Comparative Research on Mechanical Properties and Void Distribution of Cement Stabilized Macadam Based on Static Pressure and Vibration Compaction

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Abstract: Cement stabilized macadam semi-rigid base materials are widely used in road construction in China. However, a traditional static molding method and heavy compaction method cannot guide the design and engineering application of cement stabilized macadam mixture because it often appears that the compaction degree exceeds 100% in the practical engineering. In view of this, this paper carried out the research of an indoor vibration compaction method of cement stabilized macadam mixture, and compared the mechanical properties and void distribution characteristics of two kinds of compositions of mixtures under the vibration compaction method as well as static pressure molding and heavy compaction method and on-site sample after 7 days curing period, which was combined with the physical engineering project of Yu-Song Expressway in Jilin Province, China. The research results show that the maximum dry density of mixture under vibration compaction is larger and the best moisture content is smaller, which has a heavy incomparable advantage on the simulation of on-site compaction. And the compressive strength and splitting strength indexes of vibration compacted specimens are close to those of an on-site sample, which are all larger than static pressure specimen. Moreover, the void distribution characteristics of vibration compacted specimens is much closer to those of the on-site sample and more universal, while static pressure specimens lack in uniformity. In addition, different results caused by the two gradation are compared. All of the above research results can verify that the vibration compaction method has more reliability and accuracy to simulate the actual properties of base material. This study provides a reference for the application of vibration compaction method in road engineering design.

Keywords: cement stabilized macadam; vibration compaction; static pressure molding and heavy compaction; mechanical properties; void distribution

1. Introduction

The semi-rigid base material of cement stabilized macadam is widely used in road base construction in China, which has the advantage of high early strength, water stability, and frost resistance. However, the preparation method of indoor heavy compaction test and static pressure specimens are only similar to the road building machinery and technology of the 1980s, whose compaction work and mechanism of strength formation are very different from the vibratory rollers that are now widely used in road building machinery. The existing indoor test have been unable to properly guide the actual design and engineering application of cement stabilized macadam mixture. On the other hand, the purpose of molding specimens is to obtain indoor samples that are similar to the actual pavement base in the
field, and to predict the performance of road base by testing the strength, modulus, and durability of the samples. However, current test methods only stay on the macroscopic mechanical behavior level, and lack the mechanism from mesoscopic view. Cement stabilized macadam mixture is the multiphase inhomogeneous materials composed of coarse aggregate, cement mortar and void, but traditional empirical design methods only assume that the mixture is a uniform whole from a macroscopic perspective, which could not meet the aggregate interface behavior research [1].

In recent years, many scholars have carried out research on other indoor compaction methods, such as the Proctor method [2,3], vibrating table tests [3], and vibration compaction molding method. In China, scholars are more committed to researching the indoor vibration compaction molding method for cement stabilized macadam, and have proved that the specimens molded by this method have higher mechanical strength, and has higher correlation with on-site samples [4–9]. For example, the unconfined compressive strength, splitting strength, and resilient modulus of cement stabilized macadam mixture prepared by the vibration compaction method are 1.87–2.37, 1.54–2.74, and 1.53–1.96 times more than those prepared by static pressure molding and heavy compaction method, and the results show that the mechanical properties have a correlation of 91.7% with the field [4]. However, the above researches are mainly analyzed from a mechanic perspective. In fact, many properties of the mixture can also be studied by mesoscopic analysis. For example, computerized tomography (CT) and two-dimensional digital image processing technology were used to study the influence of changing compaction conditions on the mesoscopic structure of asphalt mixture [10,11], and CT scanning technology was used to establish a three-dimensional mathematical expression of particle morphology [12–14], which can be seen that mesoscopic analysis can help us to study various properties of the mixture, including the properties of vibration compacted specimens.

