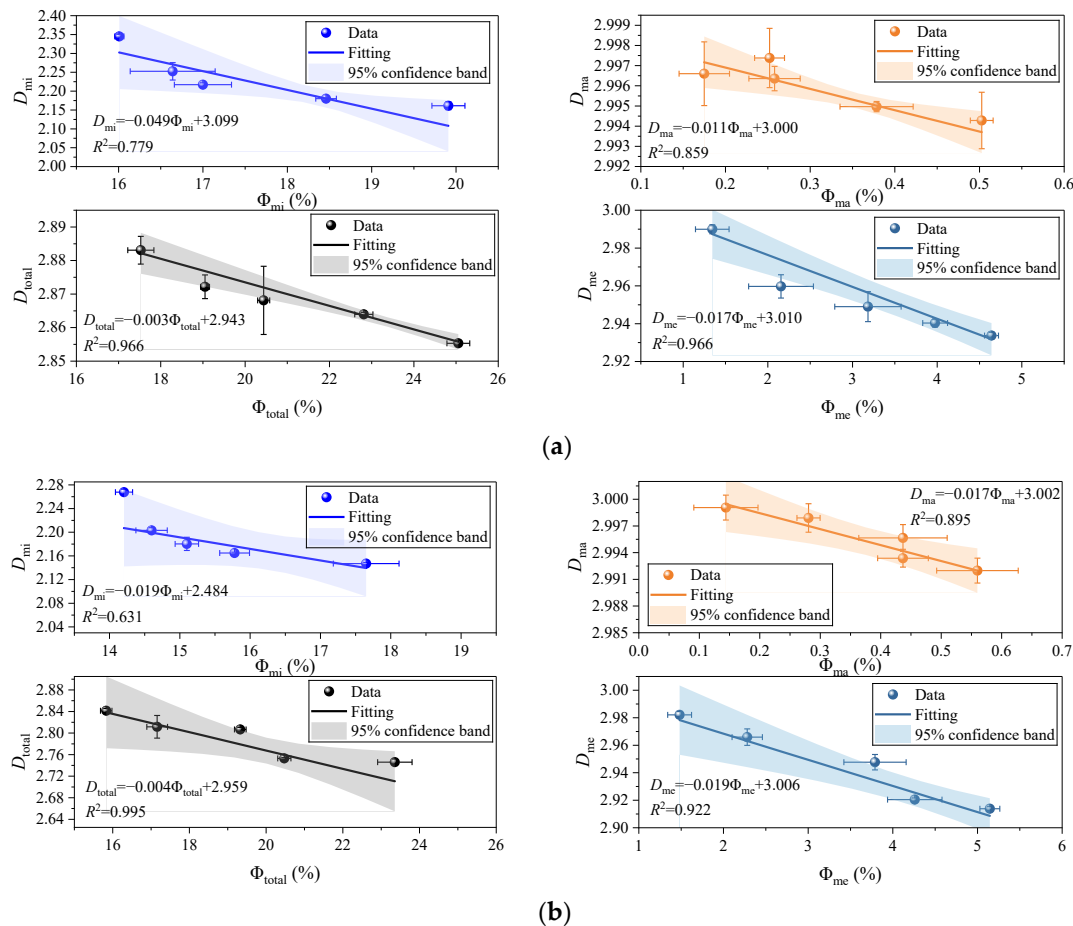


Figure 5. The relationship between porosity and fractal dimension. (a) Mass concentration 68%; (b) mass concentration 70%.

Specifically, the parameters Φ_{total} , Φ_{mi} , Φ_{me} , and Φ_{ma} in Groups A and B exhibit negative correlations with D_{total} , D_{mi} , D_{me} , and D_{ma} . This primarily stems from the following mechanism: as the cement-to-sand ratio decreases, Φ_{total} increases, enhancing pore connectivity and expanding pore space. Consequently, the structure transitions from complex and dense to sparse and simple, leading to a gradual reduction in D_{total} . Additionally, as Φ_{total} increases, Φ_{mi} , Φ_{me} , and Φ_{ma} all gradually increase. Due to the larger pore radius of mesopores and macropores, an increase in their quantity effectively expands pore space, gradually reducing the degree of pore structure complexity. Micropores serve to connect larger pore structures; when their quantity increases, the interconnectivity between pore structures strengthens, leading to a gradual decrease in D_{mi} .

