

Article

A Physical Parameter Characterizing Heterogeneity of Pore and Fracture Structures in Coal Reservoirs

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Abstract: Pore structure heterogeneity of coal reservoirs restricts the diffusion-seepage process of coalbed methane, thereby restricting the production capacity of coalbed methane. Therefore, 10 coal samples from the Linxing area are taken as an objective, and high-pressure mercury intrusion testing was used to describe the pore structure distribution of all the coal samples. On this basis, four single and multifractal models were used to perform fractal calculations, and correlation analysis was conducted on the mercury advance and retreat fractal dimension values to clarify the physical significance of mercury removal fractal dimension values. Finally, the relationship between fractal dimension values of mercury curves and pore structure parameters was clarified, and the applicability of various fractal models in characterizing pore structure heterogeneity was explored. All the samples can be divided into type A and B by using pore volume percentage greater than 1000 nm and the mercury removal efficiency. The T model has universality and the strongest correlation in characterizing the heterogeneity of pore volume distribution in samples. A fractal parameter based on high-pressure mercury injection curve was obtained, and was then used to quantitatively characterize the pore and fracture structure of coal reservoirs. This parameter is used to characterize the complexity of gas and water transport during coalbed methane production, further elucidating the coalbed methane production process under the constraint of pore and fracture structure in coal reservoirs.

Keywords: coal reservoirs; pore fracture; mercury intrusion; mercury removal; fractal dimension value



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1. Introduction

China is rich in CBM resources, among which the cumulative proven reserves of CBM are $1023 \times 10^8 \text{ m}^3$. The recoverable reserves are about $10 \times 10^{12} \text{ m}^3$, and the recoverable reserves are about $470 \times 10^8 \text{ m}^3$, ranking third in the world [1–3]. Compared to conventional reservoirs, coal reservoirs generally have the advantages of large thickness, good pore permeability conditions, and high adsorption capacity. However, the quality of the reservoir and the processes of desorption diffusion migration of coalbed methane are both influenced by the complex pore and fracture structures of coal reservoirs. Therefore, a quantitative study of coal reservoir pore structure is the basis for understanding coalbed methane enrichment law, exploration, and development [4–10].

Previous researchers have conducted qualitative and quantitative research on coal reservoir pore and fracture systems through testing methods such as low-temperature liquid nitrogen testing, nuclear magnetic resonance experiments, carbon dioxide adsorption testing, and high-pressure mercury intrusion testing. Among them, high-pressure mercury intrusion testing is used for characterizing pore and fracture structures due to its advantages of low cost, simple operation, controllable steps, high accuracy, and wide range. Chen et al. found through high-pressure mercury intrusion and scanning electron microscopy testing that intergranular pores are the main reason for the macropore increment in coal rock reservoirs [11]. Wang et al. believe that mercury intrusion testing can specifically characterize pore sizes above 18 nm, and establish classification criteria for coal rock reservoir types based on porosity, mercury saturation, and mercury removal efficiency in their research area [12,13]. Based on this, fractal theory has been used by scholars to discover that the fractal dimension value can serve as an important parameter for describing the heterogeneity of pore structure [4,14–18]. Based on using fractal models to perform fractal calculations on the mercury intrusion curve, relevant scholars show that parameters such as porosity, specific surface area, specific pore volume, and coal rock macerals are the main factors affecting the fractal dimension of coal rock pores [19–21].

In summary, previous researchers have studied the heterogeneity of pore and fracture structure distribution in coal rock reservoirs by applying mercury intrusion curves and fractal theory [6,7,22–27]. However, relevant literature indicates that mercury removal curves can better reflect the connectivity of coal reservoir pores and fractures, and there is relatively little research on fractal theory based on mercury removal curves. Whether the mercury removal curve has fractal significance still needs to be explored, and the correlation and differential distribution between the mercury removal fractal characteristics and the mercury intrusion fractal characteristics need to be clarified.

Based on this, ten coal samples were selected in the Linxing block as the research object for calculating the fractal variations of mercury intrusion and removal. Firstly, this article divides the sample types based on some pore permeability parameters and mercury intrusion testing parameters using high-pressure mercury intrusion testing [28–33]. Next, single multiple fractal dimension calculations are performed on the mercury intrusion and removal data of various samples, the fractal dimension values of mercury intrusion and removal are analyzed, and the correlation between the fractal parameters of different models is analyzed. Eventually, the fractal significance of the mercury intrusion and removal curves are clarified, and the applicability of different fractal models in characterizing the heterogeneity of pore and fracture structures in coal reservoirs is explored. To achieve a refined description of the pore and fracture structure of coal reservoirs, the IUPAC pore division scheme is adopted to divide them into three categories: smaller-pore (<100 nm), meso-pore (100–1000 nm), and macro-pores (>1000 nm) [34].

2. Research Areas and Experimental Methods

2.1. Sample Preparation

This article conducted research sample collection in the Linxing area of the eastern Ordos Basin. The coal bearing strata are the Shanxi Formation and Taiyuan Formation. Among them, the Taiyuan Formation is a set of epicontinental marine sediments, with the lower part being a barrier sedimentary environment, the middle part being a tidal flat sedimentary environment, and the upper part consisting of dark mudstone and carbonaceous mudstone deposited in the lagoon facies. The Shanxi Formation is a set of delta plain sediments, with swamp sediments in the lower part, distributary channel sandstone sediments in the middle part, and interbedded sand and mudstone in the upper part [35,36]. Basic information about the sample is shown in Table 1.

Table 1. Basic Information about the Samples.

Sample No.	Pore Volume (cm ³ ·g ^{−1})	Porosity (%)	Permeability (mD)	Mercury Removal Efficiency (%)
1	0.799	7.12	0.11	32.303
2	1.004	8.88	1.93	19.55
3	1.049	9.74	0.31	36.507
4	1.343	12.6	1.48	27.134
5	1.403	12.12	2.86	23.082
6	0.747	6.37	0.22	35.016
7	1.473	13.1	3.65	24.787
8	1.317	11.23	3.39	25.785
9	0.866	7.37	0.66	29.643
10	0.468	4.08	1.11	42.737

Firstly, the experimental samples were ground into powder form and tested for their industrial and microscopic composition. Then, the polished samples are placed at 60 °C to dry for 48 h. Secondly, the pore rupture test was carried out on the sample using the 9520 mercury porosimeter German. The maximum experimental pressure was 100 MP, the pore size measurement range was 0.019–280.310 μm, and the test temperature was room temperature. By constantly changing the magnitude of the pressure, the pore size distribution and specific surface area of the sample are measured. The pore diameter distribution of all the coal samples is as follows in Table 1.

2.2. Calculation Theory

The Menger model (M-model) is shown in Equation (1) [35,36].

$$\lg(dv/dp) \propto (D - 4)\lg(p) \quad (1)$$

where D_M is a fractal dimension and dimensionless; P is the intrusion pressure, MPa; V is the total intrusion volume, cm³·g^{−1}.

The Sierpinski model (S-model) is shown in Equation (2) [34].

$$\ln(v) = (3 - D) \ln(p - p_t + \ln a) \quad (2)$$

where V is the volume of mercury injected into the sample, mL; P is the intrusion pressure, Mpa; p_t is the threshold pressure, Mpa; D_S is the fractal dimension; a is a constant.

$q \sim D(q)$ is a basic language for describing local features of multifractals, and the calculation formula for $D(q)$ is:

$$D(q) = \frac{\tau(q)}{q - 1} \quad (3)$$

where $\tau(q)$ is the quality index function, and q is the statistical moment order. The specific process of promotion can be found in the references [37].

The data sources of the above fractal models are all mercury intrusion curves, and the heterogeneity of the pore fracture structure of the reservoir is discussed by calculating the fractal dimension. It remains to be discussed whether the mercury removal curve has fractal characteristics, and its limitations on changes in porosity and permeability. The fractal dimensions of three fractal models were calculated based on the mercury removal curve of the same sample. The differences in fractal characteristics between the mercury intrusion and removal curves of the same sample were discussed.

3. Result Discussion

3.1. Sample Type Classification Based on Pore Structure Parameters

Porosity can be used to characterize the degree of development of pore fractures in reservoir samples. Permeability can be used to measure the ability of reservoir samples to

conduct fluids. The percentage of pore volume can reflect the type of pore and fracture. The mercury removal efficiency can characterize the connectivity of pores and fractures. The heterogeneity and microscopic pore structure of coal sample reservoirs are the focus of this study. Based on this, this article classifies and discusses the porosity, permeability, pore volume percentage, and mercury removal efficiency provided by high-pressure mercury intrusion testing experiments for the given samples. Comparing the four classification schemes in Figure 1, the samples can be divided into two categories, A and B, based on the pore volume percentage greater than 1000 nm and the mercury removal efficiency (Figure 1d). Among them, the pore volume of Type A samples larger than 1000 nm accounts for less than 30%, the pore volume of 100–1000 nm accounts for less than 40%, and their mercury removal efficiency is greater than 30%. The proportion of pore volume larger than 1000 nm in Type B samples is greater than 30%, and the proportion of pore volume between 100–1000 nm is less than 40%, with a mercury removal efficiency of less than 30%.