The purpose of writing this passage lies in the fact that there are two kinds of molding methods of cement stabilized macadam in the Chinese specification. One is the heavy compaction and static pressure molding method, and the other is the vibration molding method. The former is more currently used, but it does not match the site condition well with the improvement of on-site construction methods. Besides, the latter research is not deep enough. Therefore, this study focuses on the vibration compaction method in the specification so as to prove that the vibration compaction method can better reflect the site construction conditions from a mechanic and microscopic perspective, which can facilitate the following study of vibration compaction standard.

In this paper, cement stabilized macadam mixed specimens of two kinds of gradation were prepared by the vibration compaction method as well as static pressure molding and heavy compaction method and analyzed from macroscopic and mesoscopic views combined with an on-site sample after a 7 days curing period which came from the Yu-Song test road in Jilin Province, China. Firstly, mechanical properties of the two compositions of specimens under the above methods and on-site sample were tested, and then they were scanned by industrial CT to analyze the differences of the mesoscopic structure. An attempt was made to explain the mechanical behavior of mixture from a mesoscopic view, so as to provide a reference for the research on the multi-scale problem of the mixture. By the way, different results caused by the two compositions are compared. The results of this research promoted that vibration compaction method is used to guide the design and construction of road base in the seasonal freezing area of Jilin Province in China.

2. Materials and Methods

2.1. Raw Materials

2.1.1. Cement

The cement used in this study is NO.425 of Jindong, and the technical indexes are shown in Table 1.
Table 1. Technical indicators of cement.

| Technical Index | Unit | Specified Value | Test Results | Test Methods |
|-----------------|------|-----------------|--------------|--------------|
| Fineness        | %    | ≤10             | 5.3          | T0502-2005   |
| Initial time    | min  | ≥180            | 378          |              |
| Final time      | min  | ≥360            | 433          | T0505-2005   |
| Setting Time    |      |                 |              |              |
| Soundness       | –    | Qualified       | Qualified    |              |
| 3d Strength     | Compressive MPa | ≥17 | 25.9 | T0506-2005 |
|                 | Flexural MPa   | ≥3.5 | 4.0  |              |

2.1.2. Aggregate

The aggregate was andesite broken by a jaw crushe, which was obtained from Changchun, Jilin Province. It was graded into three types of coarse aggregates and two types of fine aggregates as follows: 1# 19~31.5 mm, 2# 9.5~19 mm, 3# 4.75~9.5 mm, 4# 2.36~4.75 mm, and 5# 0~2.36 mm. Their technical indexes are shown in Tables 2 and 3.

Table 2. Technical indexes of coarse aggregates.

| Technical Index                  | Test Results | Specified Value | Test Methods |
|----------------------------------|--------------|-----------------|--------------|
|                                  | 1#           | 2#              | 3#           |              |
| Apparent density (g/cm³)         | 2.723        | 2.734           | 2.748        | ≥2.6         |
| Crushed value (%)                | –            | 12.3            | –            | ≤22          |
| Needle flake content (%)         | 14.8         | 11.9            | 4.6          | ≤18          |
| Dust content below 0.075 mm (%)  | 0.2          | 0.4             | 0.6          | ≤1.2         |

Table 3. Technical indexes of fine aggregates.

| Technical Index                  | Test Results | Specified Value | Test Methods |
|----------------------------------|--------------|-----------------|--------------|
|                                  | 4#           | 5#              |              |
| Apparent density (g/cm³)         | 2.710        | 2.705           | ≥2.6         | T0330-2005   |
| Dust content below 0.075 mm (%)  | 0.7          | 0.8             | ≤15          | T0333-2000   |

2.1.3. Mixtures

Two compositions of the mixture—the skeleton-dense gradation (GM) and the suspended-dense gradation (XM)—were selected in this paper. These two gradations are shown in Table 4, and the gradation for the on-site construction are shown in Table 5.