3.3.2. Analysis of the Correlation Between Pore Structure, Porosity and Mechanical Strength

The microscopic structure determines macroscopic mechanical behavior. Analyzing the correlation between macro- and mesoscopic characteristics and establishing models is crucial for predicting material properties and optimizing designs. Therefore, the correlation between pore structure and mechanical strength is illustrated in Figures 6 and 7.

The figure demonstrates that Φ_{total} of Group A exhibits strong correlations with σ_c , E_c , σ_t and E_t , with correlation coefficients exceeding 0.922. This indicates that the formation of filling strength is closely linked to the quantity of pore structures. As internal defects within the material, pore structures readily create stress concentration zones around them. When subjected to loading, these stress concentration zones become susceptible to crack

initiation and propagation, thereby reducing the material's load-bearing capacity. Increased void structure quantity also reduces the effective cross-sectional area bearing external forces, leading to higher stress per unit area. Furthermore, interconnected voids disrupt internal structural continuity, weaken interparticle bonding in tailings, create pathways for crack propagation, and accelerate damage evolution. Consequently, Φ_{total} exhibits negative correlations with σ_c , E_c , σ_t and E_t .

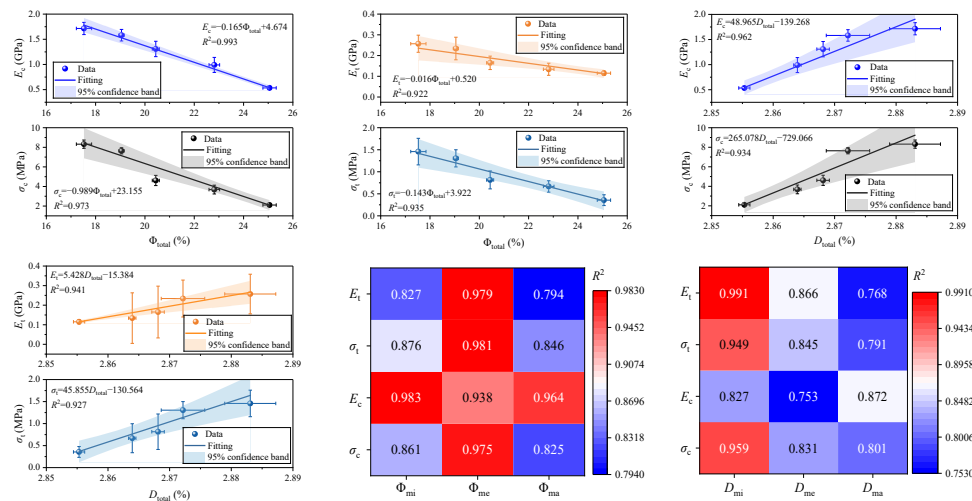


Figure 6. Pore structure–strength correlation analysis (mass concentration 68%).

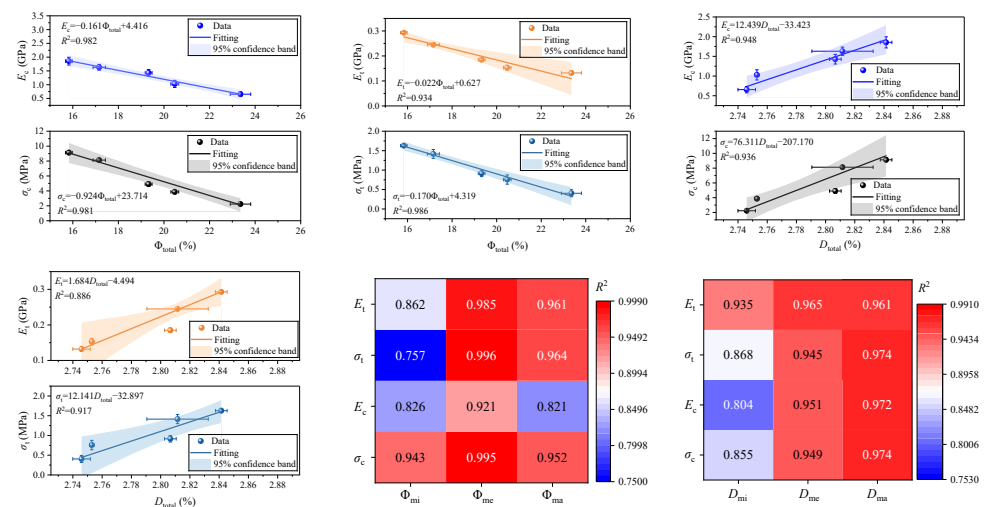


Figure 7. Pore structure–strength correlation analysis (mass concentration 70%).

