Study on influencing factors of void fraction of asphalt mixture based on grey correlation

Xiping Lv¹,², Haijun Liu³,⁴, *, Shanqiang Li³,⁴

¹ Guangdong highway Construction Co. Ltd., Guangzhou 510000, China
² South Section of FoKai Expressway Reconstruction and Expansion Project Management Office, Jiangmen 529000, China
³ Guangdong Transportation Technology Testing Co. Ltd., Guangzhou 510550, China
⁴ Guangdong Hualu Communications Technology CO. Ltd., Guangzhou 510420, China

*Corresponding author e-mail: liuhj2001@scut.edu.cn

Abstract. grey relational analysis method has been widely used because it is applicable to small samples, irregular samples and has a small amount of calculation. For the study of shear compaction forming factors affecting air void of asphalt mixture, this paper studies a set of shear compaction meter uniform specimen preparation methods, and based on this through the grey relation analysis method the study type of asphalt, asphalt content, shear compaction times and fine aggregate level matching specimen void fraction, and it is concluded that the factors impact on the specimen void fraction size. The results show that the grey correlation method is an analytical method suitable for studying the influencing factors of the voidage of asphalt mixture. Among the influencing factors, the shear compaction times, the ratio of oilstone and the mass fraction of particle size ≤0.075mm are the three main factors affecting the voidage of shear compaction specimens. The research results have certain guiding significance for asphalt mixture design and construction quality control.

Keywords: Road engineering; Asphalt mixture; Shear compactor; Grey correlation analysis; Void fraction.

1. Introduction
The void ratio of asphalt mixture is one of the most important and complicated problems in pavement design. The void ratio directly affects the rutting depth, water permeability and fatigue life of asphalt pavement.[1]

There are many factors that affect the voidage, such as the gradation of synthetic ore [2][3], the amount of asphalt [4], the compaction work [5]and the gross volume density of the specimen [6]. However, current studies on the factors affecting the void fraction of asphalt mixture mainly focus on the specimens prepared by conventional forming methods. Shear compactor, as a new forming tool to simulate the compaction of asphalt mixture, has rarely been studied on the factors affecting the void fraction of asphalt mixture. On the other hand, in the actual compaction process, due to the limited data collection, it is difficult to find the rule in the existing data by using the conventional mathematical
statistics method, while the grey correlation analysis method[7] is widely used because it is suitable for small samples, irregular samples and has the characteristics of small amount of calculation.

Compaction meter based on shear forming different type of asphalt, asphalt content, shear compaction times and fine aggregate gradation of the specimen, the introduction of grey relational analysis method research the factors influence on shear compaction molding specimens of void fraction, and it is concluded that the factors impact on the specimen void fraction size, the results of subsequent asphalt mixture design and construction quality control have important guiding significance.

2. Performance of raw materials

(1) Asphalt

In this paper, SK70# matrix asphalt and SK modified asphalt will be used for testing. Relevant tests were conducted in accordance with the test code for highway engineering asphalt and asphalt mixture (JTG E20-2011) [8], and the main technical indicators of the two kinds of asphalt are shown in table 1. The test results show that the asphalt meets the requirements of JTG E20-2011.

| Test                  | Matrix asphalt results | Modified asphalt results |
|-----------------------|------------------------|--------------------------|
| Needle penetration, 25℃, 5s, 0.1mm | 62                     | 56                       |
| Softening point TR&B, ℃ | 48                     | 76.5                     |
| Elongation 5℃, 5cm/min, cm | 52                     | 34                       |
| Rotating viscosity 135℃, Pa.S | -                      | 2.4                      |
| Elastic recovery 25℃, %  | -                      | 90                       |
| RTFOT Residues 163 ℃ | Mass loss % 0.053      | 0.04                     |
| Penetration ratio %  | 83                     | 75                       |

(2) Aggregate

The crude aggregate tested in this paper is diabase from shiniuling material yard, guigang, guangxi, and the test results are shown in table 2. The fine aggregate and mineral powder come from the limestone of malan stone field in mashui town, and the properties are shown in table 3 and 4. The results of laboratory tests show that both aggregate and powder meet the requirements of the code.

