

Analysis on Fractal-Permeability Characteristics of Construction Waste Filling Body in Gob

Zhongguo Gao^{1,*}, Yajun Xin^{2,3}, Dongying Zhang¹, Huan Li⁴, Zhuguo Chen¹,

Xiaopeng Wang¹, Guangzeng Li¹, Hongying Ji^{3,4}

¹ Qianxi County Jinpo Coal Industry Co., Ltd., Bijie, Guizhou 551700, China

² School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454000, China

³ Collaborative Innovation Center of Coal Work Safety and Clean High Efficiency Utilization, Jiaozuo, Henan 454000, China

⁴ Institute of Resources and Environment, Henan Polytechnic University, Jiaozuo, Henan 454000, China

*Corresponding Author: 2634221204@qq.com

ABSTRACT

The mine application of construction waste permeability filling body is an effective way to avoid the collapse of overlying rock strata caused by coal mining, to solve the questions of surface resource occupation and pollute the ecological environment, and to promote regional hydrogeological balance. Based on the infiltration test on twelve groups of non-cemented and cemented samples with different particle size ratio, the variation characteristics of permeability coefficient of non-cemented and cemented construction waste samples with different fine content and cement were analyzed. The porosity of non-cemented samples and cemented ones was obtained, the relationships of fine content and porosity, permeability coefficient were analyzed, the relationships of fractal dimension and porosity, permeability coefficient on non-cemented samples and cemented ones were discussed. The results showed that fine content was negatively correlated to the permeability coefficient of non-cemented samples and non-cemented ones. The porosity decreased with fine content increasing, the porosity of non-cemented samples ranged from 5.007~7.029%, and the one of cemented samples was 3.230~6.508%. Fractal dimension of non-cemented samples and cemented ones were fine aggregate > medium coarse aggregate > coarse aggregate, and the fractal dimension of non-cemented samples was less than the cemented ones, the porosity and the mass fractal dimension could well represent the relationship between the permeability and fine content.

KEYWORDS

Construction waste; Filling samples; Fractal dimension; Permeability coefficient; Porosity

1. INTRODUCTION

The accumulation of construction waste generated by the demolition of used buildings is causing serious environmental problems [1-4], and the research on the construction waste utilization has become a hot spot of continuous attention. At present, construction waste is mainly used in roadbed, permeable brick, mining filling materials and so on [5-6], which has realized the reuse of construction waste to a certain extent. The fine aggregate of construction waste and cementing materials have a main influence on the porosity and water permeability of mine filling material.

In recent years, certain progress has been made in the study of porosity and water permeability of recycled aggregates made from different materials. Su Shengqi [7], Peng Jiayi [8], Wang Shuang [9] and Li Taihang [10] et al. explored the influence of fine aggregates, particle shape and size grading on water permeability of recycled brick. Chen Shoukai et al. [11-12] analyzed key performance indexes such as porosity and permeability coefficient of pervious concrete with recycled aggregate. Gong et al. [13] used silica powder and fly ash instead of some cement as filling materials, and concluded that the multi-mixing effect of fly ash and silicon powder was the optimal. Sriravindrarah et al. [14] measured the porosity and water permeability of filling materials made from high fineness slag instead of 70% cement at 7d and 28d. Zhang Jusong [15] compared aggregate grading test and sand content test to determine the optimal grading and water-cement mass ratio; Omary[16], Geng Jian [17] and Zega et al. [18] studied the mechanical properties, microstructure, durability and adsorption capacity of recycled materials from building demolition waste. Corinaldesi et al. [19] produced concrete made of recycled concrete from recycling plants, and studied its mechanical behavior and elastic properties. Hu Qiong et al. [20] studied the effects of coarse and fine aggregate content in waste concrete on the mechanical properties and bonding properties of recycled concrete. Xu Chao et al. [21] studied the influence of the amount of cement and expansive soil on the permeability coefficient of mud consolidation. Hona et al. [22] obtained that the power function could represent the relationship between the permeability coefficient and the fractal dimension of gravel soil. Therefore, different particle gradations of aggregates have significant effects on the porosity and permeability of specimens, and the mass fractal dimension of specimens with different particle gradations was also significantly different. The porosity and permeability of specimens with different particle gradations aggregate could be obtained by the relationship between mass fractal dimension and porosity, permeability.