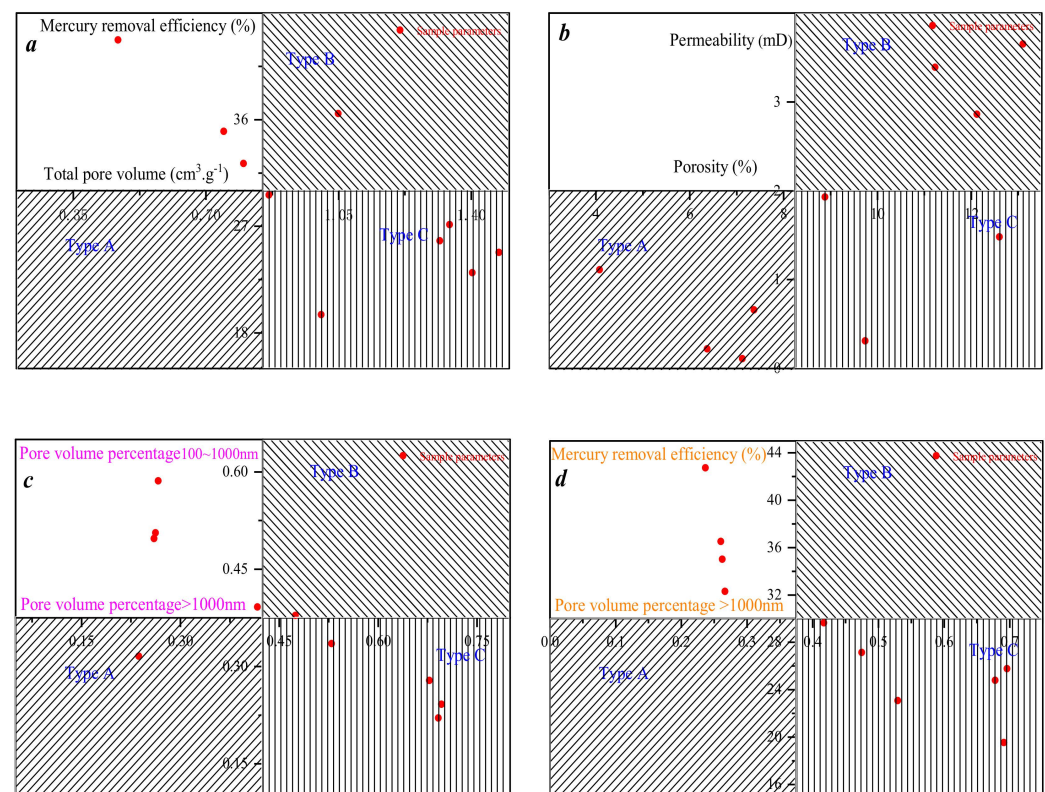


Figure 1. Sample classification scheme division using different pore parameters and mercury intrusion parameters. (a, Mercury removal efficiency (%)~Total pore volume ($\text{cm}^3 \cdot \text{g}^{-1}$); b, Permeability (mD)~Porosity (%); c, Pore volume percentage 100–1000 nm~Pore volume percentage > 1000 nm; d, Mercury removal efficiency (%)~Pore volume percentage > 1000 nm).

Figure 2a and c indicate that the cumulative mercury saturation of Type A samples is less than 60%, while the cumulative mercury saturation of Type B samples is greater than 60%. Meanwhile, Figure 2b,d indicate that the pore distribution of Type A samples exhibits a bimodal pattern, indicating that the pore size range of Type A samples is concentrated at 100 nm and 1000 nm. The pore distribution of Type B samples is a three-peak state, with peak pore sizes mainly concentrated at 100, 1000, and 4000 nm. Therefore, it can be inferred that Type A samples belong to small pore development type samples, while Type B samples belong to macropore development type samples.

Figure 3 shows that the pore volume percentage of Type A samples larger than 1000 nm is less than 30%, while the pore volume percentage of Type B samples larger than 1000 nm is greater than 50%. The average total pore volume of Type A samples is $0.7658 \text{ cm}^3 \cdot \text{g}^{-1}$, while the average pore volume of Type B samples is $1.2343 \text{ cm}^3 \cdot \text{g}^{-1}$.

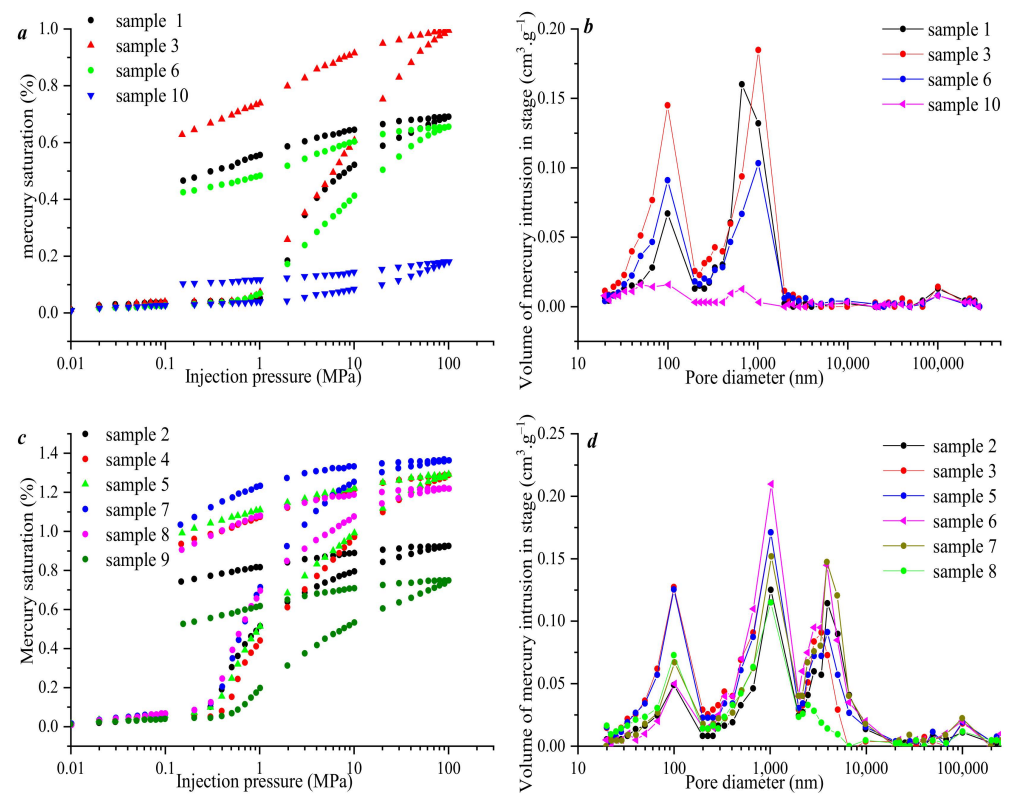


Figure 2. Sample mercury intrusion and removal curves and pore size distribution based on HPMI testing. (a, mercury saturation (%)~Injection pressure (MPa); b, Volume of mercury intrusion in stage ($\text{cm}^3 \cdot \text{g}^{-1}$)~Pore diameter (nm); c, Mercury saturation (%)~Injection pressure (MPa); d, Volume of mercury intrusion in stage ($\text{cm}^3 \cdot \text{g}^{-1}$)~Pore diameter (nm)).

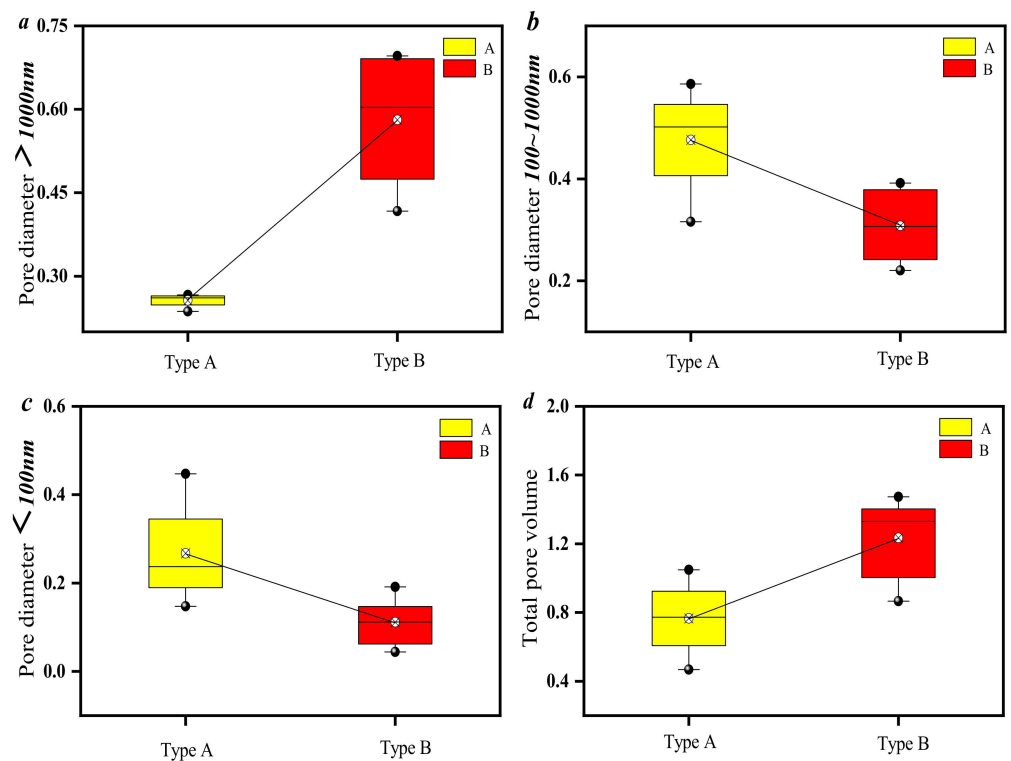


Figure 3. Comparison of pore parameters of different types of samples. (a, Pore diameter $> 1000 \text{ nm}$; b, Pore diameter 100~1000 nm; c, Pore diameter $< 100 \text{ nm}$; d, Total pore volume).