Table 4. Two design gradation of percentage (%) passing of key mesh.

| The Type of Gradation | Mass Percentage (%) Passing the Following Mesh (mm) |
|-----------------------|-----------------------------------------------------|
| XM                    | 31.5 19.0 9.5 4.75 2.36 0.6 0.075                  |
| GM                    | 100 84.0 57.5 40.0 26.5 11.5 3.5                   |

XM is the suspended-dense gradation, and GM is the skeleton-dense gradation.
Table 5. The composition of the mixtures for cement stabilized macadam base.

| The Structure Layer                  | The Composition of the Mixtures for Site Construction | Cement Dosage (%) |
|--------------------------------------|------------------------------------------------------|-------------------|
| Cement stabilized macadam base       | 36 23 8 7 26                                        | 4.0               |
| Cement stabilized macadam subbase    | 36 23 8 7 26                                        | 3.5               |

2.2. Methods

2.2.1. Specimen Preparation Methods

Two methods were chosen to prepare the specimens in this paper, which is the static pressure molding and heavy compaction method as well as the vibration compaction method. The former refers to “Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering” (JTG-E51-2009). The latter refers to the “Technical Specification for Design and Construction of Cement Stabilized Macadam by Vertical Vibration Method (DB 61/T 529-2011)”, which apply the gravity and vibration of vibration machines or instruments to load the pressed materials, overcome the cohesion and internal friction between the pressed materials, make the solid particles of the pressed materials shift, rearrange and approach each other, and finally achieve the compacting state of the pressed materials [15]. The field compaction method was based on vibration compaction.

The structure of the vertical-vibration-testing machine (VVTM) made at Tianjin Dongzheng Measurement and Control Technology Development Co. LTD Tianjin, China shown in Figure 1, which is constituted by an oscillatory system, control system, and power plant. The actual adjustable parameters of VVTM include: Quality of upper system, quality of neither system, working frequency, and static eccentric moment. Combined with the existing vibration parameters optimization research and test verification [16], the final selected vibration parameters are shown in Table 6.

![Vertical-vibration-testing machine](image-url)

Figure 1. The structure of the vertical-vibration-testing machine.
Table 6. The vibration parameters of vertical-vibration-testing machine (VVTM).

| Working Frequency (Hz) | Nominal Amplitude (mm) | Work Mass (kg) | Upper System | Nether System | Total Mass |
|------------------------|------------------------|----------------|--------------|---------------|-----------|
|                        |                        |                | 30           | 1.2           | 180       |
|                        |                        |                | 120          | 120           | 300       |

For the vibration compaction method, the vibration time must be assured because there is no unified standard. A different vibration time was used to mold the specimens, which built relationships between the vibration time and the density of specimens. Then it is determined that the vibration time of the cement stabilized macadam mixture was 100 s by combining the maximum dry density so that on-site cement stabilized macadam base could reach in the test section. The vibration time of the specimens was 90 s with a compaction degree of 98%.

2.2.2. Comparative Analysis of the Two Methods

The vibration compaction method mainly includes the following differences compared with the static pressure molding and heavy compaction method:

1. Different method of determining the moisture content: Heavy compaction method needs to measure the moisture content of the dry mixture after the compaction test. However, the vibration compaction method needs the aggregate to be dried to a constant weight before the test, which spends 4 to 6 h, and the moisture content of aggregate has to be strictly controlled before the test. It is not necessary to measure the moisture content of dry mixture after the compaction test, which can avoid an inaccurate estimation of the original moisture content because of cement hydration reaction during the test process;

2. Different order of adding cement: Vibration compaction test requires drying aggregate and cement to mix evenly before adding the predetermined amount of water, while the static pressure molding and heavy compaction method is required to add cement after the aggregate is wet;

3. Different settings for compacted work: Heavy compaction work is determined by the compaction work of road rollers of 12~15 tons which are widely used in the 1980s. However, the existing highway base layer is mostly used with more than a vibration road roller of 20 tons, which is 1.33~1.66 times of the past. Correspondingly, a higher indoor test method is needed to choose. The study shows that the compaction work per unit volume is achieved at 2687.0 Kj/m$^3$ under the static pressure compaction method C in the “Test Procedure”, but the vibration compaction work can reach 4700 Kj/m$^3$ if the vibration time is 120 s [17], which is 1.75 times of the former. Hence maybe the higher compaction work standard of vibration compaction can better satisfy the current production control;

4. Different arrangement modes of the compacted materials: A certain range of free movement of the compacted materials is realized by vibration compaction through the high-frequency vibration of the compacted instrument, and the ore particles can achieve a similar arrangement mode with on-site construction. The compaction result of mixture is closer to the compaction effect achieved in the field. However static pressure molding and heavy compaction method compacts the mixture by impact load, which is different from the actual rolling in the form of action and ore material arrangement effect.