D_{total} also exhibits strong correlations with σ_c , E_c , σ_t and E_t , with fitting coefficients all exceeding 0.927. As the overall porosity structure gradually increases in complexity, the network-like interconnections between pore structures become more intricate, strengthening the associations between individual pores and between pores and tailings particles. This characteristic disrupts the linear propagation path of cracks, forcing them to “de-tour,” “deflect,” or “branch,” thereby increasing the energy required for crack propagation (enhancing fracture toughness) and manifesting as improved macroscopic strength. Additionally, complex pores (e.g., micropores, reticular pores) can distribute stress over a larger area, effectively mitigating stress concentration and thereby promoting the development of material mechanical strength. Among the pore structure–mechanical strength correlation features, Φ_{mi} , Φ_{me} , and Φ_{ma} exhibit strong correlations with σ_c , E_c , σ_t and E_t , respectively, with fitting coefficients all exceeding 0.825. D_{mi} , D_{me} , and D_{ma} also showed good correla-

tions with σ_c , E_c , σ_t and E_t , respectively, with fitting coefficients all exceeding 0.753. This indicates that the development of mechanical strength results from the combined effects of pores with different diameters within the material.

As Φ_{mi} increases, the specific surface area of pores expands, making it prone to becoming a micro-defect concentration zone. Mesopores typically constitute the primary component of capillary pores; their increased quantity significantly reduces the material's density and strength. Macropores represent the weakest structural defects within the material, readily becoming stress concentration points and crack initiation sites under loading. In Figure 3, as the cement-to-sand ratio increases, the pore volume fractions of mesopores and macropores gradually rise, while that of micropores decreases. This indicates that mesopores and macropores progressively become the key microstructures governing the mechanical evolution of the filling material. It should be noted that a single pore structure cannot explain the cause of mechanical changes; the evolution characteristics of mechanical strength are often the result of the combined effects of micropores, mesopores, and macropores.

Figure 7 shows that a strong correlation also exists between the pore structure and mechanical strength of Group B fillings, with correlation coefficients all exceeding 0.757. Specifically, Φ_{total} exhibits negative correlations with σ_c , E_c , σ_t , and E_t , while D_{total} shows positive correlations with σ_c , E_c , σ_t , and E_t . As the number of pores increases, the complexity of the pore structure gradually decreases, reducing the effective skeletal support area within the material. When specimens are loaded, stress concentration tends to occur at pore tips, leading to a gradual decrease in strength. However, as pore complexity increases, pores form a dense network structure that effectively disperses and disrupts crack propagation paths, resulting in a gradual increase in material strength. This trend aligns with the changes observed in Figure 6. Furthermore, Φ_{mi} , Φ_{me} , and Φ_{ma} exhibit strong correlations with σ_c , E_c , σ_t , and E_t , with fitting coefficients exceeding 0.757. Similarly, D_{mi} , D_{me} , and D_{ma} demonstrate correlation coefficients above 0.804 with these mechanical properties. Similar to the formation mechanism of a mass concentration of 68%, the development of mechanical strength also stems from the combined effect of pores with different diameters within the material.

3.3.3. The Correlation Between Pore Structure Characteristics and Permeability Coefficient

According to Equation (3), the permeability coefficient K of Group A filling material ranges from 9.926 to 16.903 mD, while that of Group B filling material ranges from 7.014 to 15.691 mD. Both gradually increase as the cement-to-sand ratio decreases, indicating enhanced pore connectivity. As mass concentration increases, the permeability coefficient gradually decreases. This indicates that a smaller number of pore structures results in a relatively lower permeability coefficient. The correlation between pore structure characteristics and permeability coefficient is illustrated in Figure 8. It can be observed that in Group A, Φ_{total} , Φ_{mi} , Φ_{me} , and Φ_{ma} all exhibit strong correlations with K (coefficients > 0.932). Similarly, in Group B, Φ_{total} , Φ_{mi} , Φ_{me} , and Φ_{ma} also demonstrate strong correlations with K (coefficients > 0.881). As the number of pores increases, the pore volume gradually expands and the connectivity between pores progressively strengthens, facilitating the formation of flow pathways. Simultaneously, the increased pore volume reduces the flow resistance of fluids through the material and lowers viscous resistance, leading to a gradual increase in the permeability coefficient K . Therefore, Φ_{total} , Φ_{mi} , Φ_{me} , and Φ_{ma} all exhibit positive correlations with permeability coefficient K . Groups A and B also show strong correlations between D_{total} , D_{mi} , D_{me} , and D_{ma} with the permeability coefficient K , with fitting coefficients exceeding 0.871. Notably, D_{total} , D_{mi} , D_{me} , and D_{ma} all exhibit negative correlations with K . As the overall pore structure complexity increases, fluid flow paths

