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Article

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Application of Microwave Dielectric Constant in Coal Mine Microseismic Monitoring

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Abstract

This paper systematically investigates the variation laws of the dielectric constant in the microwave frequency band by measuring the dielectric constants of different coal types, briquettes, and pulverized coal. The effects of moisture content, pore structure, and coal rank on the dielectric constant are analyzed emphatically. The results show that the presence of water significantly improves the electrical conductivity of coal, reduces its energy storage capacity, and makes the real part curve of the dielectric constant smoother. Meanwhile, a characteristic absorption peak related to the hydrogen bond of water molecules appears in the imaginary part, which broadens with the increase of moisture content and can be used to infer the water content of coal seams and the law of water migration. Due to the heterogeneous pore structure, the dielectric constant of natural coal fluctuates violently, while that of compacted pulverized coal samples with uniform pore distribution fluctuates slightly. The change of pore structure (e.g., stress deformation and fragmentation) directly leads to a sharp fluctuation in the real part of the dielectric constant, providing a basis for the prediction of rock burst. The higher the coal rank (e.g., Shanxi coking coal), the smaller the water absorption peak, and the stronger the correspondence between the dielectric constant and the infrared spectrum. The abundance of functional groups is positively correlated with the number of absorption peaks in the imaginary part. However, high moisture content masks the microstructural characteristics of coal and interferes with the measurement results. The revealed dielectric response laws provide theoretical support for characterizing the structure, moisture content, and deformation-fracture process of coal using the dielectric constant.

Keywords: Rock burst; Dielectric constant; Microwave perturbation; Stress coupling; Field verification; Coalification degree

0 Introduction

The occurrence of dynamic disasters in coal mines is closely related to the stress evolution of coal and rock and the dynamic propagation of fractures. The coupling effect of stress accumulation, structural degradation, and groundwater infiltration is the core issue of such disasters [1-3]. As a core technology for capturing coal and rock fracture information, microseismic monitoring has become an important means for early warning of dynamic disasters in coal mines. However, single microseismic monitoring suffers from issues such as limited positioning accuracy and lagging characterization of stress evolution. Traditional monitoring technologies (e.g., vibration sensors, stress meters) can only capture abrupt changes in a single physical quantity and are mostly post-disaster responses, making it difficult to cover the multi-stage micro-evolution process of disaster incubation [4-5].

Pure and dry coal is non-conductive or weakly conductive. However, in practice, coal exhibits semiconductor properties due to the presence of impurities, moisture, and free charges in pores. A dielectric stores electric field energy through polarization; the larger the real part of the dielectric constant, the more energy is stored via polarization. An electric field causes regular relative displacement of charges inside the dielectric, forming electric dipoles, and converts electric field energy into polarized energy stored in the dielectric. This displacement is constrained by the dielectric structure and cannot form a free current; charge displacement is confined to microscopic directional movement only. In a dielectric with a small dielectric constant, the macroscopic current of free charges dissipates electrical energy in the form of heat or work rather than storing it. The variation in the dielectric constant is coupled with the stress state of coal and rock and the development degree of pores and fractures. Combining the dielectric constant with microseismic monitoring can compensate for the deficiencies of microseismic monitoring technology. Studies have confirmed that the microwave perturbation

method can identify coal quality, coalification degree, moisture content, and fracture development degree through changes in the dielectric constant [6]. Dielectric properties describe the degree of polarization of a dielectric under an external electric field [7-23], and indirectly reflect coal quality, coalification degree, and the extent of water intrusion into coal. Generally, an increase in water content causes a significant change in the dielectric constant.

In this paper, the microwave perturbation method is used to study the characteristics of the dielectric constant of coal with different coalification degrees and the variation of the dielectric constant of coal with different moisture contents. For coal with a low coalification degree, functional groups in coal dissipate energy through infrared vibration. The dielectric constant of the pore structure is approximately 1, similar to air. Inhomogeneous pore distribution introduces noise into the real part curve of the dielectric constant, causing a jagged fluctuation. Coal with high moisture content increases the dielectric constant, and water significantly interferes with the infrared and dielectric constant measurements of coal. The real part curve exhibits two broad inflection points, which can be attributed to water infiltration into the coal seam and damage to the pore structure. The imaginary part curve of the dielectric constant reflects the trend of energy loss variation. By analyzing the changes in the dielectric constant, various microscopic changes in the coal seam before the occurrence of rock burst can be determined, providing theoretical support for the early prediction of rock burst.