In this paper, the mining filling body was made from construction waste, the porosity of construction waste backfill samples with different fine contents was obtained by binarization, the mass fractal dimension of construction waste backfill samples with different fine contents was calculated and analyzed, the influence of fine contents on mass fractal dimension of construction waste backfill samples was discussed, and the relationship between mass fractal dimension of backfill body and porosity, permeability coefficient was analyzed. The research results could provide reference for the development of new permeable mine filling materials.

2. FRACTAL DETERMINATION OF CONSTRUCTION WASTE

2.1. Binary Calculation Method

The images with different fine samples were binarized by Matlab. The processed images were composed of H row and W column pixel values, and the image threshold was adjusted to set the pixel value larger than the threshold to 1, and the one smaller than the threshold to 0. So the processed images only consisted of black and white gray values. Where 1 was black, representing the pore in the binary image; 0 was white and represented the aggregate in the binary image. The pixel on the image was set to 0 or 255, so as to produce a prominent black and white outline to carry out effective image segmentation, the expression was:

$$g(x, y) = \begin{cases} 0 & f(x, y) < T \\ 255 & f(x, y) \geq T \end{cases} \quad (1)$$

Where: (x,y) were image coordinate points; f(x,y) the gray value of the unprocessed image; g(x,y) the gray value of the processed image.

2.2. Mass Fractal Calculation of Particle Size Distribution

The particle grading curve was represented by the M distribution characteristics of mass percentage content less than a certain particle size [23], as follows:

$$M(<d) \propto d^{3-D} \quad (2)$$

Where: d was the particle size, mm; D the mass fractal dimension.

The calculation process of mass fractal dimension of construction waste particles was as follows:

(1) The ratio of accumulated mass and total mass of construction waste particles smaller than each particle size range was calculated by screening, and the accumulated mass fraction was substituted into formula (2), which were converted into logarithm:

$$\ln M(<d) = (3-D)\ln d + C \quad (3)$$

(2) The sample fractal dimension D could be obtained by linear fitting analysis:

$$D = 3 - K \quad (4)$$

Where: K was the slope.

3. TEST DESIGN AND CALCULATION

3.1. Test Design

The test materials were taken from the urban construction waste dump, including red brick, blue brick, concrete block and construction waste powder. The impurities such as wood chips and plastics in the construction waste were removed, and the four particle sizes of <2mm (fine aggregate), 2~6mm, 6~8mm and >8mm were screened after mechanical crushing as filling sample aggregate, and the cementation material was 425 ordinary Portland cement.

In order to analyze the influence of fine aggregate on the permeability of filling samples, according to the proportion of construction waste particles <2mm diameter, the construction waste particle size ratio <2mm:2~6mm:6~8mm:>8mm was 2:3:4:1, 3:3:4:1, 4:3:4:1, 5:3:4:1, 6:3:4:1, 7:3:4:1, 6 groups of $\phi 40\text{mm} \times \phi 60\text{mm}$ non-cemented fill samples, A, B, C, D, E, F were prepared, respectively. Six groups of cemented filling samples A1, B1, C1, D1, E1, F1 were made by adding 15% cement to six non-cemented ratios respectively to analyze the influence of cement on the permeability. The ratio of each group of samples was shown in Table 1.

Table 1. Test grouping

particle ratio/<2mm:2-6mm:6-8mm:>8mm	Non-cemented samples		Cemented samples		
	No.	Fine content/%	No.	Fine content/%	Cement content/%
2:3:4:1	A	20.00	A1	31.18	15
3:3:4:1	B	27.27	B1	37.06	
4:3:4:1	C	33.33	C1	42.39	
5:3:4:1	D	38.46	D1	47.09	
6:3:4:1	E	42.86	E1	50.88	
7:3:4:1	F	46.67	F1	54.02	

According to the ratio in Table 1, each particle size mass was weighed for 12 groups of samples respectively, and the test was repeated three times for each group. After weighing, aggregate was put into a mixing bowl to stir evenly, and then filled into the ring knife in the penetrator layer by layer, so that aggregate was evenly spread and compacted layer by layer in the ring knife until it was level with the ring knife. After filling, the samples was photographed, and the Mallet bottle was connected to exhaust and water. The permeability of each group of filling samples was measured according to the standard of variable head permeability test. The test process was shown in Figure 1.