2.3. The Techniques Related to Test

1. X-ray computed tomography

X-ray computed tomography (X-ray CT) is an industrial computed tomography using X-rays. The images obtained by the X-ray CT can show the mesoscopic structure of the mixture. In this paper, the Compact-225 high precision industrial CT scanner manufactured by YXLON of Germany was used to scan the mixture, whose maximum imaging pixel is 1024×1024, and distinguish ability is 0.1 mm.
2. Digital image processing

The images scanned and rebuilt by X-ray CT need to be processed because of noise, distortion, and artifact. The main tools to solve these problems are MATLAB, VG Studio Max2.2, and IPP. The operation flow of two-dimensional digital image processing is shown in Figure 2.

![Figure 2. The operation flow of two-dimensional digital image processing.](image)

3. Results and Discussion

3.1. The Maximum Dry Density and the Optimal Moisture Content

The cement stabilized macadam mixture was compacted under different conditions. Then the maximum dry density $\rho_{\text{dmax}}$ and optimal moisture content $w_0$ of the heavy compacted (HC) and vibration compacted (VC) mixture under different gradations and cement doses were counted. The results are shown in Tables 7 and 8.

**Table 7.** The optimal moisture content $w_0$ and the maximum dry density $\rho_{\text{dmax}}$ of the cement stabilized macadam mixture.

| The Cement Doses $P_s$ (%) | $w_0$ (H) (%) | $\rho_{\text{dmax}}$ (H) (g/cm$^3$) |
|---------------------------|-------------|----------------------|
|                           | XM          | GM                   |
|                           | HC          | VC                   | HC          | VC                   |
| 3.0                       | 4.9         | 4.6                  | 2.200       | 2.250                |
| 3.5                       | 5.0         | 4.7                  | 2.203       | 2.256                |
| 4.0                       | 5.0         | 4.7                  | 2.205       | 2.276                |

**Table 8.** The ratio of $w_0$ and $\rho_{\text{dmax}}$ under vibration compaction versus static pressure compaction.

| The Cement Doses $P_s$ (%) | The Radio of $w_0$ | The Radio of $\rho_{\text{dmax}}$ |
|---------------------------|--------------------|-------------------------------|
|                           | XM                 | GM                            |
| 3.0                       | 0.938              | 1.023                         |
| 3.5                       | 0.940              | 1.024                         |
| 4.0                       | 0.940              | 1.032                         |

It can be seen from the results that $w_0$ of vibration compacted mixture is reduced compared with that of heavy compacted mixture, with a ratio of 0.881–0.940, average value of 0.910, as well as a $\rho_{\text{dmax}}$ of 1.023–1.032 times of the heavy compacted mixture, with an average of 1.028 times. In our opinion, the reasons are as follows: The vibration compaction method has greater compaction work, so aggregate particles are closer to each other, and less water is needed for the movement and arrangement, which causes the smaller optimal moisture content when the maximum degree of compaction is reached. Similarly, the water occupying the original void position will also be squeezed out due to the effect of vibration compaction on the rearrangement of particles, which shows that water
is squeezed out at the bottom of the test mold on the macro level. That will reduce the density lost due
to water occupying, so $\rho_{d_{\text{max}}}$ will increase correspondingly.

On the other hand, $w_0$ of GM gradation is smaller than that of the XM gradation, with a ratio of
0.804–0.860, and an average value of 0.829. Besides, $\rho_{d_{\text{max}}}$ is 1.015–1.025 times that of the XM gradation
and has an average time of 1.020. It shows that GM graded cement stable macadam mixture based
on the vibration compaction method has the advantages of small best moisture content and compact
arrangement. This is because GM gradation has an excellent embedded crowded frame structure.
Coarse aggregate squeeze each other, which could form a stable skeleton structure in the small void.
Besides, fine aggregate and cement form the set of cement mortar together, which could fill the void
compact closely.

