Experimental Research on the Influence of Vibration Intensity on Performance of Cement Stabilized Macadam

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Abstract. In order to study the influence of different vibration intensity on the performance of cement stabilized gravel. Vibration mixing tests of cement stabilized gravel with 5% cement factor were carried out under different vibration intensity, Through the preparation and maintenance of cylindrical specimen and the mid-beam specimen, The unconfined compressive strength test and the drying shrinkage test were carried out, Vibratory mixing can significantly improve the strength of cement stabilized gravel and reduce the level of intensity variation, As the vibration intensity increases, the increase range of specimen strength increases first and then decreases, Considering the mechanical reliability factors, It is reasonable to increase the strength of the material when the vibration intensity is D=2 ~ 3. Vibration mixing can improve drying shrinkage property of cement stabilized gravel, the vibration mixing reduces the water loss rate of the specimen at the later stage of shrinkage, with the increase of vibration intensity, the variation of dry shrinkage coefficient becomes smaller during shrink age period, and the coefficient of dry shrinkage decreases with it, Therefore, the greater the vibration intensity, the better drying shrinkage property of cement stabilized gravel. Vibration mixing can improve the mechanical behavior and cracking resistance of cement stabilized gravel simultaneously, it has a wide application prospect.

Keywords: Cement stabilized macadam; Vibration mixing; Vibration intensity; Unconfined compressive strength; dry shrinkage property

1. Introduction
Cement stabilized macadam has been widely used in semi-rigid base construction of high grade pavement in China, and the application practice has proved that in the pavement structure with cement stabilized macadam as the roadbase, the roadbase is used for bearing and the surface is only used for function. In order to improve the bearing capacity, it requires cement stabilized macadam to have good mechanical properties, erosion resistance and crack resistance [1-2]. For cement stabilized macadam itself, obtaining higher mechanical properties often means that the crack resistance is deteriorated. To solve this problem, a large amount of research on materials and basic structure design have been carried out by domestic and foreign researchers. Among which the optimization of the gradation and mix ratio is the main means to achieve reasonable mechanical properties and cracking resistance [3-5]. From the material study, it was found that increasing the amount of cement is beneficial to improve the mechanical properties of cement stabilized macadam, but at the same time increase the probability of occurrence of cracks [6], adding a certain amount of fly ash can effectively reduce the occurrence of shrinkage cracks, but is not conducive to the formation of early intensity [7]. Adding a certain amount of fiber material to the fine aggregate can improve the crack resistance ability under the precondition.
of ensuring the mechanical properties of the cement stabilized macadam, but it is difficult to be mixed uniformly in the mixture hence it is difficult to make [8]. Although the application of these measures has improved the bearing capacity of the cement stabilized macadam roadbase, their respective weaknesses are also obvious, cracking and breaking of roadbase still occurs from time to time.

Although the research methods for material and basic body design are sophisticated, however, studies on the mixing process necessary for the production of materials have not been given enough attention, so that the great potential for improving the mix structure and performance by enhance the mixing process has not been fully realized [9]. It is difficult to uniformly distribute the components of the finished product that are not fully mixed. The most intuitive result is that the variability of the properties of the finished product is increased, so that the material has a weak point reducing the mechanical properties and crack resistance of materials. During mixing, not only the physical mixing but also the chemical interaction between the particles of each component is performed between the components of the mixture after the cement is added, the structure and state of the material not only undergoes a change in quantity but also undergoes a qualitative change. Therefore, stirring is the key process to form the properties of the mixture [10]. How to increase the mixing strength to make the material more uniform is an effective way to improve the performance of cement stabilized macadam, and vibratory mixing is an effective method to increase the mixing strength of cement concrete to improve the properties of the material [11]; In this paper, the influence of different vibrational strengths on the performance of cement stabilized macadam during vibration stirring is studied by using different degrees of vibration strengthening on the cement stabilized macadam when it is made by conventional mixing.

2. Material and Methods

2.1. Vibration Mixer for Test

The vibration mixer used in the test was a 30-liter single horizontal shaft vibratory mixer, which is independently arranged for agitating and vibration driving. Mixing drive motor in the stirring shaft outer ring drives mixing device to mix the material normally, the vibration driving motor drives the eccentric installation eccentric connection device to make it connected to the mixing shaft and mixing blades to generate a certain strength of forced vibration to achieve vibration mixing. The main parameters of the mixer are shown in Table 1.

| Volume (L) | Vane Quantity | RPM (r/min) | Line Speed (m/s) | Mixing motor power (kW) | Vibration motor power (kW) |
|------------|---------------|-------------|------------------|-------------------------|---------------------------|
| 30         | 7             | 48          | 1.0              | 1.1                     | 3.0                       |