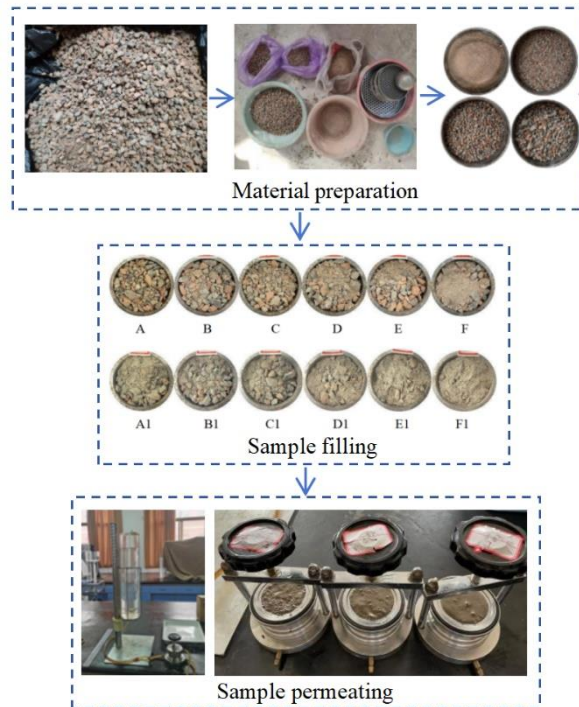


Figure 1. Test process diagram

3.2. Porosity Calculation

Matlab was used to binarize 12 groups of photos of filling samples, and the porosity of construction waste filling samples could be obtained by numerical calculation. The calculation results of porosity were shown in Table 2.

Table 2. Porosity and Permeability coefficient on samples

Non-cemented samples	No.	A	B	C	D	E	F
	Porosity/%	7.029	6.752	6.491	6.053	5.566	5.007
	Average permeability / (10-2cm/s)	1.63	1.06	1.04	0.53	0.55	0.49
Cemented samples	No.	A1	B1	C1	D1	E1	F1
	Porosity/%	6.508	6.024	5.691	4.853	4.130	3.230
	Average permeability / (10-2cm/s)	1.44	1.17	1.25	0.87	0.78	0.76

3.3. Mass Fractal Dimension Calculation

According to equation (3), the $\ln M (<d) - \ln d$ relationship was obtained, and the $\ln M (<d) - \ln d$ relationship was shown in Figure 2. As could be seen from Figure 2 the $\ln M (<d) - \ln d$ relationship of

fine aggregate, medium coarse aggregate and coarse aggregate presented obvious three-stage characteristics, and the difference at each stage became smaller with the increase of fine content, and the slope changed more obviously at the limit particle size of 2mm.

