Pang, C. T., Ting-Shu, H. E., Gao, B., Wang, M. G., Ning, J. H., & Liu, J. H. (2012). "Effect of compound mineral admixtures on mortar mechanical properties." *Concrete, 29*(5), 113–117.
Wang, J., Wu, X. L., Wang, J. X., Liu, C. Z., Lai, Y. M., & Hong, Z. K., et al. (2012). "Hydrothermal synthesis and characterization of alkali-activated slag–fly ash–metakaolin cementitious materials." *Microporous & Mesoporous Materials, 155*, 186–191.
Wei, X. P., Lai, J. Y., Zhang, R. S. (2013) "Management and resource of construction waste." *Journal of Wuhan Institute of Technology*，35(3): 25–29.
Yan, F. (2013) "Effect of Waste Clay Brick on the Clinker Formation and Property of Recycled Cement Clinker." Dissertation, *Dalian University of Technology*.
Zheng, L. (2012) "Properties of Concrete with Recycled Clay-Brick-Powder." Dissertation, *Shandong University*.
Zhou, S., Huang, X., Liang, X., & Zhao, P. (2012). "Analysis of the hydration process of slag in the cement using dsc-tg method." *Materials Review*. 2012 (S1): 358–360.

Application of 3D Fractal Dimension in Describing Surface Morphology of Aggregates

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ABSTRACT

The micro-texture of pavement layer aggregate has a direct influence on the skid resistance of pavement. In this paper, the 3D coordinate data of three kinds of aggregates surface is collected based on the surface profiler. Using the box counting method, the MATLAB program is compiled and the 3D fractal dimension of the rock surface is calculated. The results show that the method has good effect on describing the 3D microstructure of the aggregate surface. After that, the difference analysis of fractal dimension of three kinds of different aggregate is carried out. The significant level of microstructure difference between different aggregates is obtained. The results show that there is a significant difference between the surface microstructure of basalt and the other two aggregates. And, there is no significant difference between the surface microstructure of limestone and red sandstone aggregate.

KEYWORD: Aggregate; micro-texture; 3D fractal dimension; variance analysis

INTRODUCTION

The pavement performance is an important issue for pavement engineers (Hou et al. 2014, 2016). In pavement structure, the rough degree of surface aggregates is directly related to the skid resistance of pavement (Sun et al. 2010, Zhang et al. 2013). In the course of pavement service, due to the constant rolling and friction of the tires, the surface roughness of the new pavement will continue to decline, leading to decrease of anti-slide performance of the road surface (Zhang et al. 2013, Sun et al. 2011). In practice, we often use the pendulum friction tester to test the asphalt concrete surface layer, the friction coefficient of asphalt concrete surface is determined by the pendulum value. But the relationship between the friction coefficient and the surface topography is not clear. And anti-sliding performance of the road surface evaluated by pendulum value cannot directly reflect the influence of the surface topography of a piece of rock on the anti-slide performance. The morphology of the rock surface is complex, rough and random (Jiang et al. 2003). The surface morphology of aggregates also influences the interfacial behavior between asphalt binder and aggregate (Guo et al. 2014; Guo et al. 2016; Tan & Guo 2013, 2014). Therefore, it is very important to find a kind of surface topography parameter which is independent of scale.

In 1977, fractal geometry theory proposed by French mathematician Mandelbrot. A new method is provided for describing the irregular surface topography. According to the fractal geometry theory, the dimension of a straight line is 1, the dimension of the plane is 2, and the dimension of a cube is 3. The dimension of a broken line is between 1 and 2, and the dimension of a rough surface is between 2 and 3. Since the theory of fractal dimension has been proposed, several significant achievements in the description of rough surface have been achieved. Xia et al. (1997) have applied fractal theory to describe the structure of rock mass. Sun et al. (2010) have studied the relationship between the fractal dimension of the surface microstructure and the anti-sliding property of asphalt pavement. Li et al. (2006) distinguish different kinds of weeds by calculating the fractal dimension of the digital photos of weed leave. Xu et al. (2013) use satellite remote sensing images to calculate the fractal dimension of the coastline of each period in China. Zhang et al. (2013) use image processing and counting box counting method based on the fractal dimension analysis of the asphalt concrete surface layer.