2.2. Testing Design

2.2.1. Materials. According to the requirements of “JTG/TF20-2015 Technical Guidelines for Construction of Highway Roadbases”, Using specifications for 0–5 mm, 5–10 mm, 10–20 mm and 20–30 mm limestone gravel aggregates, the proportion of crushed stones in cement stabilized macadam base materials is shown in table 2. The strength and dry shrinkage coefficient of cement stabilized macadam mixture are directly related to the amount of cement used [12]. In order to study the influence of vibration mixing on the strength and dry shrinkage coefficient of material, the cement dosage was taken as 5.0% so that the original mixture had higher material strength and dry shrinkage coefficient to eliminate the effect of experimental error on the results. At this point, the maximum dry density is 2.436 g/cm³ and the optimum moisture content is 5.18%. The synthetic gradation of the mixture is shown in Table 3, which shows that it is within the recommended gradation scope of the specification and is close to the required median value, so that it meets the requirements of use.
Similarly, conventional strength, the unconfined compressive strength, is shown as the trend of increasing strength with the increase of vibration intensity. For 7d unconfined compressive strength, with the increase of vibration strength, the 18.14%, 27.21%, 31.53% and 33.9% were increased respectively than conventional forced stirring.

It shows that applying a certain amount of vibration strengthening to the mixture during conventional mixing can significantly increase the strength of the cement stabilized macadam. Similarly, from Figure 2 we can see that with the increase of vibration intensity, the intensity variation

| Table 2. Aggregate ratio for test |
|----------------------------------|
| Mineral specifications(mm)       | 19-31.5 | 9.5-19 | 4.75-9.5 | 0-4.75 |
| Ratio(%)                        | 15      | 42     | 14       | 29     |

| Table 3. Synthetic gradation of test materials |
|-----------------------------------------------|
| Size (mm) | Ratio (%) | Mass percentage through the size of the following sieve holes |
|          |           | 31.5 | 19  | 9.5 | 4.75 | 2.36 | 0.6  | 0.075 |
| Synthetic Gradation | 100 | 75.6 | 42.1 | 28.8 | 19.6 | 9.8  | 2.1   |
| Standard requirements median [13] | 100 | 77   | 48   | 27   | 22   | 11.5 | 1.5   |
| Standard requirement [13] | 100 | 68-86 | 38-58 | 22-32 | 16-28 | 8-15 | 0.3   |

2.2.2. Methods. Vibration intensity \( D = Aw^2/g \), which is a dimensionless value, \( g \) is the gravitational acceleration (m/s^2), \( w \) is the vibration circle frequency (rad/s) and \( A \) is the amplitude (mm). When the amplitude \( A \) is constant during the test, adjusting the circular frequency \( w \) can realize different vibration intensity \( D \), with the increase of the vibration intensity \( D \), the viscosity of the fine material in the mixture will decrease, and the aggregation between the particles will be easily destroyed under the mixing action. At the same time, the increase of the overall fluidity of the mixture creates favorable conditions for uniform mixing, but excessive vibration strength will seriously weaken the reliability of the machine, so choose 0 (No vibrations conventional forces mixing), 1.0, 2.0, 3.0, 4.0 total five levels of vibration intensity to test.

Mixing tests were performed on the materials determined in 1.2.1 under different vibrational intensities, the mixing time was 30s. Specimens were made with size of 150 mm x 150 mm cylindrical specimens and 400 mm x 100 mm x 100 mm mid-beam specimens. The cylindrical specimens were cured, and then the unconfined compressive strengths of 3d, 7d, and 14d were respectively tested. After drying for 7 days, the middle beam specimens were tested for drying shrinkage. All laboratory test methods and data processing were referenced to "JTG/TF20-2015 Technical Guidelines for Construction of Highway Roadbases" and "Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering" (JTG E51-2009).

3. Results

3.1. Influence of Vibration Intensity on Compressive Strength

The mixture prepared under stirring at different vibration strengths was molded into a cylindrical specimen with a height of 150 mm and a diameter of 150 mm (with a compaction of 98%) according to the standard of the maximum dry density and the optimum moisture content, and subjected to the unconfined compressive strength test. The ages of the specimens were 3d, 7d and 14d, respectively. The test results are shown in Table 4 and Figure 1-2.

It can be seen from the data in table 4 that with the change of vibration intensity, unconfined compressive strength is shown as the trend of increasing strength with the increase of vibration intensity. For 7d unconfined compressive strength, with the increase of vibration strength, the 18.14%, 27.21%, 31.53% and 33.9% were increased respectively than conventional forced stirring.