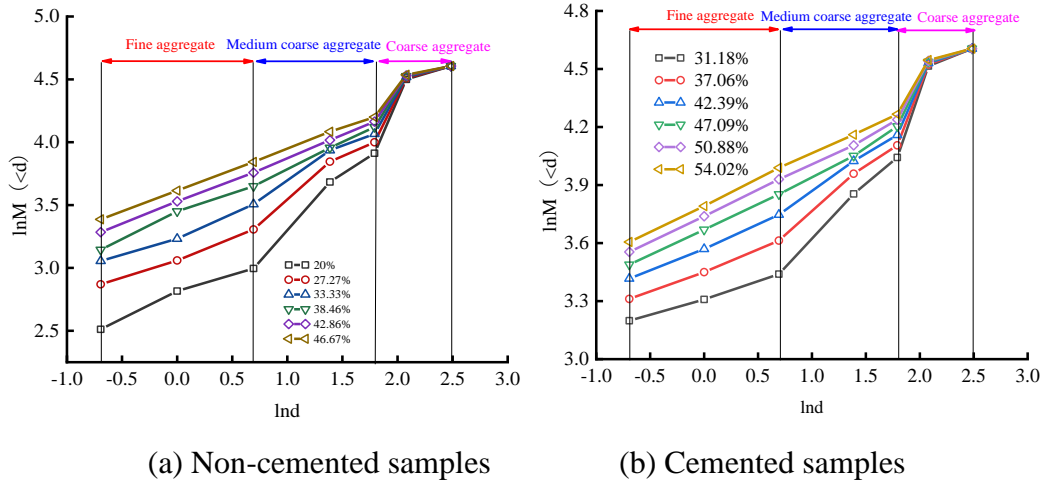


Figure 2. lnM (<d) -ln d relationship

Table 3. Fractal dimension on the aggregate in filling samples

No.	Fractal dimension/D			Correlation coefficient/R ²			No.	Fractal dimension/D			Correlation coefficient/R ²		
	Fine	Medium	Coarse	Fine	Medium	Coarse		Fine	Medium	Coarse	Fine	Medium	Coarse
A	2.6505	2.1660	2.0000	0.957	0.966	0.574	A1	2.8261	2.4512	1.3576	0.995	0.992	0.587
B	2.6824	2.3691	2.1254	0.989	0.949	0.582	B1	2.7827	2.5515	1.5473	0.996	0.987	0.583
C	2.6746	2.4906	2.2223	0.970	0.957	0.589	C1	2.7618	2.6250	1.7084	0.996	0.996	0.599
D	2.6351	2.5721	2.2996	0.971	0.999	0.595	D1	2.7376	2.6798	1.8433	1.000	0.989	0.604
E	2.6583	2.6309	2.3627	0.999	1.000	0.599	E1	2.7293	1.9422	2.3627	1.000	0.990	0.607
F	2.6701	2.6753	2.4151	1.000	0.995	0.603	F1	2.7231	2.7479	1.8222	0.999	1.000	0.611

According to the slope K (K=3-D) of each section of the curve line, the mass fractal dimension D of each sample was calculated, and the fractal dimension D of the three sections was: fine aggregate > medium coarse aggregate > coarse aggregate, and the calculation results were shown in Table 3. The results showed that there were three fractal dimensions of construction waste particle of each filling samples.

4. TEST RESULTS AND ANALYSIS

4.1. Relationship Between Porosity and Fineness

Based on the test data, the relationship curve (Figure 3) between porosity and fine content of the cemented samples and the non-cemented ones was drawn.

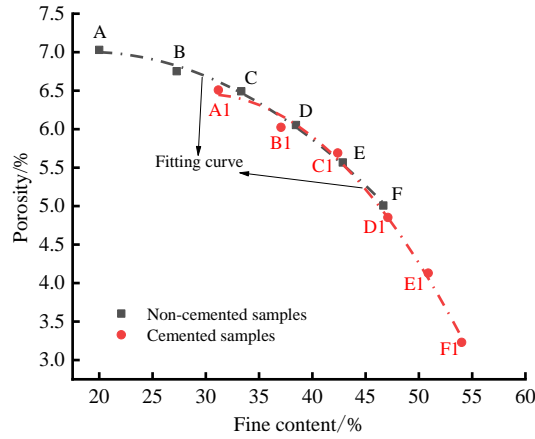


Figure 3. Relationship curves of porosity and fineness

As can be seen from Figure 3, the porosity of the construction waste filling samples decreased with the increase of fine aggregate, and the cement reduced further the porosity of the filling samples. The porosity decreased by 0.277% from group A to group B as the fine aggregate increased from 20.00% to 27.27% in the sample. The fine content of group B to C increased from 27.27 to 33.33%, and the porosity decreased by 0.261%. The fine content of group C~D increased from 33.33 to 38.46%, and the porosity decreased by 0.438%. The fineness of group D to E increased from 38.46 to 42.86%, and the porosity decreased by 0.487%. The fine content of group E~F increased from 42.86 to 46.67%, and the porosity decreased by 0.559%. With the fineness increasing from 31.38% to 37.06% from group A1 to B1, the porosity decreased by 0.484%. The fine content of group B1~C1 increased from 37.06% to 42.39%, and the porosity decreased by 0.333%. The fine content of groups C1~D1 increased from 42.39% to 47.09%, and the porosity decreased by 0.838%. The fineness of D1~E1 group increased from 47.09% to 50.88%, and the porosity decreased by 0.723%. The fine content of E1~F1 group increased from 50.88% to 54.02%, and the porosity decreased by 0.900%.