3.2. Description of Fractal Characteristics of Mercury Intrusion and Removal Based on a Single Fractal Model

According to the M model, the D_M value is calculated. Figure 4a shows a good linear relationship between $\log P$ and $\log (dv/dp)$, indicating the fractal significance of the selected sample's mercury intrusion curve. Meanwhile, Figure 4c shows that the average value of D_M for Type A samples is 3.23, and the average value of D_M for Type B samples is 3.13, indicating that the pore distribution heterogeneity of Type A samples is stronger than that of Type B. The Type A samples are smaller-pore and meso-pore developed samples with significant changes in pore structure, while Type B samples are macro-pore developed samples with small changes in pore structure.

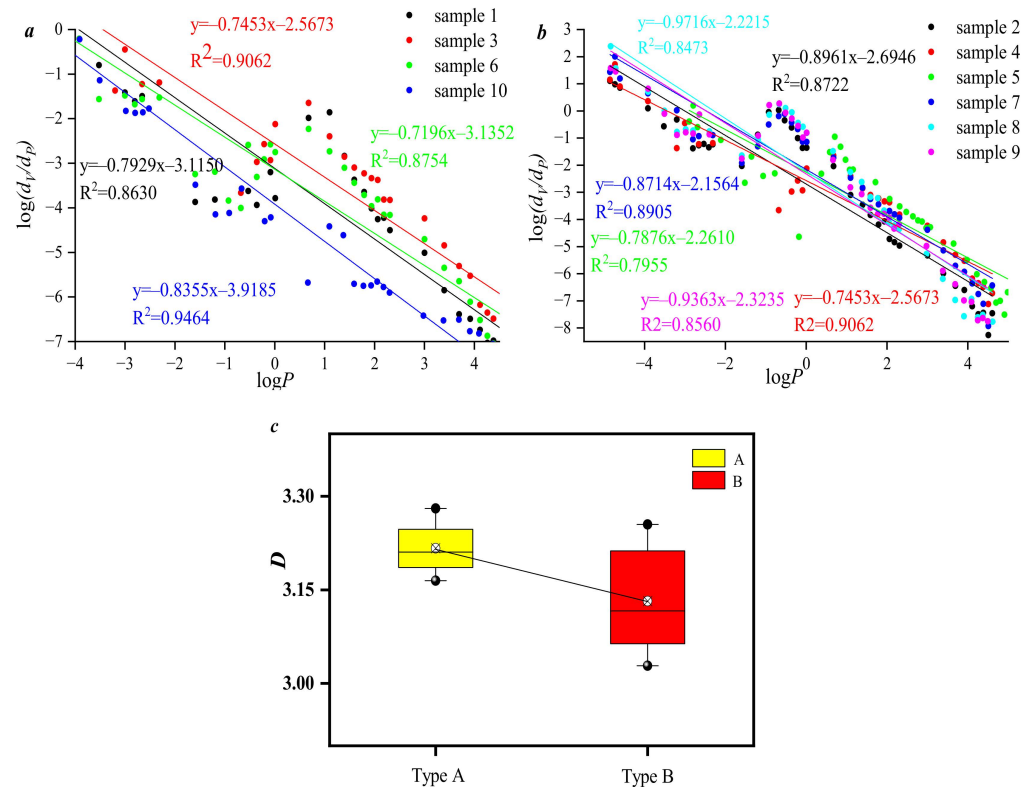


Figure 4. Fractal dimension of M-model for mercury intrusion data of different types of samples. (a, Single fractal dimension of type A sample M model; b, Single fractal dimension of type B sample M model; c, Single fractal dimension).

At the same time, the D_M value was calculated for the mercury removal data of typical samples. Figure 5 shows that there is also a good linear relationship between $\log P$ and $\log (dv/dp)$, indicating that the mercury removal curve of the selected sample has fractal significance. Figure 5c shows that the average value of D_M for Type A samples is 2.87, and the average value of D_M for Type B samples is 2.78, indicating that the pore distribution heterogeneity of Type A samples is stronger than that of Type B samples. This result is consistent with the previous conclusion.

According to the S model, the D_M value is calculated. The correlation coefficient shows a good linear relationship between $\log P$ and $\log V$, indicating that the selected sample's mercury intrusion curve has fractal significance (Figure 6). The calculation shows that the average value of Type A D_S is 2.53, and the average value of Type B D_M is 2.47, indicating that the heterogeneity of pore volume distribution in Type A is stronger than that in Type B (Figure 6c). The Type A samples are smaller-pore and developmental samples, with significant changes in pore surface area. However, Type B samples are macroporous samples with small changes in pore surface area [35,36].

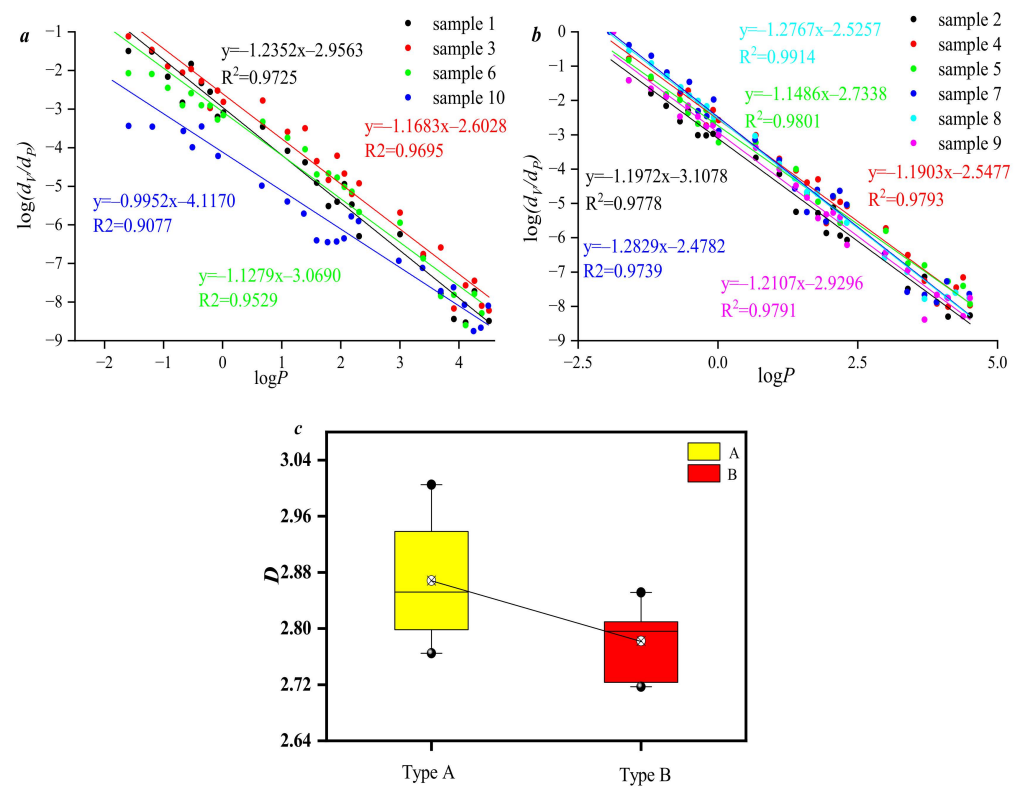


Figure 5. Fractal dimension of M-model for mercury removal data of different types of samples. (a, Single fractal dimension of type A sample M model; b, Single fractal dimension of type B sample M model; c, Single fractal dimension).