lengthen, and the friction surface area along flow channels expands. This reduces the number of effective permeation pathways, causing the permeability coefficient to gradually decrease. Additionally, micropores serve to connect larger pores. As the number of pores increases, pore volume expands and inter-pore connectivity strengthens, facilitating flow pathways. When the complexity of micropores increases, their networked interlacing structure also contributes to an increase in permeability.

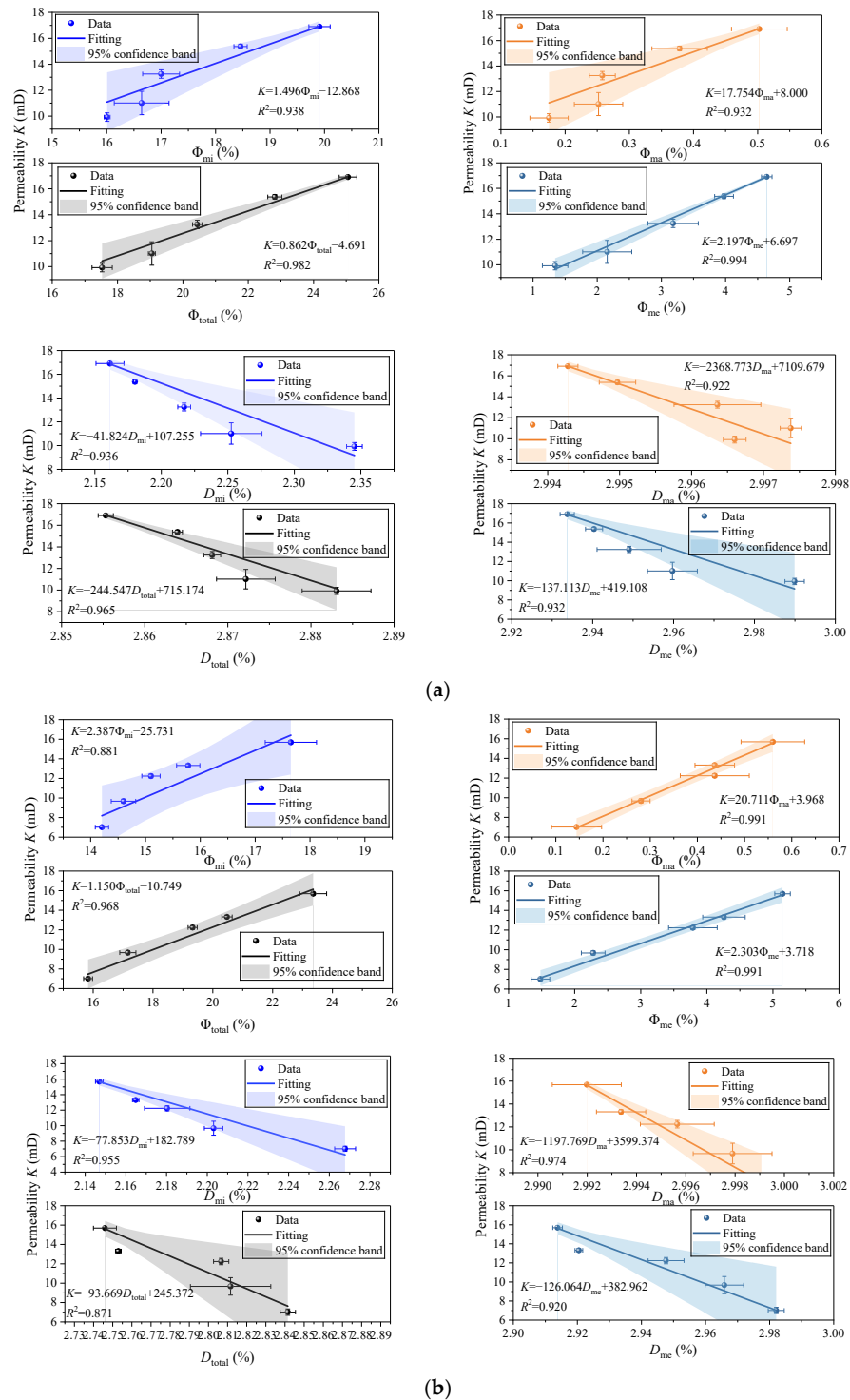


Figure 8. Pore structure–permeability correlation analysis. (a) Mass concentration 68%; (b) Mass concentration 70%.

4. Discussion

Based on the analysis results of the correlation between pore structure characteristics and mechanical strength, a correlation analysis model linking microstructure and mechanical strength was established. In Figures 6 and 7, due to the differences in σ_c and σ_t exhibited by the 68% and 70% mass concentration fillers, the correlation between pore structure and mechanical