With the addition of 15% cement, the porosity of samples in groups A~A1, B~B1, C~C1, D~D1, E~E1 and F~F1 decreased by 7.412%, 10.782%, 12.325%, 19.825%, 25.799% and 35.490%, respectively. Obviously, the porosity of cemented sample was smaller than that of non-cemented sample. With the increase of fine content, the porosity of both cemented and non-cemented samples showed a decreasing trend, and the decreasing range gradually increased. The porosity decreasing range of cemented samples was greater than that of non-cemented samples with fine content increasing.

There was an obvious quadratic functional relationship between porosity and fineness content, and the relationship between porosity φ_1 and fine content x on the non-cemented samples was as follows:

$$\varphi_1 = 6.105 + 0.095x - 0.003x^2 \quad (5)$$

The correlation coefficient $R^2=1$.

The relationship between porosity φ_1 and fine content x on the cemented samples was as follows:

$$\varphi_2 = 1.574 + 0.326x - 0.005x^2 \quad (6)$$

The correlation coefficient $R^2=0.99$.

4.2. The Relationship Between Fractal Dimension and Fineness

The normalization was based on the proportion fraction of fine aggregate, medium coarse aggregate and coarse aggregate in the construction waste filling samples (the cement content did not affect the proportion fraction of particle aggregate). The content of coarse aggregate in the samples was very small, and the coarse aggregate could be ignored after normalization, the medium aggregate 1 and the fine aggregate varied in the range 0.17~1. The mean value of fine aggregate and medium coarse one was taken as the fractal dimension of construction waste filling samples. Figure 4 drawn according to Table 3 showed the relationship between fractal dimension and fine content in the samples.

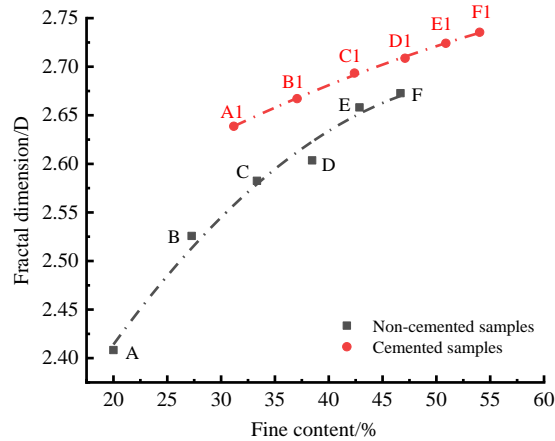


Figure 4. Relationship curves of fractal dimension and fineness

As could be seen from Figure 4, the fractal dimension of the sample increased with the increase of fine content. The fractal dimension of the non-cemented samples increased by 4.88%, 2.25%, 0.81%, 1.57% and 1.06% from group A to B, from group B to C, from group C to D, from group D to E, from group E to F, respectively. The fractal dimensions of the cemented samples increased by 1.08%, 0.99%, 0.57%, 0.57% and 0.42% in groups A1~B1, B1~C1, C1~D1, D1~E1 and E1~F1, respectively. The range of groups A~B and A1~B1 (aggregate grading 2:3:4:1~3:3:4:1), the fine content increased much, and the fractal dimension of the construction waste filling samples increased significantly.

The relationship between the fineness and the fractal dimension was in accordance with the quadratic polynomial function by fitting, the correlation coefficient $R^2=0.98$ on non-cemented samples, the correlation coefficient $R^2=1$ on non-cemented ones.

4.3. The Relationship Between Fractal Dimension and Porosity

Figure 5 showed that the fractal dimension gradually decreased with the porosity increasing in both cemented samples and non-cemented ones. The fractal dimension of the cemented samples was larger than that of the non-cemented samples, which was also in conformity with the relationship between permeability coefficient and fractal dimension. The smaller the porosity, the higher fine aggregate content, the more the number of tiny pores, the greater the fractal dimension. The cement addition made the fine aggregate embed in the binder, and also increased the number of small pores and the fractal dimension.