| A pilot project | Specified value | Aggregate size 11-16mm | 6-11 mm | 3-6mm |
|-----------------|-----------------|-------------------------|---------|-------|
| Apparent relative density (a)g/cm³ | ≥2.5           | 2.877                   | 2.847   | 2.931 |
| Gross volume relative density (a)g/cm³ | ----          | 2.839                   | 2.784   | 2.854 |
| Needle flake particle content (%) | ≤15            | 6.8                     | 7.7     | 7.8   |
| Water absorption rate (%) | ≤3.0           | 0.47                    | 0.81    | 0.92  |
| Crush value (%) | ≤28             | 13.4                    | -       | -     |
| Los Angeles abrasion loss (%) (grade C) | ≤30           | 11.8                    | -       | -     |
Table 3. Test results of fine aggregate

| A pilot project                      | Specified value | specifications |
|-------------------------------------|-----------------|----------------|
|                                     |                 | 3-5mm          | 0-3mm         |
| Apparent relative density (g/cm³)   | ≥2.5            | 2.811          | 2.812         |
| Gross volume relative density (g/cm³)| ----            | 2.736          | 2.721         |
| Water absorption rate (%)           | ≤3.0            | 0.97           | 1.20          |
| Robustness (%)                     | ≤12             | -              | 3.8           |
| Sand equivalent                     | ≥60             | 67             | 62            |

Table 4. Results of mineral powder detection

| A pilot project                      | Specified value | The test results |
|-------------------------------------|-----------------|-----------------|
|                                     |                 |                 |
| Apparent density (g/cm³)            | ≥2.5            | 2.759           |
| Water content (%)                   | ≤0.6 mm         | 0.3             |
|                                    | < 0.6 mm        | 100             |
|                                    | < 0.3 mm        | 96.5            |
|                                    | < 0.15 mm       | 90.5            |
|                                    | < 0.075 mm      | 82.5            |

3. Preparation of asphalt mixture specimen

3.1. Mix ratio design

The typical gradation GAC-16 in Guangdong province is adopted in this paper. The synthetic gradation composition of asphalt mixture is shown in Table 5. The influence of medium coarse aggregate and fine aggregate in the gradation of synthetic ore on the voidage of asphalt mixture is different, and the literature[9] shows that the influence of the change of coarse aggregate position in the gradation curve on the voidage is only one third of that of fine aggregate. Therefore, the proportion above coarse aggregate is kept unchanged in this paper, and only the influence of fine aggregate in synthetic gradation on the voids of asphalt mixture is studied. The composition of fine aggregate gradation is shown in Table 6.

Table 5. Radiation composition of GAC-16 asphalt mixture

| Mesh size (mm) | 16  | 13.2 | 9.5  | 4.75 | 2.36 | 1.18 | 0.6  | 0.3  | 0.15 | 0.075 |
|----------------|-----|------|------|------|------|------|------|------|------|-------|
| Synthesis grading | 98.3 | 78.8 | 54.7 | 33.6 | 23.6 | 15.5 | 12.3 | 8.9  | 7.1  | 5.5   |
| Design range    | 95 – 100 | 65 – 85 | 47 - 68 | 28 – 46 | 18 to 35 | 15 – 29 | 12 – 23 | 8 to 18 | 6 to 13 | 4 – 8|

Table 6. Gradation composition of GAC-16 fine aggregate

| Serial number | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|---------------|------|------|------|------|------|------|------|------|------|------|
| Particle size ≤4.75mm (%) | 31.9 | 33.6 | 33.6 | 31.9 | 31.9 | 33.6 | 31.6 | 31.6 | 31.6 | 31.9 |
| Particle size ≤2.36mm (%) | 23.6 | 20.9 | 23.6 | 20.9 | 20.9 | 23.6 | 21.6 | 21.6 | 21.6 | 20.9 |
| Particle size ≤0.075mm (%) | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    | 5    |

3.2. Specimen preparation

The compaction principle of the asphalt Shear Box Compactor (SBC) is based on the simulation of the stress process during the driving of the field vehicle load. It can provide a constant pressure and a cyclic shear force with a constant shear angle, thus achieving high precision and consistency in the target compaction density. SBC requires about 30kg of asphalt mixture when it is formed. Compared with the
traditional Marshall compactor, rotary compactor and wheel compactor, it is closer to the compaction effect of the actual road surface. The void ratio of the formed specimen is more uniform.