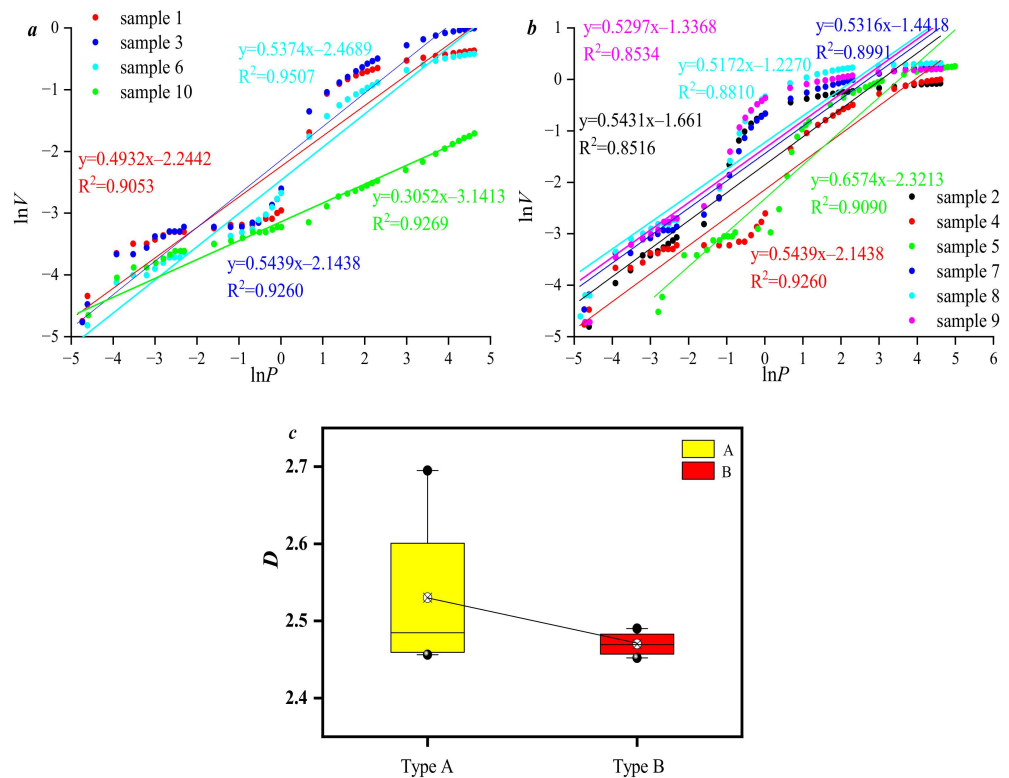


Figure 6. Comparison of fractal dimensions of mercury intrusion based on the S model. (a, Single fractal dimension of type A sample S model; b, Single fractal dimension of type B sample S model; c, Single fractal dimension).

The D_S value for the mercury removal data of the selected sample is calculated. From the correlation coefficient, it can be concluded that there is also a good linear relationship between $\log P$ and $\log V$, indicating that the mercury removal curve of the selected sample also has fractal significance (Figure 7). It can be seen that the average value of Type A D_S is 2.92, and the average value of Type B D_M is 2.96, indicating that the pore volume roughness of Type A samples is greater than that of Type B samples (Figure 7c). This conclusion is different from the mercury intrusion data of the S model mentioned earlier, which may be due to the pressure applied to the sample during the mercury intrusion process, damaging some of the small pores in Type A samples. This results in a change in the amount of modification to their pore surface area.

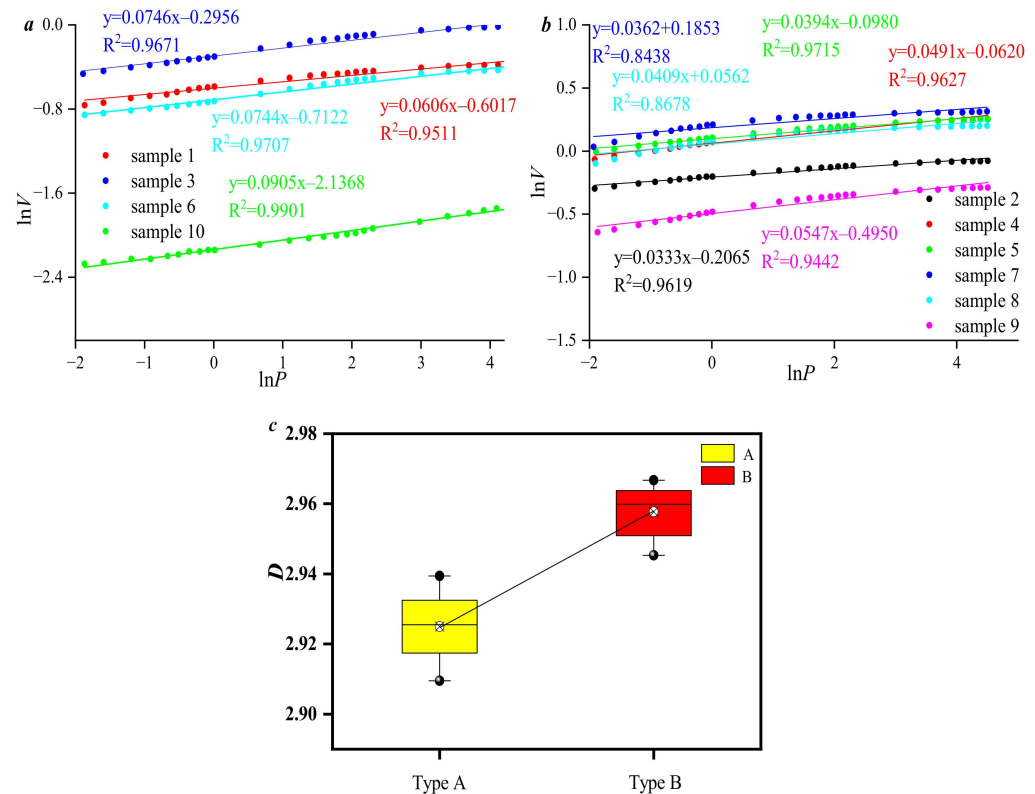


Figure 7. Comparison of fractal dimensions of mercury removal based on the S model. (a, Single fractal dimension of type A sample S model; b, Single fractal dimension of type B sample S model; c, Single fractal dimension).

The D_T value is calculated based on the thermodynamic model. The results show that there is a good linear relationship between $\ln(W_n(r_n^2))$ and $\ln(V_n^{1/3})/r_n$, indicating that the mercury intrusion curve of typical samples has fractal significance (Figure 8). The results show that the average D_M value of Type A sample is 2.93, and the average D_T value of Type B sample is 2.83, indicating that the pore size distribution heterogeneity of Type A sample is stronger than that of Type B sample (Figure 8c). This result is similar to Figure 6c, indicating that the surface roughness of reservoir pores can be characterized using both thermodynamic and S models.

At the same time, the DT value for the mercury removal data of the selected sample is calculated. According to the correlation coefficient, there is also a good linear relationship between $\ln(W_n(r_n^2))$ and $\ln(V_n^{1/3})/r_n$, indicating that the mercury removal curve of the selected sample also has fractal significance (Figure 9). As shown in Figure 9c, the average DM value of Type A sample is 3.03, and the average DT value of Type B sample is 2.86.

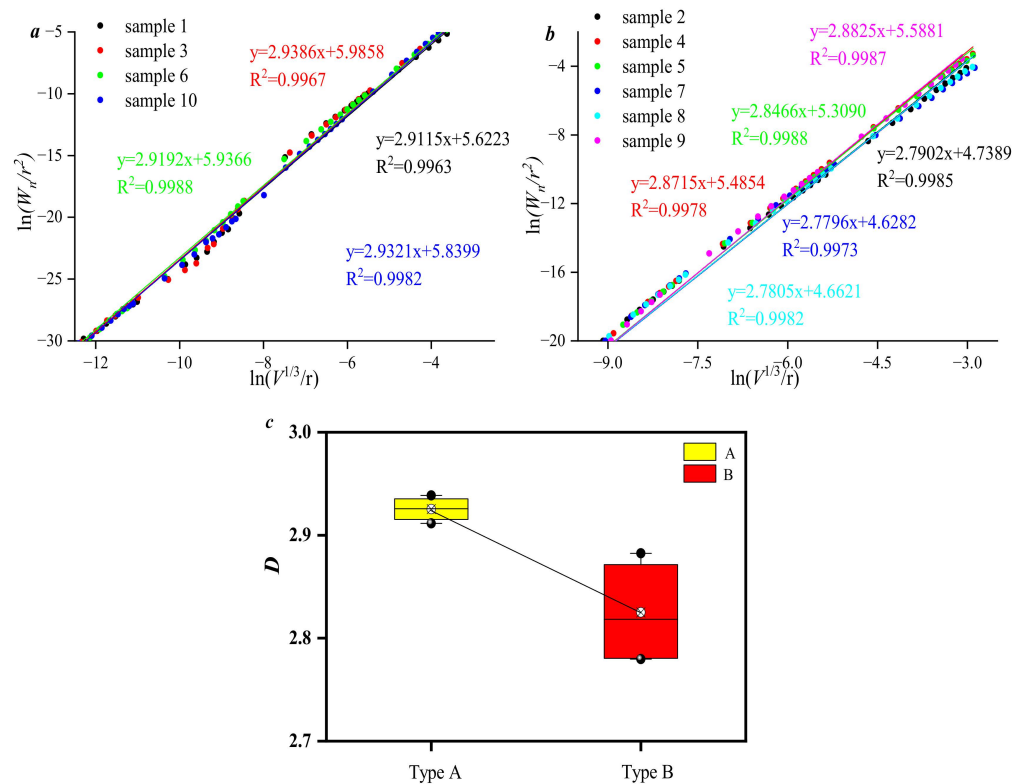


Figure 8. Comparison of fractal dimensions of mercury intrusion based on the T model. (a, Single fractal dimension of type A sample T model; b, Single fractal dimension of type B sample T model; c, Single fractal dimension).