1 Experiments

1.1 Theory of Microwave Transmission in Media

Compared with ordinary electromagnetic waves, microwaves differ only in wavelength. Microwaves refer to electromagnetic waves with a wavelength range of 1 - 1000 mm, corresponding to a frequency range of 0.300 - 300 GHz. Media such as coal, water, and semiconducting materials absorb microwaves and generate heat. In practice, lossy media are characterized by complex dielectric parameters. According to

electromagnetic field theory, the complex permittivity is expressed as $\varepsilon = \varepsilon' - j\varepsilon''$, where the loss factor is $\tan\delta_\varepsilon = \frac{\varepsilon''}{\varepsilon'}$. Generally, the loss in such media is caused by electrical conductivity, so it can also be expressed as $\varepsilon'' = \frac{\sigma}{\omega}$, where σ is the electrical conductivity, ω is the angular frequency, and ε 0 is the vacuum permittivity.

$$k = \omega\sqrt{\mu\varepsilon'}\left(1 - j\frac{\varepsilon''}{\varepsilon'}\right)^{1/2}$$

Express the complex number as:

$$k = \beta - j\alpha$$

It is not difficult to derive that:

$$\alpha = \omega\left\{\frac{\mu\varepsilon'}{2}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right)\right\}^{1/2} \qquad \beta = \omega\left\{\frac{\mu\varepsilon'}{2}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} + 1\right)\right\}^{1/2}$$

It can be seen that when a plane microwave propagates in a nonlinear medium, in addition to its phase varying with distance according to the propagation constant, its amplitude also decays exponentially with distance according to the attenuation constant. In this case, the wave impedance is

$$\eta = \sqrt{\frac{\mu}{\varepsilon}} = \sqrt{\frac{\mu}{\varepsilon'}}\left(1 - j\frac{\varepsilon''}{\varepsilon'}\right)^{1/2}$$

In good conductors, the electric field and magnetic field are no longer in phase; instead, the electric field always leads the magnetic field. Microwaves experience rapid attenuation when propagating in good conductors and can hardly penetrate deep into their interiors. Generally, the electromagnetic field energy is concentrated on the surface of good conductors. For this reason, a skin depth is defined to describe the penetration ability of microwaves into conductors, with its specific definition formula given as:

$$\delta = \frac{1}{\alpha}$$

That is, the thickness that microwaves propagate when their amplitude decre

ases to 0.37 of the original value. For the variation of permittivity with frequency, the Debye formula is given by:

$$\varepsilon_r^{'}(\omega) = \varepsilon_{r(\infty)} + \frac{\varepsilon_{r(0)} - \varepsilon_{r(\infty)}}{1 + \omega^2\tau^2}$$

$$\varepsilon_r^{''}(\omega) = \frac{(\varepsilon_{r(0)} - \varepsilon_{r(\infty)})\omega\tau}{1 + \omega^2\tau^2}$$

$$\tan\delta(\omega) = \frac{(\varepsilon_{r(0)} - \varepsilon_{r(\infty)})\omega\tau}{\varepsilon_{r(0)} - \varepsilon_{r(\infty)}\omega^2\tau^2}$$

Wherein $\varepsilon_{r(0)}$ is the permittivity under static conditions, corresponding to the case of a constant electric field $\omega = 0$; $\varepsilon_{r(\infty)}$ is the permittivity at high frequencies, corresponding to the case of optical frequency; and τ is the relaxation time. The plotted curves are divided into the real part and the imaginary part, where the real part curve represents the electrical energy storage and the imaginary part curve represents the energy loss.

1.2 Experimental Apparatus and Sample Preparation

Longjiabao long-flame coal, Fuxin long-flame coal, Shanxi coking coal and Huolinhe lignite were selected as the test samples in this experiment. The coaxial probe method was adopted for the test, which is a microwave measurement method for obtaining the complex microwave permittivity of materials by attaching an open-ended coaxial probe tightly to the measured material and measuring the reflection coefficient (or input admittance) at the probe terminal. The microwave frequency was set in the range of 0.400～19.0 GHz. Coal samples with the dimension of 8×8×8 cm were prepared for the test. The complex permittivity of the coal samples was measured using an Agilent PAN Series E8362B microwave network analyzer equipped with an electronic calibration kit, an 85070E probe and the Agilent 85071E software toolkit, with the probe calibrated prior to the measurement.