Most of these results are discussed in the two-dimensional fractal dimension of a section of a rough surface, and the fractal dimension of the whole surface topography is not much. Jiang et al. (2003) use the 3D fractal dimension describes the titanium alloy surface roughness. The results show that the fractal dimension in different scales is more accurate and stable than the roughness of the measured value R_a. Wang et al. (2000) use 3D laser scanner to get 3D profile information of rock fracture surface.

According to the existing research results， at different scales, the aggregate particles and asphalt materials have different features (Wang et al. 2000, Chen et al. 2009, Hou et al. 2015a, 2015b). This provides the possibility of using fractal dimension to discuss the surface roughness of aggregates. In this paper, three kinds of 3D surface topography of rock samples are collected by surface profiler. MATLAB is used to conduct a three-dimensional fractal dimension analysis. Finally, the SPSS statistical software is used to analyze the correlation between the fractal dimensions of the surface topography of the three kinds of rock. It is proved that the 3D fractal dimension can effectively describe the surface roughness of rock.

1. DETERMINATION OF FRACTAL DIMENSION

At present, the mainly calculation methods of fractal dimension include box-counting method, power spectrum method, the Murkowski method, semi variance method and fracture island method (Ge et al. 1997, Li et al. 2002). To compare these different methods by referring to the related research results, it is considered that the box-counting method is more suitable to describe the 3D morphology of aggregate.

1.1 The calculation principle of the box counting method

Based on the definition of measuring the dimension, this method uses box which the length is 1 to cover the surface of aggregate, then the box is divided into a collection which contains n3 small boxes, as shown in Figure 1, the length of each box are 2-n, to cover the entire surface with these boxes, and counting out the number of the boxes which contains the fragments of aggregate surface, thus the fractal dimension of the 3D surface can be calculated by the following equation (1)：

$$D = \lim_{n \to \infty} \frac{\log M(n)}{n \log 2} \tag{1}$$

where *M(n)* is the number of the boxes which contains the aggregate surface, n is the dichotomy of the 2^n box length.

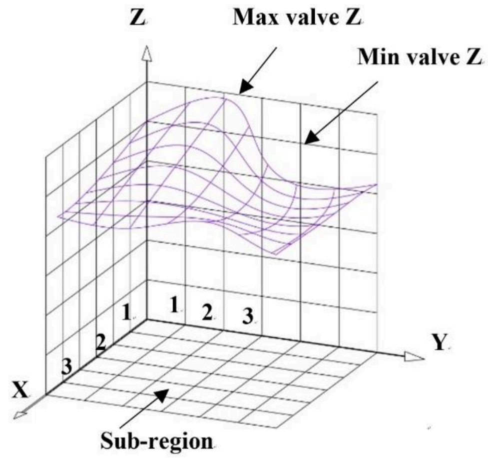

Figure 1. The diagram of 3D fractal dimension calculated by box-counting method.

In this paper, the collected data is put into MATLAB firstly, and the initial height of the original box is determined by the maximum and minimum height of the topography of aggregate, n=1, 2, 3… to divided the original box into 2^{3n} small boxes, checking whether the surface data is contained in each box. After that, the double logarithmic curve of the divided times n with the number of boxes $M(n)$ is plotted, thus the slope of the curve is the fractal dimension of aggregate surface and can be fitted by using the least square method.

1.2 Box counting method by MATLAB program

MATLAB software is introduced by the United States Mathworks company for numerical calculation and graphic processing of the scientific computing system environment. We use the ContourGT-K 3D surface topography scanner which are produced by BRUKER company in United States for scanning the rock samples on the surface of the three-dimensional outline, as shown in Figure 2. The scanning resolution is 640*480, and the scanning range is 4.5mm*3.4mm. After scanning, the computer will automatically generate data files which contains the coordinates of the rock surface, the data file is imported into the MATLAB for computing.