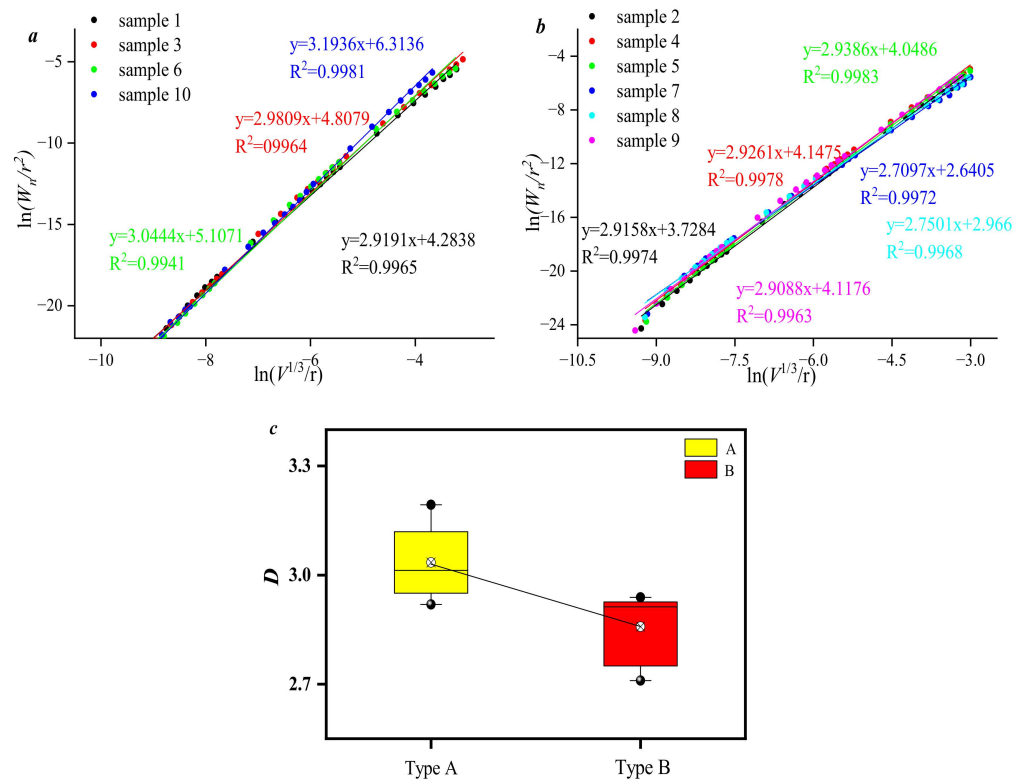


Figure 9. Comparison of fractal dimensions of mercury removal based on the T model. (a, Single fractal dimension of type A sample T model; b, Single fractal dimension of type B sample T model; c, Single fractal dimension).

3.3. Description of Fractal Characteristics of Mercury Intrusion and Removal Based on Multifractal Model

According to the multifractal dimension results of typical sample mercury intrusion data, it can be concluded that the $q \sim D(q)$ spectra of the mercury intrusion data all have a unified anti S-type. This indicates that the pore size distribution of coal reservoirs conforms to typical multifractal characteristics (Figure 10). The average value of Type A sample $D_{-10} - D_0$ is 0.54, and the average value of Type B sample $D_{10} - D_0$ is 1.17. The average value of $D_0 - D_{10}$ for Type A samples is 0.26, and the average value of $D_0 - D_{10}$ for Type B samples is 0.50. Through comprehensive comparison, it can be seen that the low value area of pore distribution in Type A samples has strong heterogeneity, while the high value area of pore distribution in Type B samples has strong heterogeneity.

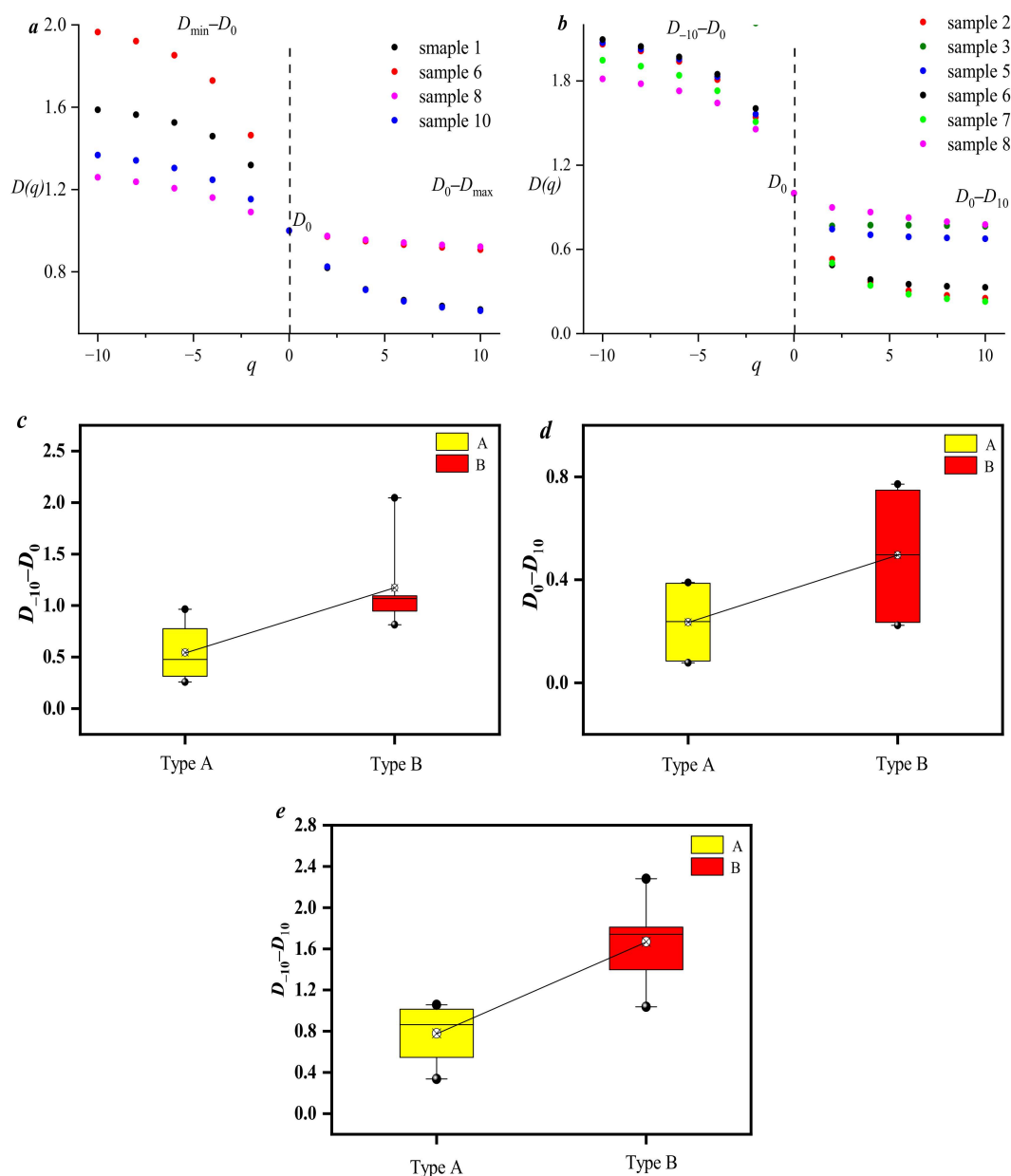


Figure 10. Comparison of multifractal dimensions and multifractal characteristics of mercury intrusion data from different types of samples. (a, $q \sim D(q)$ of type A sample; b, $q \sim D(q)$ of type B sample; c, $D_{-10} - D_0$ comparison of mercury intrusion data of type A and B samples; d, $D_0 - D_{10}$ comparison of mercury intrusion data of type A and B samples; e, $D_{-10} - D_{10}$ comparison of mercury intrusion data of type A and B samples).

Figure 11 shows that the q - $D(q)$ spectra of the mercury removal data also exhibit a unified anti S-shaped trend, indicating that the mercury removal curve of the sample also conforms to multifractal characteristics. As shown in Figure 11c–e, the average value of $D_{-10} - D_0$ for Type A samples is 0.34, and the average value of $D_{-10} - D_0$ for Type B samples is 0.33. The average value of $D_0 - D_{10}$ for Type A samples is 0.82, and the average value of $D_0 - D_{10}$ for Type B samples is 0.88. It can be concluded that the low value area of Type A pore distribution has strong heterogeneity, while the high value area of Type B sample pore distribution has strong heterogeneity, which is similar to the conclusion drawn from the multifractal model of mercury intrusion data.