It shows that applying a certain amount of vibration strengthening to the mixture during conventional mixing can significantly increase the strength of the cement stabilized macadam. Similarly, from Figure 2 we can see that with the increase of vibration intensity, the intensity variation
of all age samples of cement stabilized macadam is decreasing, which indicates that the mixture under vibration mixing has better uniformity and the difference in the strength level of the mixture is smaller.

Table 4. Unconfined compressive strength test results

| vibration intensity | Maintenance days | Single sample compressive strength MPa | Average value MPa | Variation coefficient % | 95% representative value MPa |
|---------------------|------------------|----------------------------------------|-------------------|-------------------------|-----------------------------|
| 0                   | 3d               | 5.19 5.82 3.61 4.49 3.81 4.62 4.82 3.82 3.95 | 4.46              | 16.54                   | 3.25                        |
|                     | 7d               | 5.61 5.69 4.21 4.42 3.86 4.71 4.57 4.06 4.54 | 4.63              | 13.75                   | 3.58                        |
| 1                   | 14d              | 6.08 5.95 5.33 4.22 5.54 5.62 5.07 4.52 4.74 | 5.23              | 12.27                   | 4.81                        |
|                     | 3d               | 5.62 5.13 4.94 5.19 4.46 4.24 4.77 4.28 5.02 | 4.85              | 9.45                    | 4.10                        |
| 2                   | 7d               | 5.28 5.87 5.76 4.97 5.25 4.52 5.89 6.02 5.64 | 5.47              | 9.12                    | 4.65                        |
|                     | 14d              | 5.22 6.41 5.96 5.54 6.39 5.40 5.77 6.12 5.71 | 5.84              | 7.19                    | 5.14                        |
|                     | 3d               | 5.91 4.69 5.71 5.01 4.72 5.07 4.88 4.96 4.54 | 5.05              | 9.17                    | 4.29                        |
| 3                   | 7d               | 5.74 5.21 6.10 6.29 6.48 5.13 5.89 6.16 6.03 | 5.89              | 7.84                    | 5.13                        |
|                     | 14d              | 7.17 6.27 7.52 6.72 7.91 6.57 6.85 7.21 6.96 | 7.02              | 7.10                    | 6.20                        |
|                     | 3d               | 5.98 4.89 5.32 5.17 4.38 4.56 5.07 5.21 5.28 | 5.10              | 9.12                    | 4.33                        |
| 4                   | 7d               | 5.39 6.45 5.88 6.23 6.06 6.27 6.58 6.21 5.71 | 6.09              | 6.13                    | 5.47                        |
|                     | 14d              | 7.88 7.53 8.12 7.08 7.02 6.87 7.25 7.06 7.17 | 7.33              | 5.79                    | 6.63                        |
|                     | 3d               | 5.91 5.13 6.33 4.95 5.09 5.54 5.28 5.86 5.77 | 5.54              | 8.33                    | 4.78                        |
| 5                   | 7d               | 6.90 5.87 6.49 6.21 5.64 5.65 6.38 6.16 6.51 | 6.20              | 6.85                    | 5.50                        |
|                     | 14d              | 7.16 8.06 6.78 7.60 6.73 7.88 7.19 6.89 7.83 | 7.35              | 6.91                    | 6.51                        |

Figure 1. The change of average compressive strength with vibration strength
Cement stabilized macadam is a multi-particulate medium consisting of aggregate, cement and water. It has the characteristics of low content of water, cement and fine aggregates, but high content of coarse aggregates. The cement stabilized macadam formed by mixing and curing consists of cement pastes which was formed of different sizes and shapes of aggregates and fine aggregates and cement hydration [14]. The strength of cement-stabilized macadam depends on the strength of the aggregate itself, the strength of the cementitious slurry and the strength of the bond surface between the cement paste and the aggregate. Which one is the weak point of these three factors restricts the mechanical properties of cement stabilized macadam. It can be seen from Fig. 1 that the 3d strength of the ordinary forced mixing material in the early curing period is significantly lower than that of the vibrating mixing material. The conventional forced agitation can make the components of the mixture uniformly distributed on the macroscopic, but only the flocculation unit and the large clusters of particles, such as part of the cement group and the fine aggregate group, can be rubbed, sheared and destroyed, while a large number of flocculation unit bodies still exist after the end of the mixing. Which make the fine aggregate, the cement and the water are not fully mixed uniformly, and the cement hydration in the cementitious slurry is insufficient and non-uniform during the strength growing process, this results in a slow and non-uniform strength build-up, and the overall viscosity of the gelled paste is not easy to wrap around the surface of the aggregate. After a certain age of curing, the strength of the gelling slurry is not uniform and the poor adhesion of the binding slurry and the aggregate surface is likely to have weak points, resulting in low strength but high variability of the strength of ordinary forced mixing materials. The strength variability of ordinary forced mixing compound materials is much higher than that of vibration-mixing compound materials, which results in a smaller representative strength value. This not only reduces the bearing capacity of the material but also has an adverse effect on the crack resistance of the material.