Figure 2. BRUKER company Contour GT-K 3D surface topography scanner.

The program flow chart is as Figure 3.

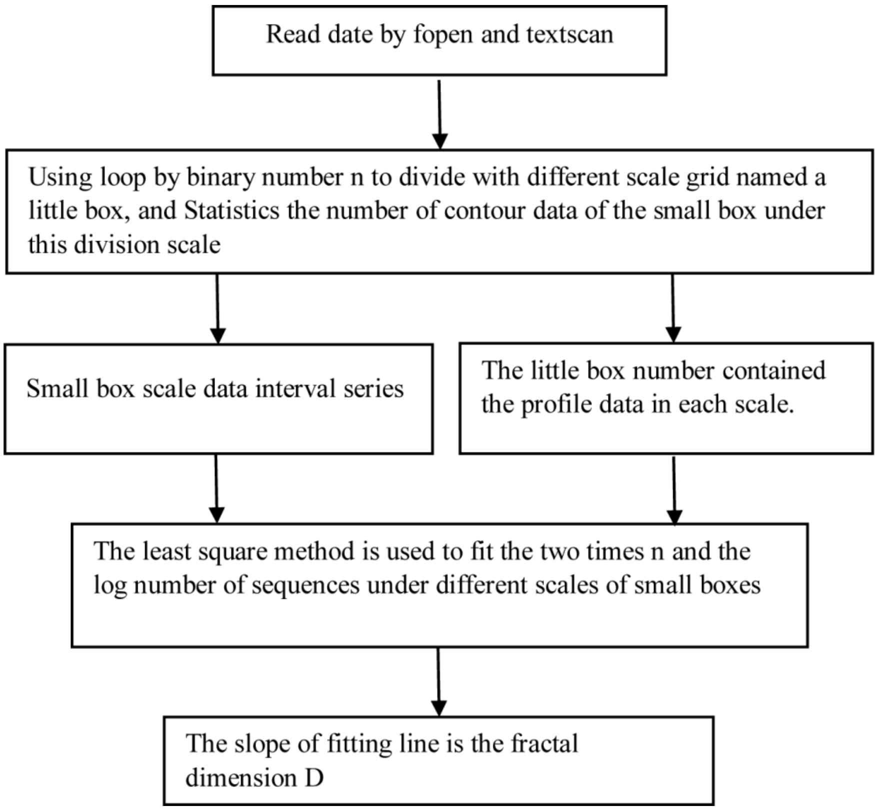

Figure 3. Computation flowchart.

Figure 4. Disc made of three kinds of rock samples.

In the computation process, consider the balance between computational time and the computational accuracy, we choose the final selection of n = 6 as the maximum number of dichotomia, which means that each side is divided into 64 parts and the minimum box ultimately homogeneous distribution of 10*7.5 sampling points. It can effectively describe the local micro profile information of rock.

2 TEST CONDITIONS AND RESULTS

According to the different types of rocks and the difference of lithology, in this paper, three kinds of typical pavement aggregates were chosen to make the sample disc, as shown in Figure 4. Including limestone, basalt and red sandstone. Rock samples are closely arranged and each of the disc occupies 1/3 area. 10 typical stone surfaces are selected for each type of rock as shown in Figure 5.

Figure 5. Scan the surface of the selected block of stone.

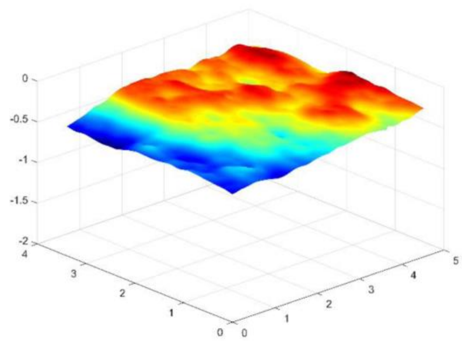

Figure 6. 3D images of the surface topography of rock in MATLAB (unit: mm).