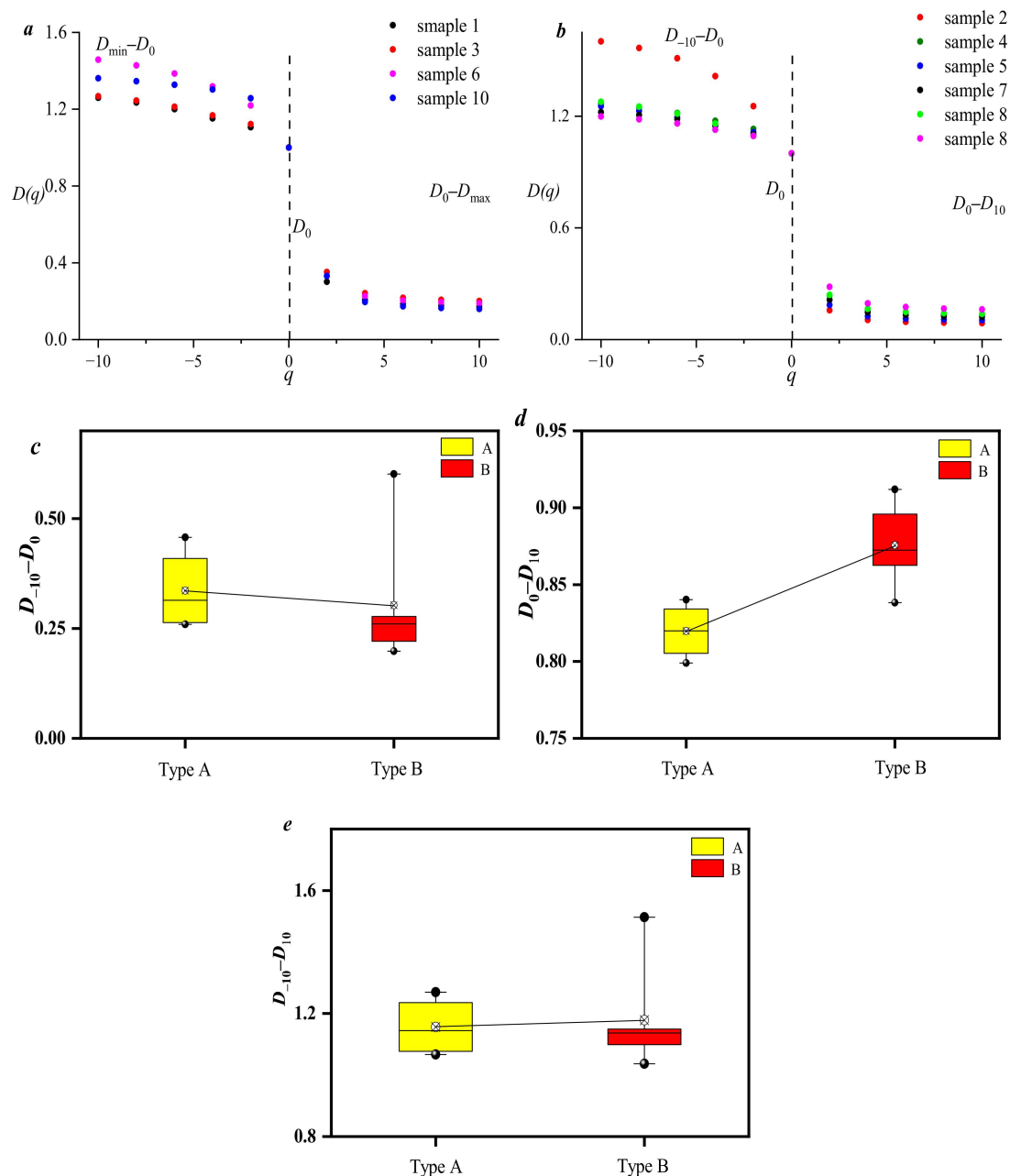


Figure 11. Comparison of multifractal dimensions and multifractal characteristics of mercury removal data from different types of samples. (a, q - $D(q)$ of type A sample; b, q - $D(q)$ of type B sample; c, $D_{-10} - D_0$ comparison of mercury removal data of type A and B samples; d, $D_0 - D_{10}$ comparison of mercury removal data of type A and B samples; e, $D_{-10} - D_{10}$ comparison of mercury removal data of type A and B samples).

3.4. Correlation Analysis of Fractal Dimension Values of Mercury Intrusion and Removal Curves Based on Different Fractal Models

Figure 12a shows that there is no significant correlation between D_M and D_S in the mercury intrusion curves of all samples, and the correlation between D_S and D_T is weak (Figure 12b). However, there is a positive correlation between D_T and D_M (Figure 12c). It can be seen that the M and T models characterize the heterogeneity of the pore volume and surface area distributions, respectively. Meanwhile, Figure 12d–f indicate that there is no significant correlation between $D_{-10} - D_0$ and $D_0 - D_{10}$, but $D_{-10} - D_{10}$ increases with the increase of $D_{-10} - D_0$ and $D_0 - D_{10}$, and the correlation of the former is greater than that of the latter. Therefore, it can be inferred that the core factor restricting the non-uniformity of pore distribution in the sample is the low value zone of pore volume.

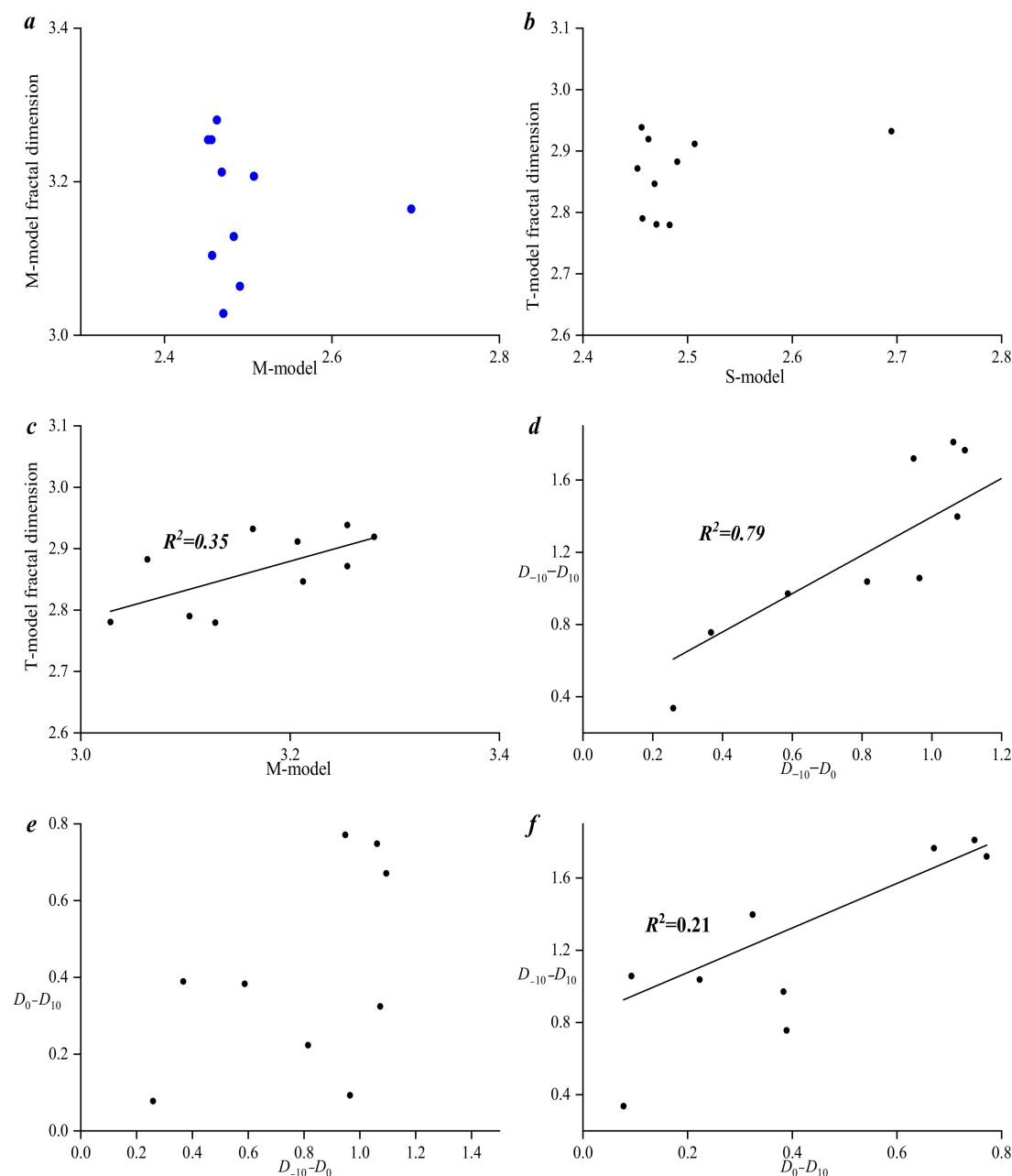


Figure 12. Correlation analysis of fractal parameters based on mercury intrusion curve. (a, M-model fractal dimension ~ M-model; b, T-model fractal dimension ~ S-model; c, T-model fractal dimension ~ M-model; d, Relationship between $D_{-10} - D_{10}$ and $D_{-10} - D_0$; e, Relationship between $D_0 - D_{10}$ and $D_{-10} - D_0$; f, Relationship between $D_{-10} - D_{10}$ and $D_0 - D_{10}$).

Figure 13a shows that there is a certain negative correlation between D_M and D_S based on the mercury removal curve, and D_S and D_T also show a negative linear correlation (Figure 13b). However, D_T and D_M are positively correlated and have a good correlation (Figure 13c). Figure 13b–f shows that there is no significant correlation between $D_{-10} - D_0$ and $D_0 - D_{10}$, and $D_{-10} - D_{10}$ increases with the increase of $D_{10} - D_0$ and $D_0 - D_{10}$, both of which are similar to the fractal dimension correlation analysis results of the single multifractal of mercury intrusion data.