1.3 Proximate Analysis and Ultimate Analysis of Coal

The experimental equipment adopted for the proximate and ultimate analyses of coal was a 5E-MAG6700 automatic proximate analyzer. This analyzer was used to

determine the mass percentages of proximate components in the coal samples: moisture (Mad), ash (Aad), volatile matter (Vad), and fixed carbon (FCad), as well as the contents of elements C, H, O, N, and S in the coal samples. The results of the proximate analysis and partial ultimate analysis of the coal samples are shown in Table 1.

Table I Data of industrial analysis and elemental analysis of coal

Raw Coal Origin	Proximate analysis w/%				Ultimate analysis w/%				
	Mad	Aad	Vad	FCad	C	H	O	S	N
Longjiabao Long-Flame Coa	2.34	32.77	44.48	55.45	79.74	5.60	12.49	0.70	1.40
Fuxin Long-Flame Coal	4.07	18.98	39.89	60.09	79.49	5.33	13.52	0.31	1.33
Shanxi Coking Coal	0.56	33.68	24.47	50.09	78.63	12.46	4.90	1.82	1.26
Huolinhe Lignite	2.42	20.14	30.12	47.23	63.47	3.72	7.97	1.33	0.95

Indicator symbols (Mad, Aad, FCad) are in italics, which conforms to the typesetting standard of physical quantity symbols in academic papers;Element symbols (C, H, O, N, S) are in uppercase, which is consistent with the international standard for chemical element symbols.

2 Results Analysis

2.1 Characteristics of Dielectric Constant of Different Coal Qualities

Long-flame coal is named for its particularly high volatile matter content, which produces a long flame during combustion. It has very weak caking property, generally does not coke, and is a non-coking coal, mainly used as power coal and chemical coal. Typical long-flame coal varieties in China include Fuxin coal and Diaobingshan coal in Liaoning Province.Coking coal is a transitional coal between coking coal, fat coal and gas coal. It has strong caking property and medium to high volatile matter content. When used alone for coking, it can form coke with good fusibility and high strength. Coking coal is a good basic coal for blending coking.Lignite is the mineral coal with the lowest coalification degree, a brownish-black, lusterless low-grade coal between peat and bituminous coal. It has strong chemical reactivity, is easy to weather in air, difficult to store and transport over long distances, and causes serious air pollution when burned. Lignite

has high moisture content, high volatile matter content (>40%), contains free humic acid, is easy to weather and break into pieces in air, and has a low ignition point (about 270° C).

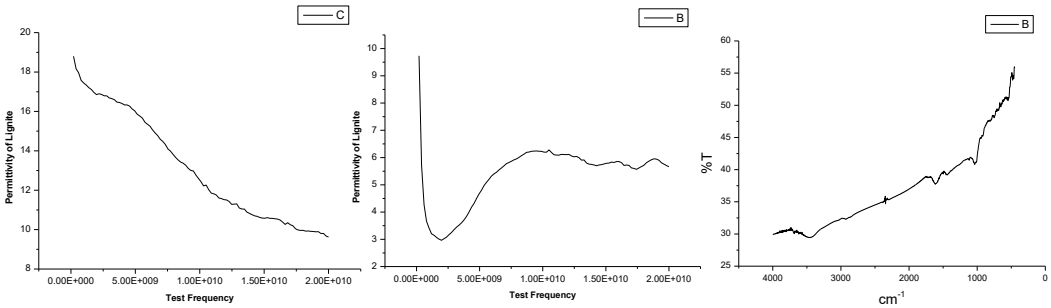


Figure 1 The real part curve, imaginary part curve of dielectric constant and infrared spectrum of Longjiabao long-flame coal in Jilin.