3.2. 7d Unconfined Compressive Strength and Splitting Strength

Unfortunately, we could only get an on-site sample after 7 days curing due to the limitation of
the site construction environment. In order to ensure the consistency of the indoor experiment and
scene, we had to cure the indoor specimens for the same days. So the 7 days unconfined compressive
strength and splitting strength were used as indexes to verify the reliability and accuracy of the two
compaction methods. Firstly, the cement stabilized macadam mixture was obtained from the on-site
paver at the same time of the basic level paving and rolling. Then indoor vibration compacted (VC)
and static pressing (SP) specimens were carried out quickly with a 98% compaction degree according
to the compaction test results, and the prepared specimens were transported to the site and were cured
together with the base after covering geotextile. After the health period, the specimens were taken out
and the on-site sample was drilled nearby, and then cut the on-site sample (OS) into $\phi 15 \text{ cm} \times h 15 \text{ cm}$
standard specimens. Finally, the corresponding mechanical strength was tested, and the representative
values were calculated under a 95% guarantee rate. The results are shown in Table 9.

| The Type of Strength                              | $R_{\text{OS}}$ (MPa) | $R_{\text{VC}}$ (MPa) | $R_{\text{SP}}$ (MPa) |
|--------------------------------------------------|------------------------|------------------------|------------------------|
| The representative values of compressive strength | 11.73                  | 12.02                  | 5.94                   |
| The representative values of splitting strength   | 1.12                   | 1.10                   | 0.45                   |

It can be seen that the mechanical strength of indoor static pressure compacted specimens is
much higher than that of the on-site sample of base, whose respective ratio is 50.6% and 40.17%.
However, the mechanical strength of the vibration compacted specimens and the on-site sample is
very close, whose respective ratio is 102.5% and 98.2%. It can verify that the vibration compaction test
is much more reliable and accurate in reflecting the actual performance of the field base than static
pressure compaction.

3.3. Void Distribution Characteristics

It inevitably forms some volume of void when molding cement stabilized macadam mixture. Although
the proportion of the void is small, void has a certain influence on the mechanical properties
and anti-freezing performance of the mixture. Therefore, studying the internal void distribution
characteristics of the mixture is of great significance for studying road performance and evaluating the
uniformity. The internal void distribution characteristics include the size, distribution of number and
spatial, distribution of void shape, research on the self-similarity, and so on. The specific parameters
are the number of cross-sectional voids, the average diameter of cross-sectional void, the parameter of
void shape, and the fractal dimension of void. Based on this, this paper analyzes the internal void
distribution characteristics of cement stabilized macadam mixture with two different molding methods
and on-site sample.
3.3.1. Reconstructed Void Measurement

In this paper, three-dimensional reconstruction of cement stabilized macadam images obtained by X-ray CT were carried out using VG Studio Max 2.2 software of Kunzhong Electrothermal Technology Co. LTD, Suzhou, Jiangsu, China. The surface measurement, defect detection, volume analysis, and other modules in the software were used to obtain the internal void information of the mixture, as shown in Figure 3. The void information is extracted by adjusting the gray threshold, and unnecessary information is eliminated according to the actual image. Finally, the void of three-dimensional reconstructed specimens is obtained, which is called “reconstructed void” in this paper. Some studies [18] have proved that the reconstructed void is close to the “measured void” measured by experiments, and can well reflect the size of the void inside the mixture. The extracted void results of reconstructed specimens are shown in Figure 4 and Table 10.

![Figure 3. Extract the void information of reconstructed specimens.](image1)

![Figure 4. The reconstructed void of different molding mixtures.](image2)
Table 10. The reconstructed void (%) of different molding mixtures.

| The Types of Gradation | Different Molding Methods |
|-----------------------|----------------------------|
| XM                    | SP  | VC   | OS  |
|                       | 8.56| 6.71 | 6.15|
| GM                    | 9.32| 7.13 | 6.46|

SP is static pressure, VC is vibration compaction, and OS is on-site sample.