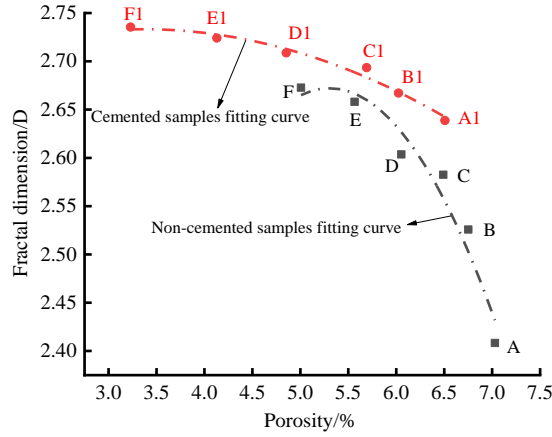


Figure 5. Relationship curves of fractal dimension and porosity

The relationship between porosity and fractal dimension could be represented by the quadratic polynomial by fitting. The relationship function between porosity and fractal dimension on non-cemented samples was as follows:

$$D = 6.105 + 0.095\varphi_1 - 0.003\varphi_1^2 \quad (7)$$

The correlation coefficient $R^2=0.92$.

The relationship function between porosity and fractal dimension on cemented samples was as follows:

$$D = 2.630 + 0.061\varphi_2 - 0.009\varphi_1^2 \quad (8)$$

The correlation coefficient $R^2=0.96$.

It could be seen from the above analysis that the porosity was inversely correlated with the fineness and fractal dimension, and the correlation coefficient $R^2>0.9$. That was, the mass fractal dimension could express the porosity of construction waste filling samples by quadratic polynomial.

4.4. Relationship between permeability coefficient and fineness

The permeability coefficient of 12 groups of samples was shown in Table 2, and the curve of the relationship between fine aggregate content and permeability coefficient was shown in Figure 6. As fine content increasing, the permeability coefficient on non-cemented samples decreased gradually and then became stable, the one on non-cemented samples fluctuated before stabilization. The permeability coefficient of the cemented samples was higher than that of the non-cemented samples in the same aggregate grading condition. For groups A~A1, the cement addition reduced the permeability coefficient of the sample by 11.66%. However, in group B~B1, group C~C1, group D~D1, group E~E1, group F~F1, the permeability coefficient increased by 10.38%, 20.19%, 64.15%, 41.82%, 55.10% respectively.

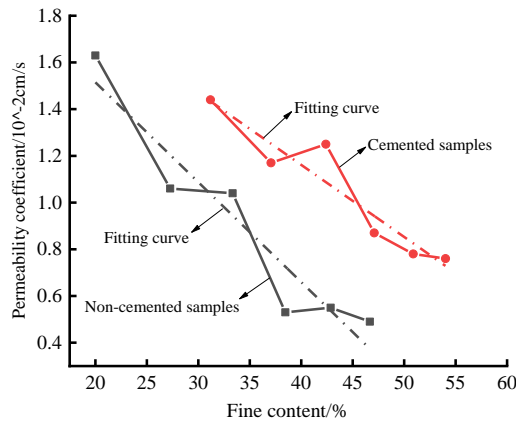


Figure 6. Relationship curves of permeability coefficient and fineness

The relationship between permeability coefficient and fineness content on non-cemented samples was as follows by fitting.

$$k_1 = 2.370 - 0.043x \quad (9)$$

The correlation coefficient $R^2=0.88$.

The relationship between permeability coefficient and fineness content on cemented samples was as follows by fitting.

$$k_2 = 2.396 - 0.031x \quad (10)$$

The correlation coefficient $R^2=0.87$.

Where, k_1 , k_2 were the permeability coefficients of non-cemented samples and cemented ones respectively, cm/s; x the fine content, %.

When the aggregate grading was 3:3:4:1, the cement had the least influence on the permeability coefficient on the samples and the growth rate. In both cemented and non-cemented conditions, the permeability coefficient tended to be stable for the first time when the aggregate gradation is 3:3:4:1~4:3:4:1.

4.5. Relationship Between Fractal Dimension and Permeability Coefficient

The relationship between fractal dimension and permeability coefficient was shown in Figure 7. As the fractal dimension of the construction waste filling samples decreased, the permeability coefficient gradually increased. The permeability coefficient was positive correlation with effective porosity. In cemented samples, the tiny ineffective pores were concentrated into effective ones by cement, and the permeability coefficient and the fractal dimension increased with the addition of cement.