Table 1. 3D fractal dimension of three kinds of rock

Rock type	Red sandstone	limestone	Basalt
1	2.153228	2.168769	2.143483
2	2.1394	2.136598	2.14928
3	2.118095	2.21431	2.089344
4	2.16513	2.162522	2.087529
5	2.179988	2.206942	2.120464
6	2.195492	2.162917	2.162467
7	2.169745	2.111247	2.117369
8	2.116401	2.140612	2.091032
9	2.14599	2.163895	2.104811
10	2.190099	2.183563	2.11134

The data file generated by the surface profiler is introduced into the matlab program as shown in Figure 6. The program will automatically carry out the fractal dimension calculation of the 30 sets of coordinate data of three kinds of rock samples. And the final result will be output after the operation is completed.

The results of 3D fractal dimension calculation of the surface profile of the three kinds of rock are as Table 1.

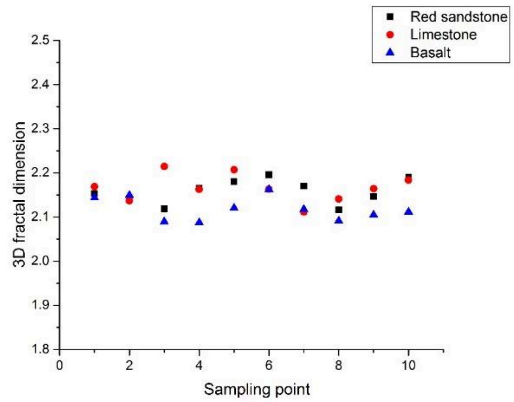

Figure 7. The index distribution of 3D Fractal dimension of rock.

3. DATA ANALYSIS AND RESULTS

After obtaining the 3D fractal dimension of 30 samples of three samples of rock samples, the correlation analysis is carried out by introducing the data into the SPSS statistical analysis software. In the analysis process, in order to find out whether there is a significant difference in the surface morphology of different kinds of rocks, in this paper, the Independent Distributed T test function of SPSS software is applied. The difference of the three kinds of rocks were analyzed, as shown in Table 2.

Table 2. Statistical analysis results of 3D fractal dimension

Comparison group	Basalt — limestone	Basalt —Red sandstone	limestone —Red sandstone
F Test Sig.	0.839	0.786	0.987
T test Sig.	0.002	0.004	0.564

Table 3. Average fractal dimension of surface topography of three kinds of rocks

Rock type	Red sandstone	limestone	Basalt
Average fractal dimension	2.1574	2.1651	2.1177

If hypothesis the significant level of hypothesis was 0.05. From the data in the table we can see that: The F Test Sig. of Basalt and limestone, basalt and red sandstone, limestone and red sandstone both greater than 0.05, indicates that the variance between the three sets of data can be considered the same. So T test can be performed by assuming that the variance is equal. The T Test Sig. of Basalt and limestone, basalt and red sandstone all less than 0.05. It shows that the 3D fractal dimension of the surface topography of basalt is significantly different from that of the other two rocks. And The T Test Sig. between limestone and red sandstone is 0.564, which is means there is no significant difference in the 3D fractal dimension of surface topography of limestone and red sandstone.

According to the fractal geometry theory and the existing research results, the surface roughness of worn surface is closely related to the three-dimensional fractal dimension, and the greater the roughness, the greater the fractal dimension. According to the fractal dimension and its average value (Table 3) of the surface morphology of rock samples calculated by the experimental data, we can get such a conclusion: the difference of surface roughness between basalt and other aggregates is obvious, and red sandstone and limestone has little difference in surface roughness. So in engineering practical, we should choose red sandstone or limestone which have greater roughness to ensure that new pavement has good anti-slide performance when considering economic and other factors.

CONCLUSIONS

The roughness of pavement layer has a direct influence on the skid resistance of pavement. In this paper, we applied the three-dimensional fractal theory to evaluation of the surface micro structures of pavement aggregates. And the surface profiles of red sandstone, limestone and basalt are collected, and the surface micro morphology of these aggregates is evaluated by calculating the 3D fractal dimensions of rock samples. Followings are the conclusions.

