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Experimental investigation on the relationship between pore characteristics and unconfined compressive strength of cemented paste backfill

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HIGHLIGHTS

- The pore characters of CPB were obtained using NMR and SEM technologies.
- The relation between pore characteristics and UCS of CPB was investigated.
- The "damaging" and "multi-damaging" pores had negatively influence on the UCS.
- UCS decreased exponentially as the porosity increased.
- UCS had a linearly inverse proportional relation to the fractal dimension.

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ABSTRACT

In this paper, the pore structure characteristics of CPB specimens were characterized using nuclear magnetic resonance (NMR) and scanning electronic microscopy (SEM) techniques, and the relationship between the unconfined compressive strength (UCS) and the pore characteristics of cemented paste backfill (CPB) was investigated. The results showed that the pores in CPB specimens were mainly small, "non-damaging" ones, which accounted for about 70 vol% of all pores in CPB specimens. Although the "damaging" and "multi-damaging" pores only accounted for 3.93 vol% and 6.99 vol% of all pores respectively, they had significant impacts on the UCS of CPB specimens. With the increase of curing time, the porosity of CPB specimens decreased gradually (i.e. the average porosities of CPB specimens at the curing time of 3 d, 14 d and 28 d were 11.07 vol%, 8.58 vol% and 7.09 vol%, respectively). Besides, the porosity of CPB specimens also decreased with the increase of solid concentration of CPB slurry. On the basis of fitting analysis, it could be observed that there was a negatively exponential relationship between the UCS and the porosity of CPB specimens and a linearly inverse relationship between the UCS and the fractal dimension. Our study demonstrates that it is feasible to study the relationship between mechanical properties and pore characteristics of CPB specimens by using the NMR technique.

1. Introduction

Cemented paste backfill (CPB) is playing more important role in the mining industry due to its technical, economic and environmental benefits. CPB provides secondary self-supporting after being placed underground for cost-effective mining operations and safety concerns. Meanwhile, it can also reduce the amount of environmental hazards and the costs of tailings management as they are diverted into underground goafs or stopes [1–6].

In recent years, a number of studies have been carried out to investigate the relationship between the pore characteristics and the macroscopic properties (i.e., strength, permeability, and shrinkage) of CPB [7,8]. Many physical methods, e.g. mercury intrusion porosimetry (MIP), micro-CT, nuclear magnetic resonance (NMR),

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Nomenclature

T_2	Transverse relaxation time, ms
T_{2B}	Free relaxation time of free fluid, ms
S	Surface area of pore, cm^2
V	Pore volume, cm^3
ρ_2	Lateral surface relaxation strength, μm/ms
D	Diffusion coefficient
γ	Gyromagnetic ratio, rad/(S·T)
G	Magnetic field gradient, Gs/cm
TE	Echo time, ms
F_S	Pore-shape factor (3 for spherical pores; 2 for tube bundle pores)
m_i	NMR T_2 spectrum amplitude of the i_{th} T_2 component of the specimen
M_b	The total amplitude of the standard specimen T_2 spectrum
S_b	Number of scans of standard specimens during NMR data acquisition
S	Number of scans of the test specimen during NMR data acquisition
G_b	Receiving gain of the standard specimen during NMR data acquisition
G	Receiving gain of the test specimen during NMR data acquisition
V_b	The total water content of the test specimen, cm^3
$V_{specimen}$	specimen volume, cm^3
σ_C	Unconfined compressive strength (UCS), MPa