Figure 1 shows the real part curve, imaginary part curve of dielectric constant and infrared spectrum of Longjiabao long-flame coal in Jilin. It can be seen from the real part curve of Longjiabao long-flame coal in Jilin that the coal has a high moisture content. Materials with high moisture content have a smoother real part curve of dielectric constant. The imaginary part absorption curve represents energy loss, and the energy loss of dielectric constant is related to the vibration of functional groups. From the imaginary part absorption curve of Longjiabao long-flame coal in Jilin, there is an absorption peak at 1.78×10^{9} Hz. Infrared spectrum analysis shows that this absorption peak should be related to the infrared vibration of water. From the infrared absorption, the wave number corresponding to the water absorption peak is 3450 cm^{-1}. The propagation speed of electromagnetic waves is the product of frequency and wavelength; resonance at 3450 cm^{-1} indicates that the frequency of electromagnetic waves is equal to the vibration frequency of water. There are several small absorption peaks in the imaginary part absorption curve of dielectric constant in Figure 1. Two obvious absorption peaks in the infrared spectrum are identified to correspond to the wave numbers of 1650 cm^{-1} and 1000 cm^{-1}, respectively. These two absorptions are assigned to the vibration peaks of carbon-carbon double bonds and hydrogen on double bonds. The simultaneous appearance

of absorption peaks at 1650 cm^{-1} and 1000 cm^{-1} can be used to judge the metamorphism degree of coal. The small absorption peaks in the curve indicate that the double bonds are in the benzene ring and the coalification degree is high. In addition, the smooth real part curve indicates that the pore structure of the coal is poorly developed, which is consistent with the coalification degree.

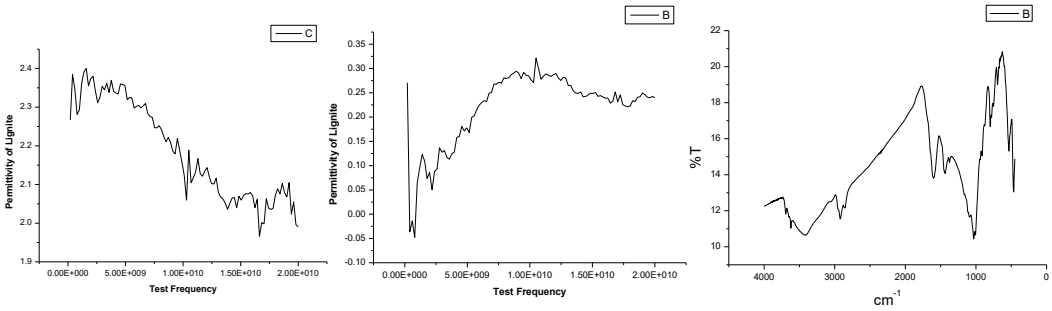


Figure 2 The real part curve, imaginary part curve of dielectric constant and infrared spectrum of Fuxin Long-Flame Coal in Liaoning.

Figure 2 shows the real part curve, imaginary part curve of dielectric constant and infrared spectrum of Fuxin long-flame coal. The moisture content of Fuxin long-flame coal is below 3%, and it can be seen from the real part curve that the coal has a low moisture content. Three peaks related to the infrared vibration of OH can be clearly observed in the imaginary part absorption curve, and these three peaks correspond to the OH vibrations of different functional groups. Only two absorption peaks are observed in the infrared spectrum, and the broad peak is formed by the merging of two peaks with close energies. There are several small absorption peaks in the imaginary part absorption curve of dielectric constant in Figure 2. Combined with the infrared spectrum, many absorption peaks can be seen in the fingerprint region, which indicates that Fuxin coal has a low metamorphism degree. Similarly, two positions with wave numbers of 1650 cm^{-1} and 1000 cm^{-1} are found, which are assigned to the vibration peaks of carbon-carbon double bonds and hydrogen on double bonds, respectively. Due to the low coalification degree, coal with abundant functional groups in the infrared spectrum has more absorption peaks in microwave. The real part curve of Fuxin coal fluctuates obviously, indicating that

the coal has many pores and low coalification degree, and the real part absorption curve of dielectric constant presents a zigzag characteristic.