strength for fillings of different mass concentrations was considered separately, without comprehensive consideration. This section addresses this limitation by discussing the process of establishing strength prediction models for fillings with varying mass concentrations and cement sand ratios, while also analyzing the reliability of these prediction models.

Figure 9 displays the correlation between pore structure and σ_c for fillings with different mass concentrations and cement sand ratios. It can be observed that Φ_{mi} , Φ_{me} , Φ_{ma} , D_{mi} , D_{me} , and D_{ma} for fillings with varying mass concentrations and cement-to-sand ratios all exhibit good correlations with σ_c and σ_t . Among these, Φ_{me} yields the best fitting results with both σ_c and σ_t , with fitting coefficients of 0.945 and 0.980, respectively. Therefore, when constructing the strength prediction model, Φ_{me} is selected as the pore structure parameter.

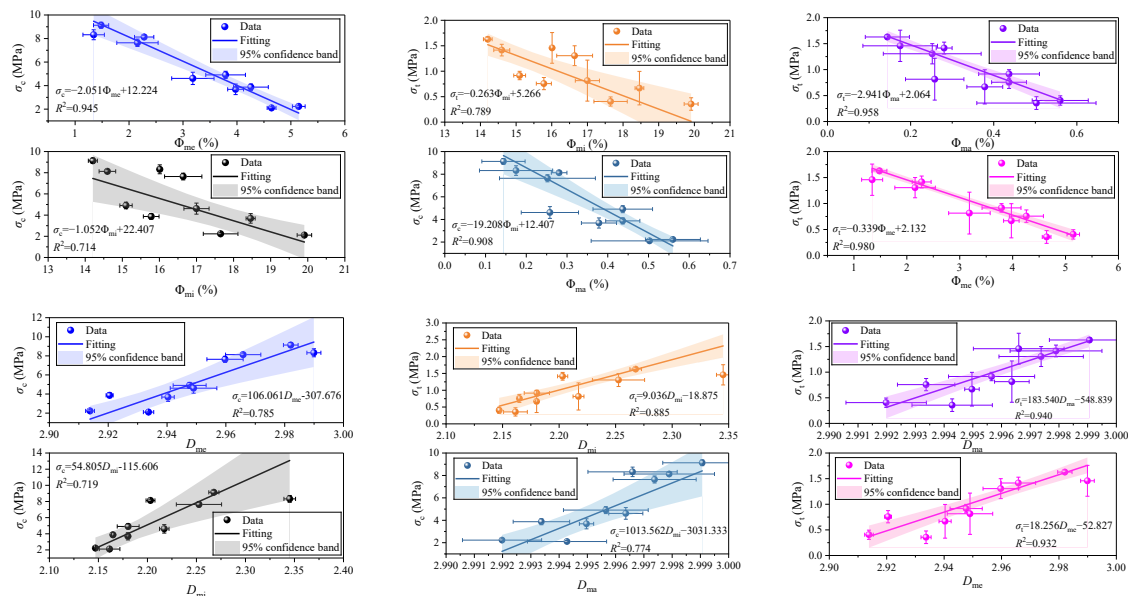


Figure 9. Pore structure–strength correlation analysis.