Abbreviations

CPB	Cemented paste backfill
NMR	Nuclear magnetic resonance
MIP	Mercury intrusion porosimetry
UCS	Unconfined compressive strength
XRD	*X*-ray Diffraction
SEM	Scanning electron microscopy
Aft	Ettringite
C-S-H	Calcium silicate hydrates

etc., have been used to study the pore geometry and pore structure of porous materials. Dong et al. [9] analyzed the effect of pore structure of coal gangue fine aggregate cement hardened mortar on the coal strength using MIP and X-ray diffraction (XRD). Rong et al. [10] investigated the pore structure evolution of sulfate-containing CPB and discussed the effect on the strength based on the pore structure information obtained from MIP. However, the MIP technique has some limitations on characterizing the pore distribution of cement based materials. For example, very small pores with diameters between 1 and 3 nm in the materials cannot be penetrated by mercury; "ink-well" pores in cement based materials can result in an inaccurate characterization of the pore structure [11–13]. Li et al. calculated the porosity and pore size of clay rock in coal stratum based on the micro-CT image [14]. Sun et al. studied the patterns of porosity evolution during the bearing failure of CPB by using X-ray CT [15]. However, there was no universal standard for three-dimensional (3D) reconstruction of CT images, which resulted in objective results and conclusions [16]. NMR is a non-intrusive technique for characterizing porous materials. The porosity, pore structure characteristics, and fluid content of rocks can be obtained through analyzing the NMR relaxation time [17,18]. Zhou et al. [19] studied the granite pore structure characteristics using NMR. Li et al. [20] used NMR to study the relationship between pore development and unconfined compressive strength (UCS) of thawed granite. Li et al. [21] studied the micropore distribution of coal with different structures using NMR and MIP techniques. Zhang et al. [22] studied the influence of admixture on chloride time-varying diffusivity and microstructure of concrete by using the low-field NMR technique. Ai et al. [23] studied the effects of curing age, solid concentration and cement/sand ratio on the evolution of pores in CPB based on the NMR T_2 spectrum.

A number of studies have been conducted to investigate the mechanical properties of CPB specimens by other non-destructive methods such as electric resistivity measurement, ultrasonic pulse velocity test, and artificial intelligence (AI) techniques. For example, Xu et al. [24] investigated the correlation between the UCS and electricity resistivity of CPB samples prepared with different solid contents and cement dosages. Yılmaz et al. [25] used ultrasonic pulse velocity (UPV) test to investigate the predictability of the UCS of CPB. Qi et al. [26] proposed a CPB strength prediction model with BRT and PSO, and found that the cement-tailings ratio was the most important variable of CPB strength. Orejarena et al. [27] used an artificial neural network methodology to model and analyze the coupled effects of sulphate and temperature on the strength of CPB material. Although these studies pave new ways for investigating the mechanical properties of CPB specimens, they haven't investigate pore distribution characteristics and pore size of CPB, which have important influence on CPB strength [20]. Therefore, NMR has a certain superiority in the study of UCS through taking pore structure characteristics of CPB into consideration.

To sum up, previous studies mainly investigated the effects of microstructure and pore distribution on the strength, permeability and durability of rock, coal or concrete, but rarely studied the microscopic pore structure of CPB by using the NMR technique. Moreover, these studies paid little attention to the relationship between the strength and the porosity and pore structure of CPB, and did not involve the fractal dimension in analyzing CPB microstructure. As well, the NMR technique had seldom been applied to study the relationship between the pore structure characteristics and the UCS of CPB. On account of this, in this study, NMR was applied to characterize the micropore structure characteristics including pore size distribution, porosity and fractal dimension of CPB specimens. Next, the relationship between the pore characteristics and UCS of CPB specimens was established.

2. Materials and methods

2.1. Materials

2.1.1. Tailings

The tailings utilized in this study were obtained from a tungstic mineral dressing plant in Jiangxi Province of China. The tailing slurry was filled in plastic buckets for natural sedimentation of seven days. After that, the upper layer clear water was removed and the left sedimentation was dried for preparing CPB specimens. Fig. 1 shows the procedure of extracting the tailings. According to the *Specification of Soil Test* i.e., SL 237-1999, SL 237-005-1999 and SL 237-004-1999 [28], the specific gravity, bulk density and porosity of the tailings were measured (as shown in Table 1). Fig. 2 presents the particle size distribution (PSD) of the tailings. As can be