1) The surface profile coordinates obtained by surface profile scanning can be correctly analyzed using the three-dimensional fractal dimensions of the surface profile of rock samples.
2) The three-dimensional fractal dimension of rock surface is closely related to its roughness. Results show that the greater the roughness, the greater the fractal dimension.
3) Based on the statistical analysis of the surface fractal dimension, it is proved that basalt is very different from limestone and red sandstone in surface roughness, and red sandstone and limestone has little difference. It is recommended that red sandstone and limestone be used as pavement aggregates.

ACKNOWLEDGEMENTS

The research performed in this paper is supported by National Natural Science Foundation of China (No.51308042, No.41372320), National Science Foundation of Shandong Province (ZR2015EQ009), and Fundamental Research Funds for the Central Universities (06500036).

REFERENCES

Chen, K. R. (2009). “Research for coarse aggregate surface area fractal.” *Fujian Building Materials*, 01, 12–14

Ge, S. R., Suo, S. F., (1997). “The Computation Methods for the Fractal Dimension of Surface Profiles.” *Tribology*, 4(17), 354–362

Guo, M., Tan, Y. Q., Zhou, S. W. (2014). “Multiscale Test Research on Interfacial Adhesion Property of Cold Mix Asphalt”. *Construction and Building Materials*, 68: 769–776.

Guo, M., Motamed, A., Tan, Y. Q., Bhasin, A. (2016). “Investigating the Interaction between Asphalt Binder and Fresh and Simulated RAP Aggregate”. *Materials & Design*, 105: 25–33.

Hou, Y., Wang, L., Yue, P., Pauli, T and Sun, W. (2014). “Modeling Mode I Cracking Failure in Asphalt Binder by Using Nonconserved Phase-Field Model.” *Journal of Materials in Civil Engineering*, 26(4), 684–691.

Hou, Y., Yue, P., Wang, L and Sun, W. (2015a). “Fracture Failure in Crack interaction of Asphalt Binder by Using a Phase Field Approach.” *Materials and Structures,* 48(9): 2997–3008.

Hou, Y., Wang, L., Pauli, T., and Sun, W. (2015). “Investigation of the Asphalt Self-healing Mechanism Using a Phase-Field Model.” *Journal of Materials in Civil Engineering*. 27(3): 04014118.

Hou, Y., Sun, F., Sun, W., Guo, M., Xing, C., and Wu, J. (2016). “Quasi-brittle Fracture Modeling of Pre-Flawed Bitumen Using a Diffuse Interface Model.” *Advances in Materials Science and Engineering*, Vol. 2016, Article ID 8751646, 7 pages.

Jiang, S. W., Jiang, B., Li, Y., Deng, H., Zheng, C. Q. and Yin, G.F., (2003). “Calculation of Fractal Dimension of Worn Surface.” *Tribology*, 6(23), 533–536

Li, J., Zhu, J. Z. and Zhu, Q. K., (2002). “Review on methods of calculating fractal dimension.” *Journal of Beijing Forestry University*, 2(24), 71–78

Li, Z. C., Ji, C. Y., (2006). “Calculation of weed fractal dimension based on image analysis.” *Transactions of the Chinese Society of Agricultural Engineering*, 11(22), 175–178

Lian, J. F., Shen, N. Q. and Zhang, J. K., (2001). “Calculation of weed fractal dimension based on image analysis.” *Chinese Journal of Rock Mechanics and Engineering*, s (20), 1695–1698

Sun, H. L., (2011). “Study on anti-sliding performance of Asphalt Pavement.” *Highway,* 07, 73–78

Sun, Y. Y., (2010). “Research on the Fractal Nature of the Surface Micro-structure of Coarse Aggregate and the Relationship with the Anti-slide Performance of Asphalt Pavement.” *South China University of Technology*

Tan, Y. Q., Guo, M. (2013). “Using Surface Free Energy Method to Study the Cohesion and Adhesion of Asphalt Mastic”. *Construction and Building Materials*, 47: 254–260.