Simultaneously, parameters representing the inherent characteristics of the filling material itself are denoted as E_c and E_t , respectively. A predictive model for the mechanical strength of filling materials with varying mass concentrations and cement-to-sand ratios is established, as shown in Equations (4) and (5). In these models, Φ_{me} is an independent variable with respect to both E_c and E_t . It should be noted that E_c and E_t characterize the characteristics of the filling body itself (such as aggregate particles, etc.), while Φ_{me} is selected for the characterization of pore structure characteristics; the introduction of $\Phi_{me} \times E_c$ and $\Phi_{me} \times E_t$ explains the combined effect of macroscopic and microscopic parameters. Both E_c and E_t models are constructed using average values. After obtaining the fundamental parameters, the validity of the models will be cross-validated using data from parallel samples.

$$\sigma_c = \alpha_0 + \alpha_1\Phi_{me} + \alpha_2E_c + \alpha_3(\Phi_{me} \times E_c) \quad (4)$$

$$\sigma_t = \beta_0 + \beta_1\Phi_{me} + \beta_2E_t + \beta_3(\Phi_{me} \times E_t) \quad (5)$$

In the equation, $\alpha_0, \alpha_1, \alpha_2, \alpha_3$ and $\beta_0, \beta_1, \beta_2, \beta_3$ are model parameters.

Figure 10 presents the fitting analysis of measured versus predicted values for the strength of the filling. Here, σ_c -predicted denotes the value calculated using Equation (4) and the parameters from Table 5, while σ_c -measured represents the value obtained from experimental testing. Similarly, σ_t -predicted indicates the value calculated using Equation (5) and the parameters from Table 5, and σ_t -measured denotes the value obtained from experimental testing. It can be observed that the coefficient of determination for both the measured and predicted values of the filling strength in Figure 10a,b exceeds 0.976, indicating that the established strength prediction model effectively represents the relationship between measured and predicted values. Compared to Figures 6 and 7, the prediction model effectively addresses the strength prediction relationship for filling materials with varying mass concentrations and cement-to-sand ratios, demonstrating superior predictive capability. Furthermore, when filling materials exhibit differences in mass concentration and cement-to-sand ratio, establishing a strength model should comprehensively consider the combined effects of pore structure and material-specific characteristics. The results of cross-validation using parallel sample data for model fitting parameters also demonstrate good correlation. It can be observed that the fitting coefficients all exceed 0.972, and the slopes of the fitted lines are all close to 1, further validating the rationality of the strength prediction model.