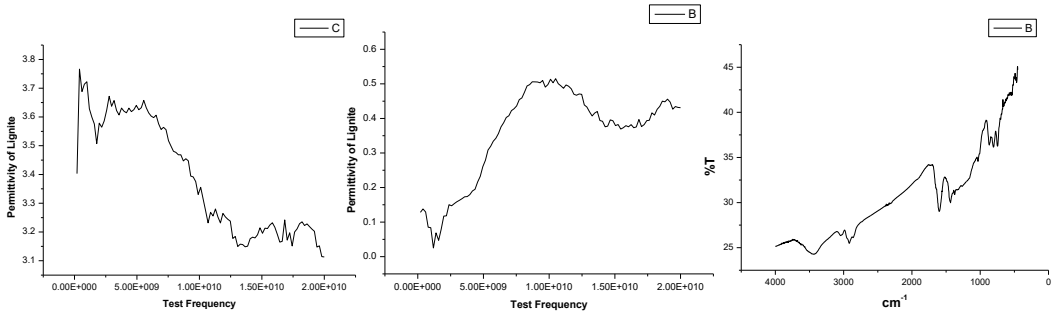


Figure 3 shows the real part curve, imaginary part curve of dielectric constant and infrared spectrum of Shanxi coking coal.

Figure 3 shows the real part curve, imaginary part curve of dielectric constant and infrared spectrum of Shanxi coking coal. The moisture content of Shanxi coking coal is extremely low. A peak related to the infrared vibration of OH can be clearly observed in the imaginary part absorption curve, and this peak corresponds to the OH vibration. The characteristics of the real part curve can be used to judge that the moisture content of coking coal is very low. Through the analysis of the imaginary part curve and infrared spectrum, coking coal with low moisture content has a very small water absorption peak. By comparing the dielectric constant with the infrared spectrum, it can be judged that the coalification degree of Shanxi coking coal is higher than that of Fuxin long-flame coal and Longjiabao long-flame coal in Jilin.

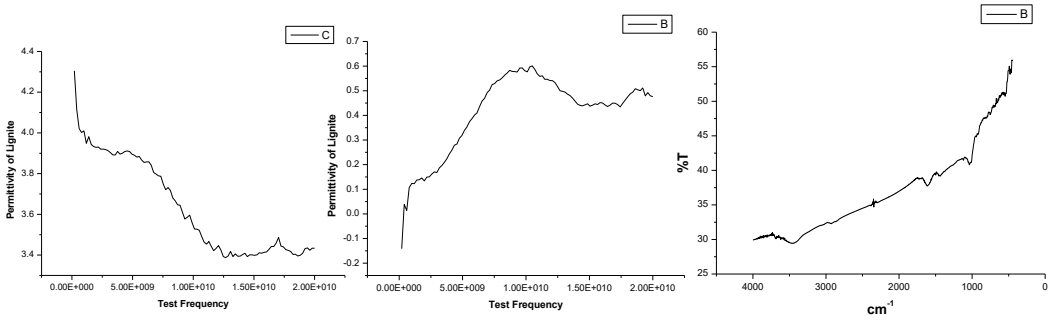


Figure 4 shows the real part curve, imaginary part curve of dielectric constant and infrared spectrum of Huolinhe lignite.

Figure 4 shows the real part curve, imaginary part curve of dielectric constant and infrared spectrum of Huolinhe coal. It can be determined from the real part curve

that Huolinhe coal has a high moisture content. Combined with the imaginary part curve and the infrared curve, it can be judged that Huolinhe coal has a low coalification degree, and the water absorption peak in the imaginary part disappears, which is related to the moisture content—coal with high moisture content makes it difficult to observe the microstructure of the coal. It can be seen from the infrared spectrum and the dielectric constant spectrum that Huolinhe coal has a low coalification degree and poor development. From the real part curve in Figure 4, it can be seen that water has caused great interference to the infrared and dielectric constant measurement of the coal; the real part curve has two wide inflection points, which can be judged to be caused by water seeping into the coal seam and damaging the pore structure. The first peak represents the moisture content, and the second peak is related to the pore structure.

2.2 Characteristics of Dielectric Constant of Coal with Different Moisture Contents

Figures 5 and 6 show the real part curves and imaginary part curves of lump coal samples with a size of 6×6×6 cm, where the real part represents energy storage and the imaginary part represents energy consumption; Figures 7 and 8 show the real part curves and imaginary part curves of cylindrical coal samples formed by compacted coal powder; Figures 9 and 10 show the real part curves and imaginary part curves of cylindrical coal sample bins formed by compacted coal powder with a moisture content of 10%; Figures 11 and 12 show the real part curves and imaginary part curves of cylindrical coal sample bins formed by compacted coal powder with a moisture content of 20%.