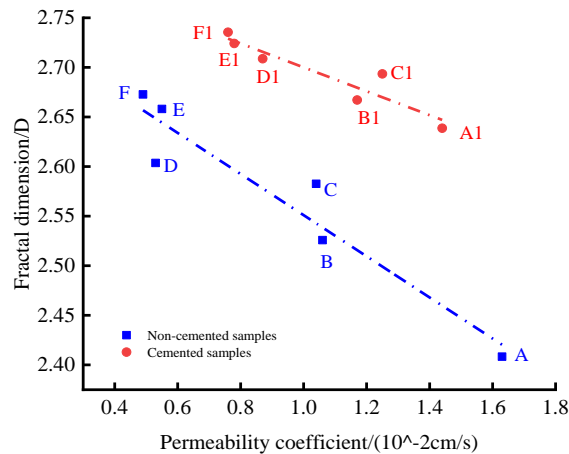


Figure 7. Relationship curves of fractal dimension and permeability coefficient

In the no cementing condition, the permeability coefficient range and fractal dimension one of construction waste filling samples were large, the permeability coefficient increased from 0.49×10^{-2} to 1.63×10^{-2} cm/s, the span was 1.14 cm/s, the fractal dimension decreased from 2.6727 to 2.4083, the span was 0.2644, indicating the performance of construction waste filling samples was unstable in no cementing. In the cementation condition, the permeability coefficient and fractal dimension of the construction waste filling samples had small span, the permeability coefficient increased from 0.76×10^{-2} to 1.44×10^{-2} cm/s, the span was 0.68 cm/s, the fractal dimension decreased from 2.7355 to 2.6387, the span was 0.0968. The relationship between permeability coefficient and fractal dimension on cemented samples was more stable than that of non-cemented samples.

In summary, the porosity and permeability coefficient of construction waste filling samples could be expressed by mass fractal dimension. However, because the permeability coefficient was closely related to the effective porosity, the relationship between porosity and mass fractal dimension was better than the permeability coefficient.

5. CONCLUSION

- (1) When the aggregate grading was 3:3:4:1, cement had the least influence on the permeability coefficient on the filling samples and the growth rate; The porosity of non-cemented and cemented construction waste filling samples decreased with fine content increasing, and the decreasing range increased gradually.
- (2) The reduction rate of the average permeability coefficient on the filling samples was the most when the aggregate grading was 4:3:4:1~5:3:4:1; When the aggregate grading was 3:3:4:1, the permeability coefficient on the non-cemented filling samples appeared the first stable step. However, the cemented filling samples was an inflection point and then tended to be stable.
- (3) When the aggregate grading was 2:3:4:1~3:3:4:1, the fractal dimension growth rate of construction waste filling samples was the most; the permeability coefficients of non-cemented samples and cemented ones tended to be stable for the first time when the aggregate gradation was 3:3:4:1~4:3:4:1.
- (4) Both the porosity and permeability coefficient on construction waste filling samples could be expressed by mass fractal dimension, and the correlation between porosity and mass fractal dimension was better than that of permeability coefficient, and the quadratic polynomial could characterize the relationship between porosity and fractal dimension of construction waste filling samples.

ACKNOWLEDGEMENTS

National Natural Science Foundation Project (51374091); Guizhou Provincial Key Technology R&D Program ([2021] general 350); Henan Province key research development and promotion special (science and technology research) project (232102321132, 232102320253)