Tan, Y. Q., Guo, M. (2014). “Micro- and Nano-characteration of Interaction between Asphalt and Filler”. *Journal of Testing and Evaluation*, 42 (5): 1089–1097.

Wang, J. A., Xie, H. P., Tian, X. Y. and Kwasniewski Marek A, (2000). “Scale effect on fractal measurement of rock fracture surfaces.” *Chinese Journal of Rock Mechanics and Engineering*, 1(19), 11–17

Xia, Y. Y., Zhu, R. G., (1997). “Application study in structural rock mass using fractal theory.” *Chinese Journal of Rock Mechanics and Engineering*, 4(16), 69–74

Xu, J. Y., Zhang, Z. Q., Zhao, X. L., Wen, Q. K., Zuo, L. J., Wang, X. and Yi, L., (2013). “Spatial-temporal analysis of coastline changes in northern China from 2000 to 2012.” *Acta Geographica Sinica*, 5(68), 651–660

Zhang, L. G., Qian, Z. D., Yang, L. G. and Jia, W. B., (2013). “Description of Surface Morphology and Skid Resistance of Asphalt Concrete Pavement with Fractal Theory.” *Highway*, 05, 85–88

Experimental Research on Mix Design and Pavement Performance for Special Basalt Fiber Reinforced OGFC Asphalt Mixture

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ABSTRACT

In order to improve the stability and deformation resistance capacity of permeable open-graded friction course (OGFC) asphalt mixture, a kind of flocculent special basalt fiber with good performance is used as a reinforced stabilizer. By selecting different mixing contents of the basalt fiber, the mixture ratios of OGFC-13 were designed, then various pavement performances of the OGFC-13 mixtures under the optimum asphalt aggregate ratios were tested. The results show that the special basalt fiber can adsorb asphalt very well to bond the coarse aggregate skeleton into a solid whole; then, all the pavement performances of basalt fiber reinforced OGFC-13, including high temperature, low temperature and water stability, etc., are obviously improved. However, when the mixing content of basalt fiber is too high, a part of basalt fiber reinforced asphalt mortar will distribute in the connected voids of OGFC-13 to cause the reduction of void ratio, and a few basalt fiber with uneven dispersion is easy to form the weak points in the mixture structure, so as to influence the mixture pavement performances. Therefore, the suitable range of mixing content of the special basalt fiber is determined as 0.3%~0.5%, and the optimum mixing content is 0.4%. The results can provide references for the engineering application of permeable noise reduction asphalt pavement.

KEYWORDS: special basalt fiber; fiber reinforced; open-graded friction course (OGFC); mix design; pavement performance; mixing content

1. INTRODUCTION

Since the late 1950s, fiber as stabilizer and reinforcer has been more and more widely applied in asphalt mixture, which can be divided into two major categories: organic fiber and inorganic fiber (Tang, Sheng and Sun, 2008; Li and Chen, 2014; Zha, Cai and Cao, 2014). Among them, the organic fiber includes natural plant fiber and synthetic fiber etc., for example, the former has lignin fiber which is widely applied in SMA mixture to play a stabilizing role (Peng, 2005; Zhang and Chen, 2006), and the latter has polyester fiber and other fibers which are used for improving the tensile strength of asphalt concrete to play a reinforcing role (Wu, Ji and Ma, 2015; Zha, Chen and Cheng, 2012; Song, Zhang and Wu, 2012). The inorganic fiber includes mineral fiber and metal fiber etc., and the mineral fiber is more applied in asphalt mixture, which mainly has basalt fiber and asbestos fiber etc. (Wu, Jiang, Lv, Xiao, Ding and Yu, 2015; Tang, Gao and Zhao, 2012; Tian, Zeng, Wu, Xia and Zhu, 2008). As asbestos is carcinogenic, its fiber is rarely applied in pavement engineering. However, many researches and applications show that, compared with other fibers, the basalt fiber is excellent in performance, good in