According to the Marshall design method, the optimum proportion of asphalt was determined to be 4.7%, 6 sets of specimens were formed according to the optimum proportion of asphalt, the forming temperature was 140℃, and 4 sets of specimens were formed according to the optimum proportion of asphalt, the forming temperature was 160℃±0.5%. The shear Angle of the shear compactor is 4°, the vertical pressure is 0.7mpa, the compaction frequency is 16 seconds/cycle, and the molding size of the specimen is 450 × 150 × 170mm.

In order to reduce the effect of test operation on the void fraction of specimens, this paper studies a set of methods for preparing uniform specimens based on forming a large number of shear compaction specimens. The specific steps are as follows:

(1) remove the preheated test mold from the oven and load it into the shear compactor;
(2) pour the well-mixed asphalt mixture into the test mold in three layers, about one third of the mixture in each layer, and use the preheated ramming rod to level the surface from both sides to the middle in order, and insert the ramming around 25 times; Ramming from the edge, along the spiral line to the center evenly ramming, ramming should be vertical pressure, no impact.
(3) after filling the mixture, cover the top immediately and start the instrument to start the test.

4. Grey correlation analysis

4.1. Characteristics of factors influencing void ratio
Asphalt mixture voidage is a key index in pavement design. There are many factors influencing the voidage variation of laboratory test pieces, which can be summed up as internal factors and external conditions. Internal factors are mainly reflected in the quality of the material itself, including raw material (asphalt and aggregate) performance, asphalt consumption, ore gradation and other factors, while external conditions mainly include compaction conditions and compaction temperature. When the external conditions and internal factors are combined, they will have a comprehensive effect on the voidage of the specimen. Because of the coupling effect of multiple factors and the complexity of asphalt mixture itself, it requires a lot of data and long-term research to study the factors affecting void ratio, so researchers cannot solve this problem well. Gray correlation analysis method is widely used because it is applicable to small samples, irregular samples and has the characteristics of small amount of calculation. For the "gray" problem of void ratio of asphalt mixture, gray correlation analysis has obvious advantages.

4.2. Steps of grey correlation analysis
In this paper, a typical GAC-16 gradation in Guangdong province was used to conduct the experiment. According to the analysis steps, the gray correlation degree of factors such as shear compaction times, oilstone ratio, gross volume density and aggregate content in each section of fine aggregate on the void fraction of the mixture was calculated, as shown below.

(1) in the original data of the test, the influencing factors in table 7 such as shear compaction times, 25℃ needling degree, and whetstone ratio are called behavior sequences, where \( x_1 = (x_1(1), x_1(2), \ldots x_1(n)) \) \( i = 0, 1, 2, \ldots n \). The voidage column of the research object is called the characteristic behavior sequence of the system \( x_0 = (x_0(1), x_0(2), \ldots x_0(n)) \)

(2) conduct dimensionless processing on the original data to get the initialization of the new sequence, and the initialization of the new sequence is, where \( X_1 = (X_1(1), X_1(2), \ldots X_1(n))X_1(m) = x_1(m)/x_1(1)i0, 1, 2, m \). In this paper, initial value is used for processing, and the processing results are shown in table 8.

(3) find the difference sequence, record: \( \Delta_0,i(k) = |X_0 - X_i| \) Where \( \theta = 1, 2, m \). The dimensionless processed data is substituted into the equation to obtain the difference sequence, as shown in table 9.
(4) find the maximum difference and the minimum difference in the difference sequence of the influencing factors, record: \( M = \max \max \Delta a_l(k) \) \( m = \min \min \Delta a_l(k) \).