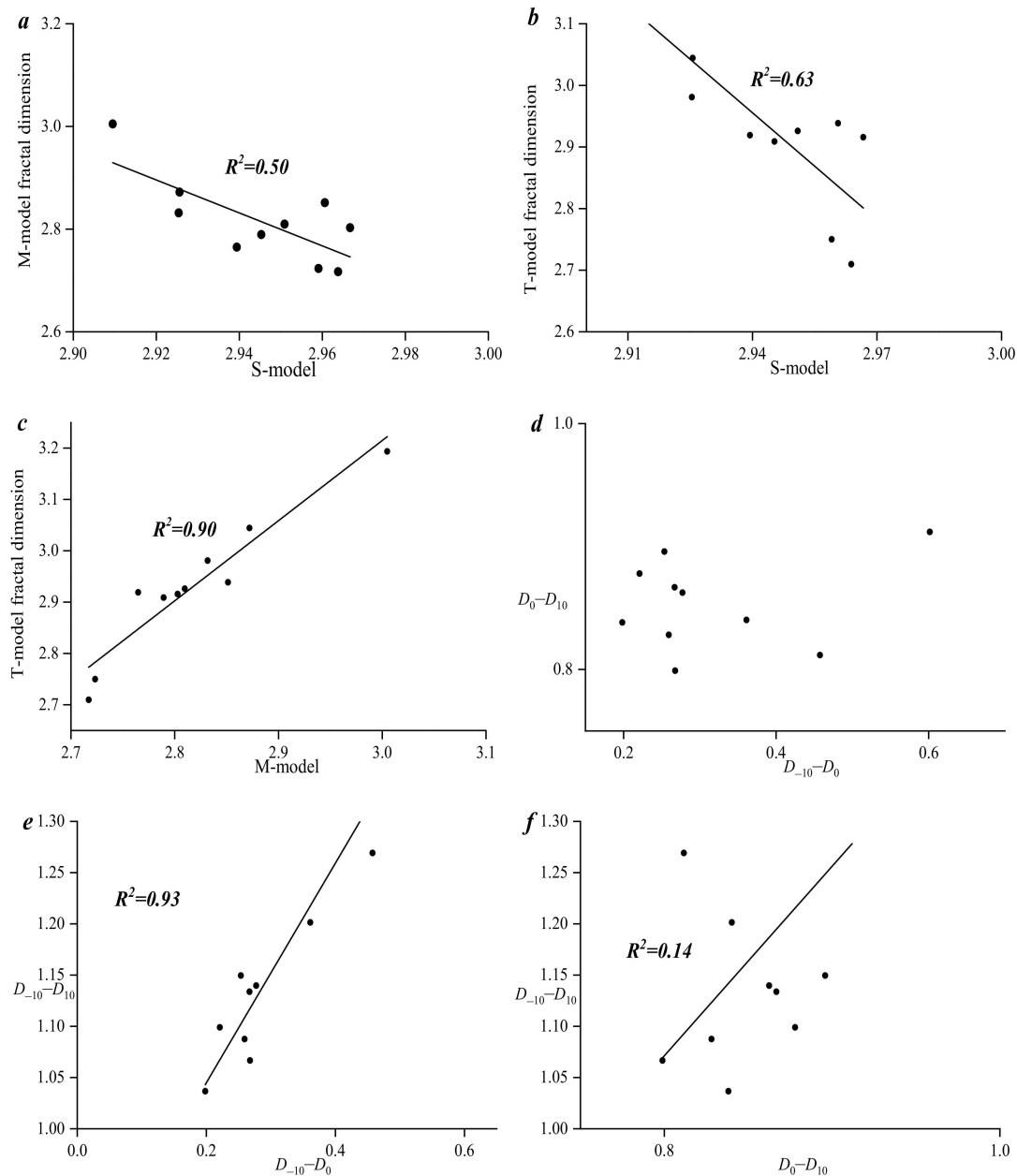


Figure 13. Relationship between fractal dimension values calculated from mercury removal data using different fractal models. (a, M-model fractal dimension $\sim$ S-model; b, T-model fractal dimension $\sim$ S-model; c, T-model fractal dimension $\sim$ M-model; d, Relationship between $D_0 - D_{10}$ and $D_{-10} - D_0$; e, Relationship between $D_{-10} - D_{10}$ and $D_{-10} - D_0$; f, Relationship between $D_{-10} - D_{10}$ and $D_0 - D_{10}$).

As shown in Figure 14a, there is no significant correlation between the D_M of the mercury intrusion curve and the D_M of the mercury removal curve, and there is also no correlation between the D_S of the mercury intrusion curve and the D_S of the mercury removal curve (Figure 14b). However, there is a certain positive correlation between the D_T

of the mercury intrusion data and the D_T of the mercury removal data (Figure 14c). This indicates that the T model has similarities in describing pore surface heterogeneity through mercury intrusion or removal data. Figure 14d–f indicate no correlation between $D_{-10} - D_0$ in the mercury intrusion data and $D_{-10} - D_0$ in the mercury outlet data. However, the $D_0 - D_{10}$ of the mercury intrusion curve is correlated with the $D_0 - D_{10}$ of the mercury removal curve. This indicates that during the process of mercury intrusion and mercury removal data processing, the changes in pores located in the high-value areas of pore volume are not significant, which can be used to prove that the dominant factor restricting the overall non-uniformity of pore distribution in the sample is the pore volume in the low value areas.

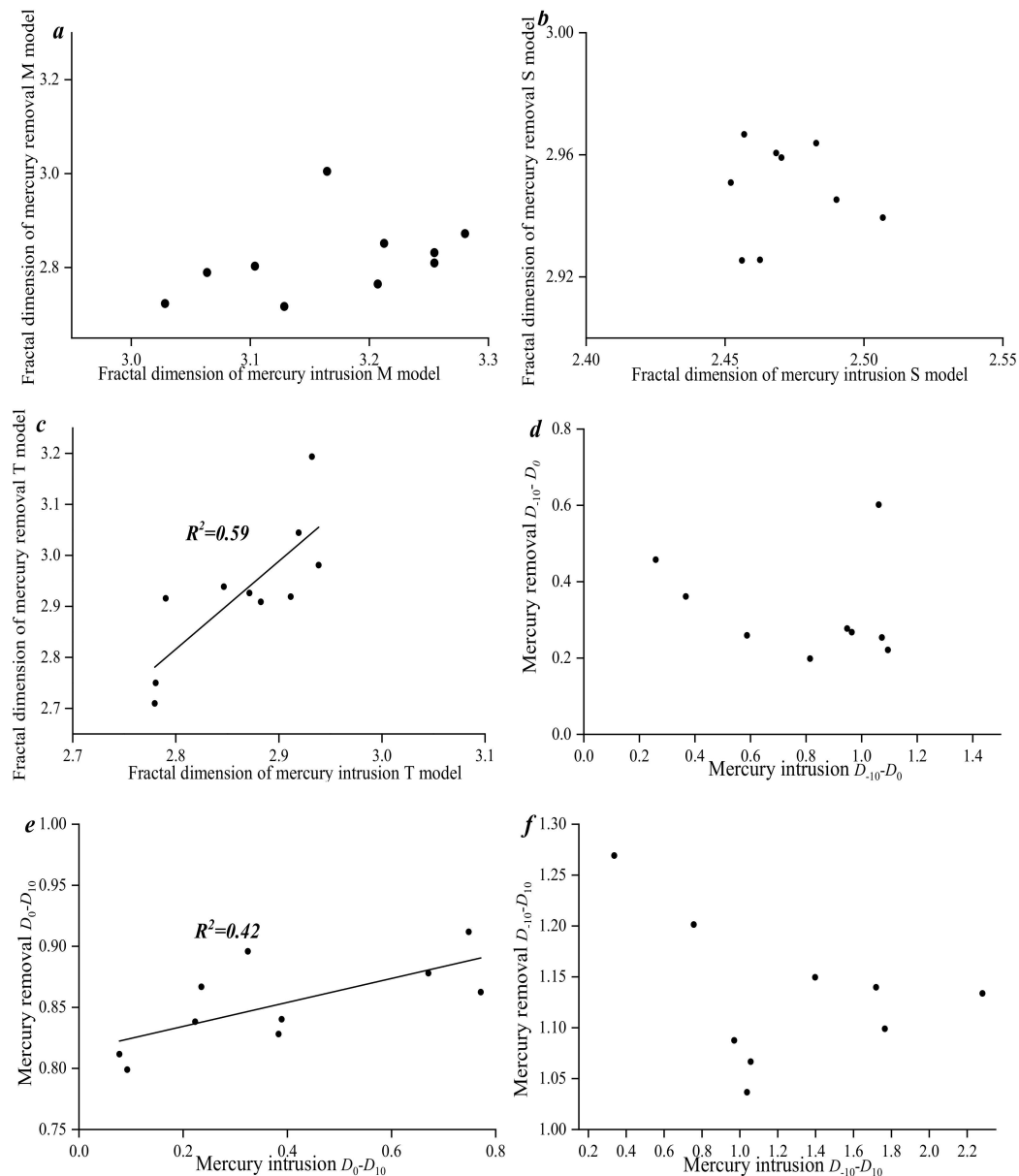


Figure 14. Correlation analysis of fractal dimension values for mercury intrusion and removal curve calculation. (a, Relationship between Fractal dimension of mercury removal M model and Fractal dimension of mercury intrusion M model; b, Relationship between Fractal dimension of mercury removal S model and Fractal dimension of mercury intrusion S model; c, Relationship between Fractal dimension of mercury removal T model and Fractal dimension of mercury intrusion T model; d, Relationship between Mercury removal $D_{-10} - D_0$ and Mercury intrusion $D_{-10} - D_0$; e, Relationship between Mercury removal $D_0 - D_{10}$ and Mercury intrusion $D_0 - D_{10}$; f, Relationship between Mercury removal $D_{-10} - D_{10}$ and Mercury intrusion $D_{-10} - D_{10}$).