Comparing the real part curves, the energy absorption curves of cylindrical coal samples with 10% and 20% moisture content are smoother. Since the dielectric constant of water is 83.82, the presence of water masks the noise in the samples, making the curves smoother and showing a downward trend. Water increases the electrical conductivity of the material while reducing its energy storage capacity. Figures 5 and 7 are the real part curves of lump coal samples and cylindrical coal samples of coal powder at room temperature (with moisture content below 2%), respectively. It can be seen from the figures that the fluctuation of dielectric constant with

microwave change in Figure 5 is more obvious than that in Figure 7. Figure 7 shows cylindrical coal samples formed by compacted coal powder; due to the compaction of coal powder, the pore distribution in the sample block is relatively uniform, thus showing the characteristics of small fluctuation. The large fluctuation in Figure 5 is related to the natural pore structure of coal; the distribution of coal pore structure is related to the fluctuation of dielectric constant, and the pore structure causes severe fluctuation of dielectric constant. It can be concluded that when coal deforms and breaks under stress, its microstructure will change significantly, and these changes will inevitably affect the dielectric constant. The dielectric constant can just predict various deformations and fractures of coal before the occurrence of rock burst. Comparing Figures 5, 7 and 11, the higher the moisture content, the smoother the curve; the water seepage in coal can be clearly observed by comparing the curves.

Comparing the imaginary part curves, we find that the imaginary part curves of dielectric constant of coal powder with 2% moisture, 10% moisture and 20% moisture all have a large absorption peak, which does not exist in briquettes. The absorption peaks in Figures 9 and 11 are more obvious, and the absorption peaks gradually widen with the increase of water content, indicating that this absorption peak should be related to water. The absorption peak represents the energy loss of the material; water molecules are polar molecules, and there are hydrogen bond interactions between molecules. With the increase of microwave frequency, the hydrogen bonds between molecules are broken, and the absorption peak is the energy absorption caused by the existence of hydrogen bonds. From the comparison of Figures 8, 10 and 12, it can be seen that the width of the absorption peak is proportional to the moisture content of coal. The dielectric constant can judge the moisture content of coal seams; it can be concluded that when the coal seam deforms, groundwater enters the coal seam, and at this time, a significant absorption peak will appear in the dielectric constant of the system. This law provides a new basis for judging the water migration during the deformation and fracture of coal. Comparing Figures 10 and 12, with the

increase of water content, the absorption curve becomes more horizontal, which is related to the high dielectric constant of water.