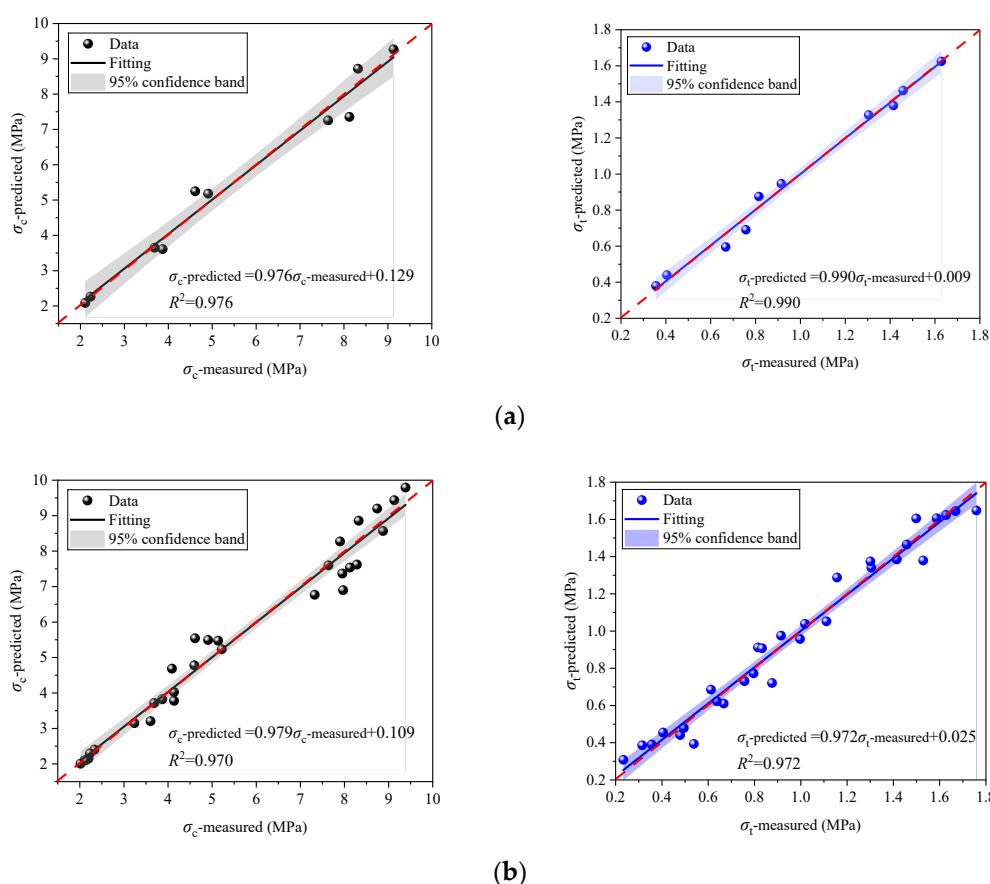


Figure 10. Fitting results of measured and predicted strength values. (a) The model fitting result using the average strength value. (b) Cross-validation of strength prediction models.

Table 5. Values of model parameters.

Strength	/	α_0	α_1	α_2	α_3
Compression	Value	−0.261	0.199	6.068	−0.735
Strength	Equation	$\sigma_c = -0.261 + 0.199\Phi_{me} + 6.068E_c - 0.735(\Phi_{me} \cdot E_c)$			
	/	β_0	β_1	β_2	β_3
Tensile	Value	0.618	−0.228	3.398	0.803
	Equation	$\sigma_t = 0.618 - 0.228\Phi_{me} + 3.398E_c + 0.803(\Phi_{me} \cdot E_t)$			
		$R^2 = 0.964$ $p < 0.0001$ $R^2 = 0.985$ $p < 0.0001$			

5. Conclusions

The main conclusions of this paper are as follows:

- (1) The Φ_{total} gradually increases as the cement-to-sand ratio decreases, with Φ_{mi} dominating over 79% of the total. The porosity component corresponding to the T_2 spectrum of centrifugal specimens shows a significant reduction, indicating substantial free water separation from the filling material. As the cement-to-sand ratio decreases, hydration products gradually diminish, leaving voids between tailings particles unfilled. Consequently, Φ_{total} , Φ_{mi} , Φ_{me} , and Φ_{ma} progressively increase. As mass concentration increases, the filling material becomes denser, resulting in more hydration products and reduced pore space, thereby decreasing Φ_{total} .
- (2) As the cement-to-sand ratio decreases or the mass concentration diminishes, the complexity of total pores, micropores, mesopores, and macropores progressively increases, revealing a strong correlation between porosity and fractal dimension. σ_c , E_c , σ_t and E_t are positively correlated with the cement-to-sand ratio. The reduction in hydration products lowers the bonding strength between tailings particles, accelerating the expansion of pore tips under loading. As mass concentration increases, the internal structure of the filling material becomes denser, resulting in enhanced bonding strength. Under load conditions, the number of pore tip expansions decreases, leading to increased strength.
- (3) Pore structure characteristics exhibit strong correlations with mechanical strength, confirmed by strength prediction models. As Φ_{total} increases, the solid skeleton area gradually decreases, the number of expanding pore tips increases, and the pressure resistance under loading gradually decreases. When D_{total} increases, the networked interlacing structure between pores also becomes more complex, which helps mitigate stress concentration phenomena.
- (4) The K of Group A filling material is located between 9.926 and 16.903 mD, while the K of Group B is located between 7.014 and 15.691 mD. It gradually increases as the cement-to-sand ratio decreases and gradually decreases as the mass concentration increases. A strong correlation also exists between pore structure characteristics and K . As pore quantity increases, pore connectivity gradually enhances, reducing fluid flow resistance. However, increased pore complexity lengthens seepage pathways, diminishing the number of effective permeable channels and thereby decreasing K values.

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Data Availability Statement: The dataset is available on request from the authors; the raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: Author Wei Wang was employed by the company Tibet Huatailong Mining Development Co., Ltd. Authors Yajun Wang, Weixing Lin, Long Dou, Dongrui Liu and Yuding Wang were employed by the company Changsha Institute of Mining Research Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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