(5) find the grey correlation coefficient, denoted, where \( m = 1,2, \ldots, m \), and this paper takes 0.5, the results are shown in table 10. \( y_{0,i}(k) = \frac{m+\mu M}{\Delta a_l(k)+\mu M}i \cdots \mu \in (0,1)\mu \)

Calculate the grey correlation degree and proportion of the influencing factors, and take the mean value of the grey correlation coefficient, where \( m = 1,2, \ldots, m \), \( y_{0,i}(k) = \frac{1}{n} \sum_{k=1}^{n} y_{a_l}(k) i \cdots \)The influence of each factor on the voidage of the mixture was sorted, as shown in table 11.

### Table 7 Grey correlation analysis of raw data of shear compaction specimens

| Specimen number | Asphalt type | Void ratio (%) | Shear compaction times (times) | 25°C needle penetration (0.1mm) | Whetstone ratio (%) | Gross volume density \((g/cm^3)\) | Particle size 4.75mm mass fraction (%) | Particle size 2.36mm mass fraction (%) | Particle size 0.075mm mass fraction (%) |
|-----------------|--------------|----------------|-------------------------------|--------------------------------|---------------------|---------------------------------|-------------------------------|---------------------------------|----------------------------------|
| 1               | SK modified  | 6.67           | 20                            | 56                             | 3.7                 | 2.497                           | 31.9                         | 23.6                            | 5                                |
| 2               | SK modified  | 5.13           | 30                            | 56                             | 4.2                 | 2.519                           | 33.6                         | 20.9                            | 5.5                              |
| 3               | SK modified  | 3.65           | 40                            | 56                             | 4.7                 | 2.538                           | 33.6                         | 23.6                            | 5                                |
| 4               | SK modified  | 1.96           | 50                            | 56                             | 5.2                 | 2.565                           | 31.9                         | 20.9                            | 5.5                              |
| 5               | SK modified  | 8.67           | 10                            | 62                             | 4.7                 | 2.407                           | 31.9                         | 20.9                            | 5.5                              |
| 6               | SK modified  | 5.49           | 20                            | 62                             | 4.7                 | 2.490                           | 33.6                         | 23.6                            | 5                                |
| 7               | SK modified  | 4.33           | 30                            | 62                             | 4.7                 | 2.521                           | 31.6                         | 21.6                            | 5.5                              |
| 8               | SK modified  | 3.84           | 30                            | 62                             | 4.7                 | 2.534                           | 31.6                         | 21.6                            | 5.5                              |
| 9               | SK modified  | 3.52           | 30                            | 62                             | 4.7                 | 2.542                           | 31.6                         | 21.6                            | 5.5                              |
| 10              | SK modified  | 2.8            | 40                            | 62                             | 4.7                 | 2.561                           | 31.9                         | 20.9                            | 5.5                              |

### Table 8. Dimensionless processing of raw data

| Factors affecting the | Specimen number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|-----------------------|-----------------|---|---|---|---|---|---|---|---|---|----|
| Void ratio (%)        | 1.00            | 0.77| 0.55| 0.29| 1.30| 0.82| 0.65| 0.58| 0.53| 0.42|
| Shear compaction times (times) | 1.00 | 1.50| 2.00| 2.50| 0.50| 1.00| 1.50| 1.50| 1.50| 2.00|
| 25°C needle penetration (0.1mm) | 1.00 | 1.00| 1.00| 1.00| 1.11| 1.11| 1.11| 1.11| 1.11| 1.11|
| Whetstone ratio (%)   | 1.00            | 1.14| 1.27| 1.41| 1.27| 1.27| 1.27| 1.27| 1.27| 1.27|
| Gross volume density \((g/cm^3)\) | 1.00 | 1.01| 1.02| 1.03| 0.96| 1.00| 1.01| 1.01| 1.01| 1.03|
| Particle size 4.75mm mass fraction (%) ≤ | 1.00 | 1.05| 1.05| 1.00| 1.00| 1.05| 0.99| 0.99| 0.99| 1.00|
| Particle size 2.36mm mass fraction (%) ≤ | 1.00 | 0.89| 1.00| 0.89| 0.89| 1.00| 0.92| 0.92| 0.92| 0.89|
| Particle size 0.075mm mass fraction (%) ≤ | 1.00 | 1.10| 1.00| 1.10| 1.10| 1.00| 1.10| 1.10| 1.10| 1.10|