REFERENCES

- [1] LIU Bingnan, ZHANG Xiaojuan. Analysis of Economic Benefits on the Reutilization of City Construction Waste in China [J]. *Ecological Economy*, 2012(2): 318-320.
- [2] ZHOU Wenjuan, CHEN Jialong, LU Hongbo. Status and Countermeasures of Domestic Construction Waste Resources [J]. *Architecture Technology*, 2009(8): 741-744.
- [3] YU J H. Exploration and research on classified recycle and reuse of construction waste [J]. *Shanxi Architecture*, 2019, 45(4): 191-192.
- [4] LI X P. Recycling and reuse of waste concrete in China: Part I. Material behavior of recycled aggregate concrete [J]. *Resources, Conservation and Recycling*, 2008, 53(1): 36~44.
- [5] ZHANG Junhui, DING Le, ZHANG Anshun. Application of Recycled Aggregates from Construction and Demolition Waste in Subgrade Engineering: a Review [J]. *Chian J. Highw. Transp.*, 2021, 34(10): 135-154.
- [6] XIAO Jie, WU Chaofan, ZHAN Zhehong, et al. Research on Performances of Cement Stabilized Brick and Concrete Recycled Aggregate Base [J]. *Chian J. Highw. Transp.*, 2017, 30(2): 25-32.
- [7] SU Shengqi, LU Jiacheng, LI Jiapeng, et al. Effect of Recycled Fine Aggregate on Permeability of Layer [J]. *Materials Reports*, 2019, 33(S2): 226-228.
- [8] PENG Jiayi, ZHANG Jiafa, SHEN Zhenzhong, et al. Effect of grain shape on pore characteristics and permeability of coarse-grained soil [J]. *Rock and Soil Mechanics*, 2020, 41(2): 592-600.
- [9] WANG Shuang, LI Xiaochun, WANG Shaoquan, et al. Study of Gravel-soil Gradation Characteristics Influence on the Permeability Coefficient [J]. *Chinese Journal of Rock Mechanics and Engineering*, 2015, 34(S2): 4394-4402.
- [10] LI Taihang, QI Chengzhi, WANG Xiaojiao, et al. Study on the Influence of Recycled Building Aggregate on the Impermeability of City Wall Soil [J]. *Materials Reports*, 2020, 34(S1): 220-223+248.
- [11] CHEN Shoukai, CHEN Jialin, WANG Lunyan, et al. Key Performance Statistics of Recycled Aggregate Pervious Concrete and Prediction Analysis [J]. *Journal of Building Materials*, 2019, 22(2): 214-221.
- [12] CHEN Shoukai, CHANG Chengyan, GUO Lei, et al. Influence of Recycled Aggregates Content on the Performance of Pervious Concrete [J]. *Journal of Basic Science and Engineering*, 2018, 26(1): 98-108.
- [13] GONG P, ZHOU Y. Influences of Mineral Admixture on Properties of Porous Pervious Concrete Made of Recycled Aggregates [J]. *Advanced Materials Research*, 2014, 3149(919-921): 1934-1938.
- [14] SRIRAVINDRARAJAH R, WANG N D H, ERVIN L J W. Mix Design for Pervious Recycled Aggregate Concrete [J]. *International Journal of Concrete Structures and Materials*, 2012, 6(4) : 239-246.
- [15] ZHANG Jusong, ZHANG Tianhua, SONG Dongsheng, et al. Several Factors of Effect on Strength of Porous Concrete [J]. *Journal of Shenyang Jianzhu University (Natural Science)*, 2006(5): 759-763.
- [16] OMARY S, GHORBEL E, WARDEH G. Relationships between recycled concrete aggregates characteristics and recycled aggregates concretes properties [J]. *Construction and Building Materials*, 2016, 108: 163-174.
- [17] GENG Jian, SUN Jiaying, MO Liwen, et al. Micro-structure Characteristics of Recycled Fine Aggregate and Its Concrete [J]. *Journal of Civil, Architectural & Environmental Engineering*, 2013, 35(2): 135-140.
- [18] ZEGA C J, DI MAIO Á A. Use of recycled fine aggregate in concretes with durable requirements [J]. *Waste Management*, 2011, 31(11): 2336-2340.
- [19] CORINALDESI V. Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates [J]. *Construction and Building Materials*, 2010, 24(9): 1616-1620.
- [20] HU Qiong, CHEN Weiwei, ZOU Chaoying. Experimental study on bonding properties of recycled concrete [J]. *JOURNAL OF HARBIN INSTITUTE OF TECHNOLOGY*, 2010, 42(12): 1849-1854.
- [21] XU Chao, HUANG Liang, XING Haofeng. Influence of cement-bentonite slurry mixing ratio on permeability of cutoff wall [J]. *Rock and Soil Mechanics*, 2010, 31(2): 422-426.
- [22] HE Na, CHEN Ningsheng, ZHU Yun-hua, et al. Experiment study of fractal feature and relationship between fractal dimension and permeability coefficient of gravelly soil in debris flow source area [J]. *Rock and Soil Mechanics*, 2014, 35(9): 2543-2548.

- [23] DUAN Xiangbao, LIU Yunhua, YANG Chao, et al. Preliminary Study on Fractal Law of Levees Soil Seepage Deformation and Failure [J]. Water Resources and Power, 2013, 31(7): 100-103, 214.