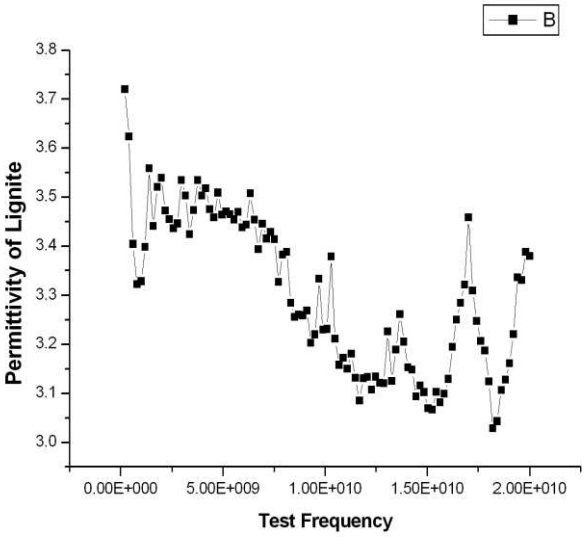


Fig.5 Relation between the permittivity of lignite and test frequency

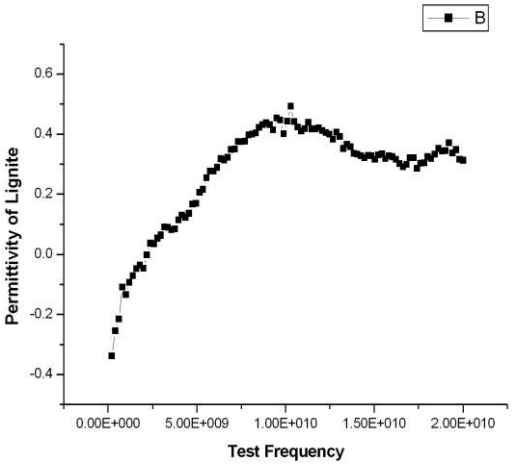


Fig.6 Relation between the permittivity of lignite and test frequency

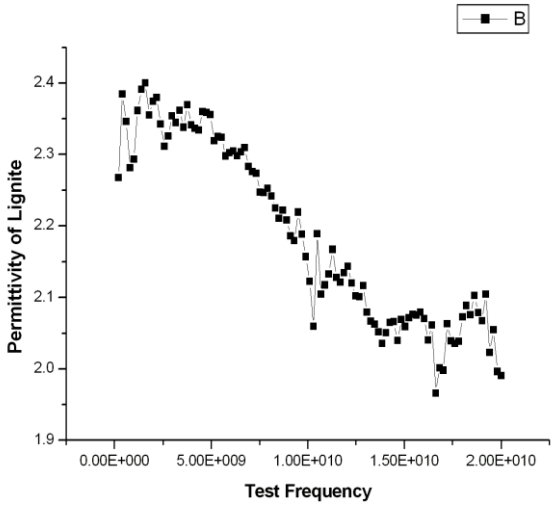


Fig.7 Relation between the permittivity of lignite and test frequency

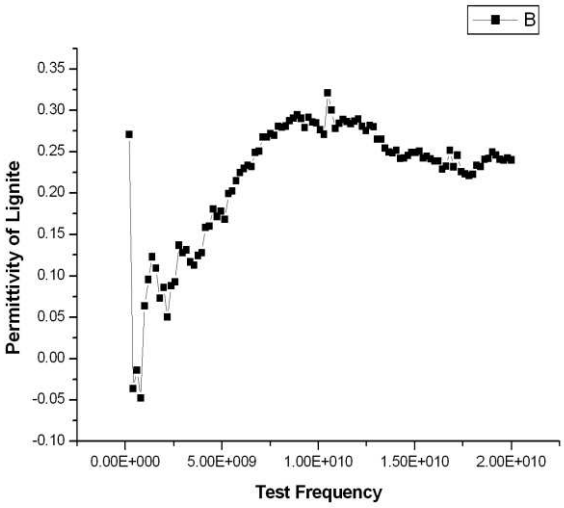


Fig.8 Relation between the permittivity of lignite and test frequency

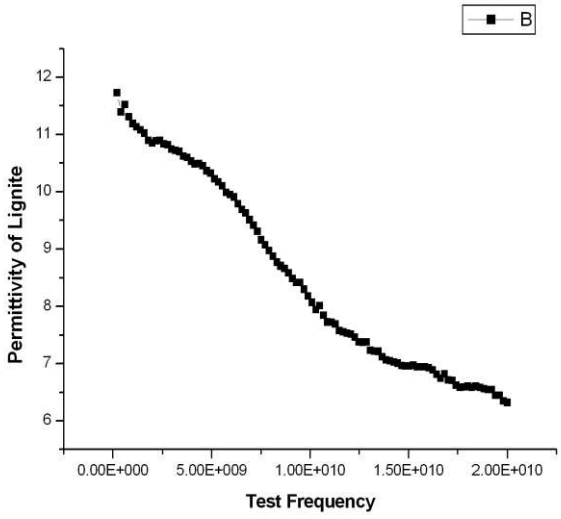


Fig.9 Relation between the permittivity of lignite and test frequency

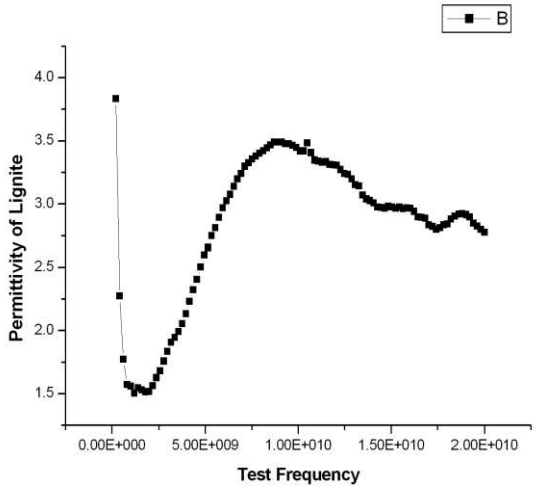


Fig.10 Relation between the permittivity of lignite and test frequency

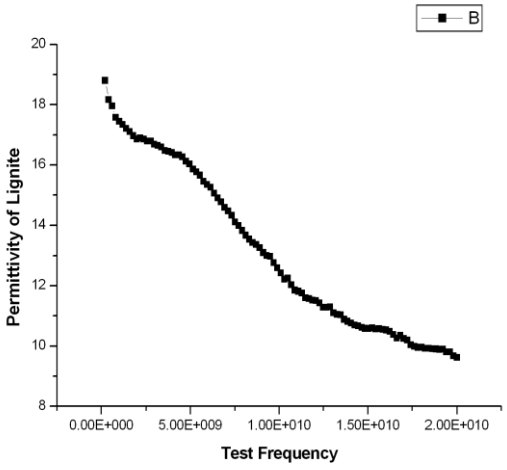


Fig.11 Relation between the permittivity of lignite and test frequency

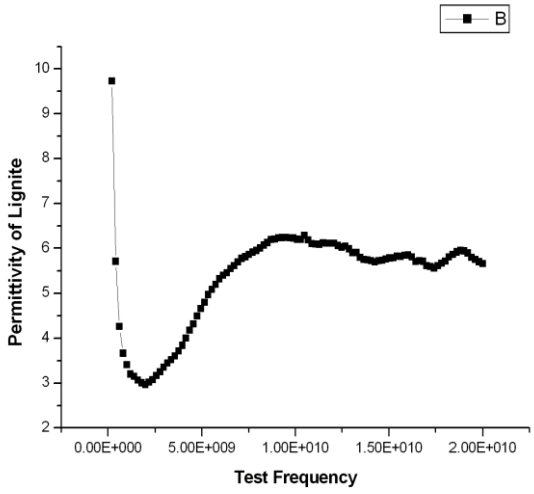


Fig.12 Relation between the permittivity of lignite and test frequency

3 Conclusions

In this paper, the variation law of dielectric constant was studied by measuring the dielectric constants of different coal types, briquettes and coal powder. The research shows that:

1、The moisture content of Shanxi coking coal is extremely low. Through the analysis of the imaginary part curve and infrared spectrum, coking coal with low moisture content has a very small water absorption peak. By comparing the dielectric constant with the infrared spectrum, it can be judged that the metamorphism degree of Shanxi coking coal is higher than that of Fuxin coal and Longjiabao long-flame coal in Jilin.

2、It is difficult to observe the microstructure of coal with high moisture content. It can be seen from the infrared spectrum and dielectric constant spectrum that Huolinhe coal has a low coalification degree and poor development. Water has caused great interference to the infrared and dielectric constant measurement of coal; the real part curve has two wide inflection points, which can be judged to be caused by water seeping into the coal seam and damaging the pore structure.

3、Comparing the real part curves, the pore distribution in the cylindrical coal sample bins formed by compacted coal powder is relatively uniform, thus showing the characteristics of small fluctuation. The large fluctuation is related to the natural pore structure of coal; microwaves resonate with coal pores, and the resonance affects the dielectric constant. It can be concluded that when coal deforms and breaks under stress, the abundant pore structure will cause severe fluctuation in the real part of the dielectric constant.

4、The imaginary part curves of dielectric constant of coal powder with 2% moisture, 10% moisture and 20% moisture all have a large absorption peak. The absorption peak gradually widens with the increase of water content. The absorption peak represents the energy loss of the material; water molecules are polar molecules, and there are hydrogen bond interactions between molecules. When the hydrogen bonds between molecules are broken, the absorption peak is enhanced.

5、The real part curve of dielectric constant of coal with high moisture content looks smoother. The imaginary part absorption curve represents energy loss, and the energy loss of dielectric constant is related to the vibration of functional groups. When the absorption frequency of infrared vibration resonates with the microwave frequency, an obvious absorption peak will appear in the curve. The infrared absorption of coal with low metamorphism degree can correspond to microwaves; coal with abundant functional groups in the infrared spectrum has more absorption peaks in the imaginary part of the dielectric constant.

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