### Table 9. Difference sequence of influencing factors

| Factors affecting the | Specimen number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|-----------------------|-----------------|---|---|---|---|---|---|---|---|---|----|
| Shear compaction times (times) | 0.00 | 0.73| 1.45| 2.21| 0.80| 0.18| 0.85| 0.92| 0.97| 1.58|
| 25°C needle penetration (0.1mm) | 0.00 | 0.23| 0.45| 0.71| 0.19| 0.28| 0.46| 0.53| 0.58| 0.69|
| Whetstone ratio (%) | 0.00 | 0.37| 0.72| 1.11| 0.03| 0.45| 0.62| 0.69| 0.74| 0.85|
| Gross volume density \((g/cm^3)\) | 0.00 | 0.24| 0.47| 0.73| 0.34| 0.17| 0.36| 0.44| 0.49| 0.61|
| Particle size 4.75mm mass fraction (%) ≤ | 0.00 | 0.28| 0.51| 0.71| 0.30| 0.23| 0.34| 0.41| 0.46| 0.58|
| Particle size 2.36mm mass fraction (%) ≤ | 0.00 | 0.12| 0.45| 0.59| 0.41| 0.18| 0.27| 0.34| 0.39| 0.47|
| Particle size 0.075mm mass fraction (%) ≤ | 0.00 | 0.33| 0.45| 0.81| 0.20| 0.18| 0.45| 0.52| 0.57| 0.68|
Table 10. Grey correlation coefficient of influencing factors

| Factors affecting the Specimen number | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|--------------------------------------|----|----|----|----|----|----|----|----|----|----|
| Shear compaction times (times)       | 1.00 | 0.60 | 0.43 | 0.33 | 0.58 | 0.86 | 0.56 | 0.54 | 0.53 | 0.41 |
| 25℃ needle penetration (0.1mm)      | 1.00 | 0.60 | 0.44 | 0.33 | 0.65 | 0.55 | 0.44 | 0.40 | 0.38 | 0.34 |
| Whetstone ratio (%)                 | 1.00 | 0.60 | 0.43 | 0.33 | 0.95 | 0.55 | 0.47 | 0.44 | 0.43 | 0.40 |
| Gross volume density (g/cm³)        | 1.00 | 0.60 | 0.44 | 0.33 | 0.52 | 0.68 | 0.50 | 0.46 | 0.43 | 0.38 |
| Particle size 4.75mm mass fraction (%) | 1.00 | 0.55 | 0.41 | 0.33 | 0.54 | 0.61 | 0.51 | 0.46 | 0.43 | 0.38 |
| Particle size 2.36mm mass fraction (%) | 1.00 | 0.72 | 0.40 | 0.33 | 0.42 | 0.63 | 0.53 | 0.47 | 0.43 | 0.39 |
| Particle size 0.075mm mass fraction (%) | 1.00 | 0.55 | 0.47 | 0.33 | 0.67 | 0.69 | 0.47 | 0.43 | 0.41 | 0.37 |

Table 11. Grey correlation degree and proportion of influencing factors

| Factors affecting the | Grey correlation | Accounted for | The sorting |
|-----------------------|------------------|---------------|-------------|
| Shear compaction times (times) | 0.586 | 15.47 | 1 |
| 25℃ needle penetration (0.1mm) | 0.513 | 13.54 | 7 |
| Whetstone ratio (%) | 0.561 | 14.82 | 2 |
| Gross volume density (g/cm³) | 0.534 | 14.10 | 4 |
| Particle size 4.75mm mass fraction (%) | 0.522 | 13.79 | 6 |
| Particle size 2.36mm mass fraction (%) | 0.530 | 14.00 | 5 |
| Particle size 0.075mm mass fraction (%) | 0.541 | 14.28 | 3 |