As can be seen from the reconstructed void results in Table 10 and Figure 4, the size of void has the following relationship: The static pressure specimens > vibration specimens > on-site sample, and the latter two are much closer. The ratio of reconstructed void results is 1.39 and 1.44 under the static pressure specimens and on-site sample, but is 1.09 and 1.10 under the vibration compacted specimens and on-site sample. The reason can be analyzed by considering that the vibration compaction has a greater compaction work compared with static pressure, and the compressed materials can achieve rearrangement because they have a greater force and displacement under greater compaction work. The movement of large particles also provides the possibility for cement mortar to fill void effectively. Therefore, the change of the molding method from static pressure to vibration compaction also changes the arrangement mode of aggregate, thus affecting the volume parameters after molding. In addition, the aggregate particles can be more tightly packed in the rolling process of the vibration roller due to a lack of mold limitation in the on-site compaction, and the cement mortar can fully fill the skeleton void molded by coarse aggregate, so the on-site sample has a lower void ratio.

On the other hand, the void ratio of GM gradation mixed was 0.76% higher than that of XM type under the static pressure condition, while the void between the two-gradation mixed with the vibration method was small. This demonstrates that the bulk aggregate can move more freely to form an effective embedded structure in the process of the vibration compaction, which is conducive for the second or even finer aggregate and cement to fill void.

3.3.2. The Study on Vertical Distribution of Void

The images obtained by X-ray CT scan are two-dimensional images. Some studies have shown that the finite information of two-dimensional images can reflect the three-dimensional void information of the mixture when the number of scanned sections is greater than 32, with a guarantee rate of 95% and an error control of 2.5%. In this paper, for each specimen, 90 vertical cross-section images were selected for data collection after removing the upper and lower 5 mm images of the end sections. The results show that they could meet the research requirements.

The size and number of voids of each section of GM and XM graded mixture specimens were calculated to study the uniformity of the vertical distribution of the void parameters of mixture. The specific parameters include [19]: The number and average diameter of cross-sectional void, where the diameter of cross-sectional void is the diameter of the equivalent circle of the average void of each section. The mathematical expression is as follows:

\[ d = 2 \times \sqrt[4]{\frac{A}{N\pi}} \] (1)

where \( A \) is the total area of the void extracted from a cross-sectional image of the mixture, and \( N \) is the number of voids extracted from a cross-sectional image of the mixture.

As seen from Figure 5, the size and number of voids of the specimens of GM and XM graded cement stabilized macadam mixture molded by static pressure and vibration compaction are generally characterized by uneven longitudinal distribution. The specimens can be divided into “top”, “middle”, and “bottom” in depth. According to different molding methods graded by GM and XM and on-site sample, the curve shape of the number of cross-sectional voids shows the characteristics of “high at both ends and low at middle”. This is because the number and size of void of a top and bottom mixture
is large in the process of molding the cement stabilized macadam mixture due to the disturbance of the molding and cutting machine on the specimens.

![Graphs showing vertical distribution of void](image)

**Figure 5.** The vertical distribution of void of mixture.

Different molding methods have a greater influence on the number and size of the void of mixture. The number and equivalent diameter of void of static pressure specimens is larger than vibration specimens. And the two curves corresponding to static pressure specimens show large fluctuations, which fluctuates with the depth of specimens, and there is a phenomenon that the distribution of top and bottom is obviously asymmetric. The reason is that traditional static pressure specimens are close-grained by the static pressure between aggregates, so the moving range of aggregates is limited, and the fine aggregate and binder cannot fill the void well. In particular, for GM gradation, the static friction force of the static pressure on coarse aggregate often causes the original aggregate to crush, which will form more void. Therefore, the static pressure specimens have a large void space, large number of void, and great variability of vertical distribution. For vibration specimens, the number and size of a void still fluctuate in the vertical distribution due to tamp the aggregate when molding specimens indoor and the uneven rolling of the base, but the numerical change is not significant and the difference between the two ends is small. In addition, indoor vibration compacted instrument and road vibration roller have great compaction power, so a high frequency vibration of the mixture makes the mixture liquefied and compacted, and the aggregate is filled closely after a full movement, which greatly reduces the number and size of the void.