3.5. Correlation Analysis between Pore Volume Parameters and Fractal Dimension

The pore volume parameters and different single fractal dimensions under mercury intrusion data were used for correlation analysis. As shown in Figure 15, there is a negative correlation between total pore volume and D_T and D_S , and a positive correlation between pore volume less than 100 nm and D_T and D_S . Pore volume between 100–1000 nm has a positive correlation with D_M and D_T , while pores larger than 1000 nm have a strong positive correlation with D_M and D_T . In summary, the T model has universality and the strongest correlation in characterizing the heterogeneity of pore volume distribution in samples.

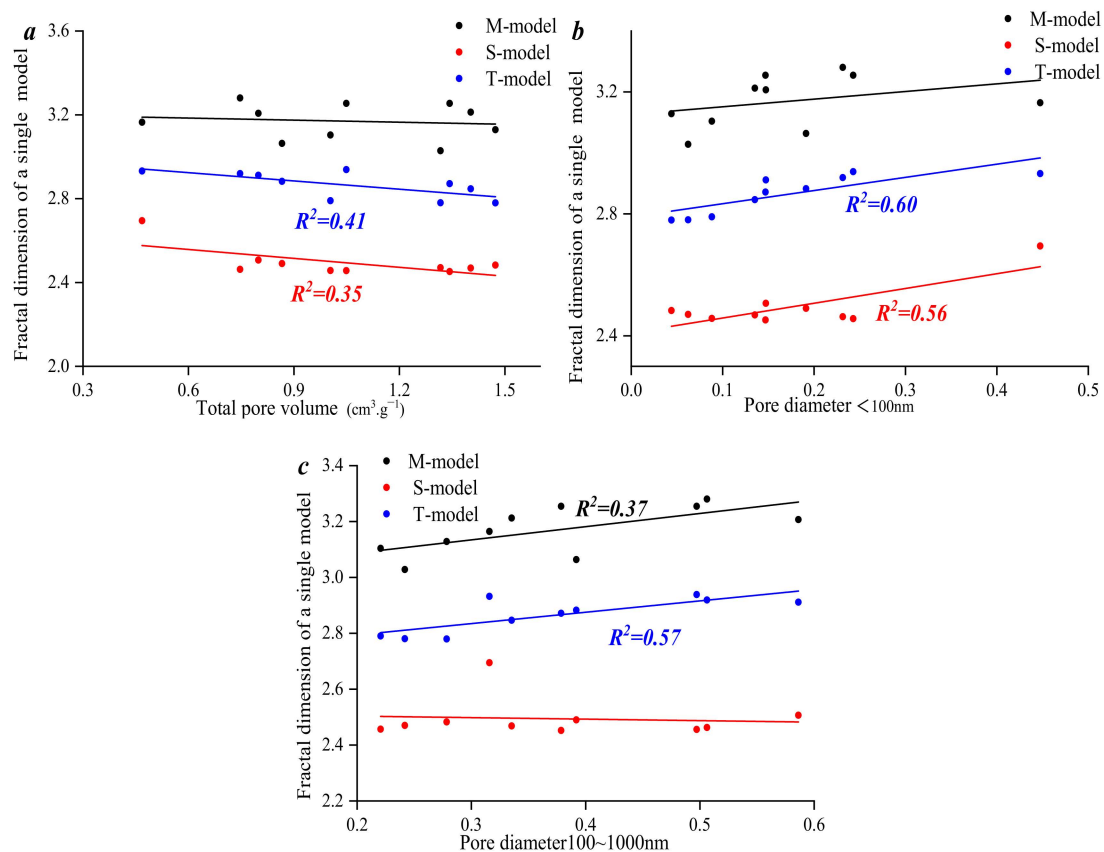


Figure 15. Relationship between pore volume and fractal dimension of mercury intrusion at different stages. (a, Relationship between Fractal dimension of a single model and Total pore volume ($\text{cm}^3 \cdot \text{g}^{-1}$); b, Relationship between Fractal dimension of a single model and Pore diameter < 100 nm; c, Relationship between Fractal dimension of a single model and Pore diameter 100–1000 nm).

Correlation analysis between pore volume and different single fractal dimensions under mercury removal data is performed. As shown in Figure 16, there is a negative correlation between the total pore volume and D_M and D_T and a positive correlation with D_S . The pore volume with a pore size less than 100 nm has a positive correlation with D_M , a negative correlation with D_S , and a positive correlation with D_T . There is a negative correlation between the pore volume of 100–1000 nm and D_S . There is a negative correlation between pore volume with a pore size greater than 1000 nm and D_M , a positive correlation with D_S , and a negative correlation with D_T . To sum up, it is speculated that the strong adsorption of coal reservoirs leads to significant differences in the fractal dimension values of mercury intrusion compared to the conclusions of this section.

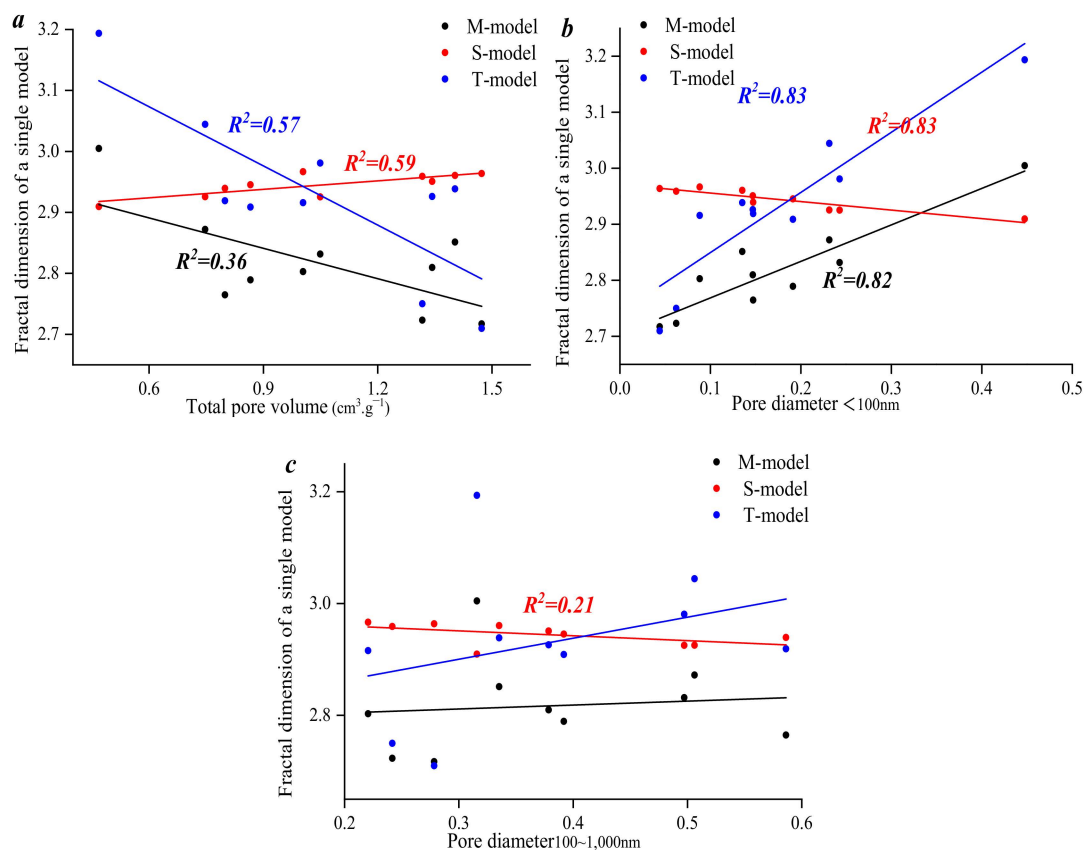


Figure 16. Relationship between pore volume and fractal dimension of mercury removal curve at different stages. (a, Relationship between Fractal dimension of a single model and Total pore volume ($\text{cm}^3 \cdot \text{g}^{-1}$); b, Relationship between Fractal dimension of a single model and Pore diameter < 100 nm; c, Relationship between Fractal dimension of a single model and Pore diameter 100~1000 nm).

4. Conclusions

Four types of single and multiple fractal models were used to perform fractal calculations on the intrusion and removal mercury curves, and correlation analysis was conducted on the intrusion and mercury removal fractal dimension values, in order to clarify the physical significance of the mercury removal fractal dimension values. Finally, the relationship between the fractal dimension values of the mercury intrusion and removal curves and the pore structure parameters is clarified, and the applicability of each fractal model in characterizing the heterogeneity of the pore structure is explored. The understanding obtained in this article is as follows:

1. Both the mercury intrusion and removal curves exhibit obvious fractal characteristics. The fractal dimension values of mercury intrusion and removal based on M and T models are consistent, showing that the pore distribution heterogeneity of Type A samples is stronger than that of Type B. However, there are significant differences in the fractal characteristics of the S model's mercury intrusion and removal, as the S model characterizes the roughness of the pore surface area.
2. The multifractal characteristics of mercury intrusion and removal exhibit consistency, with strong heterogeneity in the low value area of Type A pore distribution and strong heterogeneity in the high value area of Type B sample pore distribution. Meanwhile, the low value area of pore volume is the core constraint on the non-uniformity of pore distribution in the sample. The T model has universality and the strongest correlation, and is used to characterize the heterogeneity of pore volume distribution in samples.

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