4.3. Result analysis

According to the grey correlation analysis results of the influence of various factors on voidage in the table above, it can be seen that:

(1) in table 11, the order of grey relational degree is: shear compaction times, proportion of whetstone, mass fraction of particle size 0.075mm, gross volume density, mass fraction of particle size 2.36mm, mass fraction of particle size 4.75mm, penetration degree of asphalt at 25℃.≤≤≤

(2) shear compaction times have the greatest influence on the void fraction of asphalt mixture, indicating that shear compaction work is the key factor that dominates the void fraction of asphalt mixture. The ratio of oil to stone is second only to the number of times of shear compaction, which is consistent with the actual production experience.

(3) among the three levels of fine aggregate aggregate contents, particle size 0.075mm, particle size 2.36mm and particle size 4.75mm are ranked 3rd, 5th and 6th in the voidage distribution of asphalt mixture.≤≤≤According to the literature theory, the fine aggregate with the particle size of 0.075mm plays a complete filling role, while the aggregate with the particle size of 2.36mm can not only fill the gap of ore, but also resist the compaction of large-particle ore and increase the gap of ore.10≤≤≤

5. Conclusion

(1) the grey correlation analysis method can well reflect the influence law of each factor on the void fraction of the specimen after the shear compactor is formed, and it is a suitable analysis method for studying the factors affecting the void fraction of asphalt mixture.

(2) the order of the factors influencing the voidage of the shear compaction specimens was as follows: shear compaction times, ratio of oilstone, mass fraction of particle size ≤0.075mm, gross volume density, mass fraction of particle size ≤2.36mm, mass fraction of particle size ≤4.75mm, and penetration of asphalt at 25℃.
(3) shear compaction times have the greatest influence on the void fraction of asphalt mixture and are the key factors leading to the void fraction of asphalt mixture, followed by the ratio of oilstone and the particle size $\leq 0.075\text{mm}$ mass fraction.

References

[1] Shen jinan. road performance of asphalt and asphalt mixture [M]. Beijing: people's communications press, 2001. (in Chinese)

[2] Wu chuanhai. Influence of volume index of mineral-grade paired asphalt mixture [J]. Road construction machinery and construction mechanization, 2011, 28(11): 55-58.

[3] Li yanchun, meng yan, zhou wei-wei, li dong-lan. Grey correlation analysis of influencing factors of asphalt mixture voidage [J]. Chinese journal of highways, 2007(01): 30-34. (in Chinese with English abstract)

[4] Erica Yeung, Andrew Braham, Jim Barnat, Exploring the Effect of Asphalt - Concrete Fabrication and Compaction Location on the Six Compaction Metrics [J]. Journal of Materials in Civil Engineering, 2016, 28 (12) : 04016163.

[5] Li linping, hu bangyan, zhang fei, yu jiang. Orthogonal experimental analysis of the influence of multiple factors on the void ratio of asphalt mixture [J]. Journal of chongqing jiaotong university (natural science edition), 2016, 35(04): 47-51.

[6] Zhang zhiqiang, ren yongli, li zhi. Analysis of influencing factors on void ratio of asphalt mixture [J]. Highway, 2012(01): 157-160.

[7] Deng julong. Basic method of gray system [M]. Wuhan: huazhong university of science and technology press, 1986: 49-54.

[8] Test code for asphalt and asphalt mixture in highway engineering JTG e20-2011 [S]. Beijing: people's communications press, 2011.

[9] Liang xishan. asphalt mixture design and quality control principle [M]. Beijing: people's communications press, 2008: 5-7. (in Chinese)

[10] Xu zhihong, liu hong, wang yuhui, et al. Effect of fine aggregate on asphalt mixture performance [J]. Chinese journal of highways, 2001, 14(add): 27-30. (in Chinese with English abstract)