The void characteristics of a mixture of different gradation types will also be quite different. The number of voids generated by XM gradation is large, which is 1.8 times that of the GM gradation...
on average, but its average diameter is small, which is about 0.7 times that of the GM gradation. It can be seen that the GM gradated mixture tends to produce a thicker void.

3.3.3. The Study on Void Shape Distribution

Regardless of whether specimens are based on the vibration or static pressure molding, the shape of voids in the mixture is often complex and irregular, which can be refactored by the three-dimensional space of mixture by VG Studio Max 2.2 software. Then the parameters of the shape description, sphericity, is obtained, which is defined as the same as the voids volume of the sphere surface area and the void between the actual surface area ratio [20].

\[ F = \frac{S_D}{S} \]

where \( S_D \) is the surface area of a sphere equal in volume to the void of the mixture, and \( S \) is the actual surface area of the void, as well as \( F \) is the sphericity of void. If \( V \) is used to represent the volume of the void, the sphericity of void can be shown as:

\[ F = \frac{4\pi}{S} \left( \frac{3V^{\frac{1}{3}}}{4\pi} \right)^2 \]

According to the different parameters of two-dimensional void shape, the void is divided into three categories to determine whether void shape is regular [21,22]. Three-dimensional void can similarly be divided into three categories according to the difference of parameter sphericity \( F \), which represents three-dimensional void shape: Regular void (0.6 < \( F \) < 1.0), irregular void (0.45 < \( F \) < 0.6), and long void (0 < \( F \) < 0.45). It can be seen that cube \( F = 0.806 \), positive triangle cone \( F = 0.634 \), and ball \( F = 1.0 \) according to Formula (3), which proves that the larger the sphericity, the more significant the difference between the void and standard sphere, and the more irregular the void shape. Figure 6 shows the strip void and irregular void, respectively.

(a) The strip void. (b) The irregular void.

**Figure 6.** The schematic diagram of the strip void and irregular void.

It can be seen from Figure 7 that the void types of the XM and GM graded mixture are roughly similar in distribution. The void shape of specimens obtained by different molding methods is different when taking the void shape distribution of the on-site sample as a reference. The strip void of static pressure mixture is 70.28%, that of the vibration compacted mixtures 41.50%, and that of on-site sample is 52.34%. The void shape of vibration compacted specimens is closer to the on-site sample. The reason is that some aggregate particles cannot move freely under the action of static friction in the process of static compression molding until they are crushed. The fine aggregate continues to be squeezed,
which will destroy the original design gradation. In addition, the intermediate size of the aggregate rapidly increases to form complex and irregular void.

The fractal dimension reflects the complex degree of the geometry, the larger the fractal dimension, the higher the complexity, the less evenly the distribution of the void. The methods of solving fractal dimension include the box counting dimension method, the three-dimensional box covering method, and the islet method, etc. [24]. The box counting dimension method is widely used and the accuracy is high, so this method is used in this paper to calculate the fractal dimension of cement stabilized macadam mixture. Although different methods cause different fractal dimension results, the variation and trend of the fractal dimension should be consistent if the parameters of scan and image processing are consistent, which can reflect the characteristics of the fractal dimension of different mixtures quantitatively.

The study shows that the void of cement stabilized macadam is complex and irregular, and they have statistical self-similarity characteristics [23]. The degree of irregular void distribution is different in vibration compaction and static pressure, so fractal theory is used to quantitatively describe the irregular degree of void of cement stabilized macadam mixture.

Fractal theory regards the collection of voids in the mixture as a fractal body, and the distribution characteristic parameters of the fractal body are solved by fractal theory, which is fractal dimension. The fractal dimension reflects the complex degree of the geometry, the larger the fractal dimension, the higher the complexity, the less evenly the distribution of the void. The box counting dimension method can be understood in this way [25]: “Box” is an abstract concept, which can be a line segment, a grid, or a cube depending on different dimensions of object, and the same size of grid is used to cover the void because the images are two dimensional. If the size of the grid changes, the number of grids required to cover the entire target area changes. The relationship between the two is similar to:

$$D_b = \frac{\log(N_k)}{\log(1/k)}$$

where $k$ is unit-size of “box”, $N_k$ is the minimum number of boxes required to cover the target area of the image, and $D_b$ is the fractal dimension of the research object, which represents the quantitative relationship of $N_k$ increasing with the decrease of $k$.

The fractal dimension is calculated for the images of the two types of gradation (XM, GM) as well as the two different molding methods, and the results are shown in Table 11. It can be seen that the fractal dimension of void of different sections for one test piece has little variability and the coefficient of variation is generally less than 0.5%, which indicates that the fractal dimension has certain stability in the vertical direction.

![Figure 7. The void types of the XM and GM graded mixture.](image-url)
The calculation formula of void fractal dimension of cement stabilized macadam mixture [26] is as follows:

$$D_v = \frac{\sum_{i=1}^{n} D_{bi}}{n}$$  

(5)

where $D_v$ is the void fractal dimension of cement stabilized macadam mixture, $D_{bi}$ is the void fractal dimension in a single section image, and $n$ is the number of two-dimensional CT of specimens of cement stabilized macadam mixture.

According to the above definition, the fractal dimensions of different specimens were counted, and the results shown in Figure 8.

![Figure 8. Fractal dimension of void cement stabilized macadam mixture.](image)

According to Figure 8, different molding methods have a great influence on the fractal characteristics of void inside the mixture. The fractal dimension of voids obtained by a static pressure method is 11% higher than that by vibration compaction, with it being more likely that the former method will cause more aggregate crushing than that by vibration compaction. Besides, the vertical variation coefficient of specimens obtained by static pressure method is obviously larger than that obtained by vibration compaction and the on-site sample among the fractal dimension results of each specimens, which indicates that void of the vibration compacted specimens and the on-site sample is more uniform and continuous in the vertical distribution.

In addition, it can be seen that the distribution of void of different gradated cement stabilized macadam mixture is different, which indicates that the macroscopic difference in material compositions will also affect the meso void structure of the mixtures.

4. Conclusions

Aiming towards the problem of over 100% compactness in practical engineering, the mechanical properties of cement stabilized macadam specimens molded by static pressure and vibration compaction...
were studied, and related to on-site samples in practical engineering. In addition, the characteristics of the molding method were explained by the mesoscopic structure. The following conclusions are drawn:

(1) The test results showed that the maximum dry density of the mixture under vibration compaction were larger, and the optimal moisture content was smaller than that of heavy compaction, which indicates that vibration compaction method has incomparable advantages in rolling mechanism and field compaction simulation;

(2) After a 7 days health period, the on-site sample was complete and close with a good skeleton structure, having compressive strength and splitting strength indexes that were much higher than those of indoor static pressure specimens but close to those of vibration compaction specimens, which verifies the reliability and accuracy of the vibration compaction test;

(3) X-ray CT, VG Studio, MATLAB, and IPP software were used to collect the internal void information of the mixture. Then the reconstructed void ratio, the number of cross-sectional void, average diameters, shape parameters, and fractal dimension were calculated and counted, and the internal void distribution characteristics of the mixture under different molding methods were analyzed. The results showed that the void distribution of vibration compacted specimens was much more similar to the on-site sample than that of static pressure specimens, and the uniformity of the void distribution was: on-site sample > vibration specimens > static pressure specimens;

(4) Mechanical test and mesoscopic analysis results showed that the indexes of vibration compaction specimens were close with those of the on-site sample. Thus the vibration compaction test method is validated for its reliability and accuracy to simulate the actual mechanical properties and guide the actual construction.

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