Not only the material is subjected to the kneading and shearing effect caused by the conventional mixing, but also the vibration energy causes the material to be in a flutter state at a certain intensity and frequency, which reduces the internal friction between cement, fine aggregate and large water cluster particles. Therefore, the flocculation structure in the aggregated state can be quickly destroyed, and smaller cement, fine aggregates and clusters of water particles can be generated, and the mixture can be rapidly mixed under the conventional mixing to achieve a meso-obvious uniformity. At this time, the slurry for cementation is smaller. The cement and fine aggregate particles are mixed with water, and the activity of cement and water is increased. The hydration of the cement will be uniform, full and rapid, which is beneficial to the rapid and uniform formation of slurry strength after cementation. The vibrating energy during Vibratory mixing increases the probability of collision between the aggregates, which is beneficial to purify the surface of the aggregate, a more uniform increase in the viscosity of the slurry can more fully envelop the surface of the aggregate and increase the binding strength between the aggregate and the slurry. It can be seen from Fig. 1 that the

![Figure 2. The change of compressive strength variation coefficient with vibration strength](image-url)
vibration-mixed mixture has rapid strength generation under the same curing conditions, and each age-level strength value is higher than that of ordinary forced-mixing. Meanwhile, Fig. 2 shows that the strength variability of the vibration-mixed cement stabilized macadam is greatly reduced. They can get higher intensity representative value, which is of great significance to improve the bearing capacity and crack resistance of cement stabilized macadam.

From Fig. 1 and Fig. 2, it can be seen that with the increase of vibration intensity, the increase extent of the strength of the cement stabilized macadam presents a certain degree of difference. When the vibration intensity $D = 2 \sim 3$, the intensity of the specimens at each age increased significantly. When the vibration intensity increased to $D = 4$, the 7d and 14d strength only increased by 1.8% and 0.3% compared with the vibration intensity $D = 3$.

3.2. Influence of Vibration Strength on Dry Shrinkage Property

400 mm×100 mm×100 mm mid-beam specimens which were molded according to the same standard with mixtures prepared under different vibrational intensity were kept at a temperature of 20°C±1°C and a humidity of 98% for 6 days, saturated them for 24 hours, then they were naturally air-dried at a temperature of 20°C±1°C. The results of the 7d water lossing rate, dry shrinkage strain, and shrinkage coefficient were shown in Table 5.

| Vibration intensity | Test items                                      | Single test result | Average value | Variation coefficient |
|---------------------|------------------------------------------------|--------------------|---------------|-----------------------|
|                     | Dry shrinkage strain /µε                        | 209.06             | 291.05        | 240.54                | 248.12               | 216.53 | 223.65 | 238.16 | 12.49 |
| 0                   | Dry shrinkage coefficient /µε/%                 | 51.75              | 74.82         | 63.13                 | 63.46                | 53.86  | 54.82  | 60.31  | 14.33 |
|                     | Water losing rate /%                            | 4.04               | 3.89          | 3.81                  | 3.91                 | 4.02   | 4.08   | 3.96   | 2.63  |
| 1                   | Dry shrinkage strain /µε                        | 196.17             | 234.36        | 221.63                | 203.14               | 253.15 | 208.98 | 219.57 | 9.73  |
|                     | Dry shrinkage coefficient /µε/%                 | 49.17              | 62.33         | 59.10                 | 53.04                | 63.61  | 55.14  | 57.06  | 9.82  |
|                     | Water losing rate /%                            | 3.99               | 3.76          | 3.75                  | 3.83                 | 3.98   | 3.79   | 3.85   | 2.81  |
| 2                   | Dry shrinkage strain /µε                        | 219.38             | 207.56        | 227.14                | 187.63               | 197.25 | 193.68 | 205.44 | 7.52  |
|                     | Dry shrinkage coefficient /µε/%                 | 58.04              | 53.49         | 61.39                 | 49.25                | 50.45  | 52.92  | 54.26  | 8.53  |
|                     | Water losing rate /%                            | 3.78               | 3.88          | 3.70                  | 3.81                 | 3.91   | 3.66   | 3.79   | 2.59  |
| 3                   | Dry shrinkage strain /µε                        | 191.17             | 210.25        | 213.52                | 182.56               | 189.65 | 177.97 | 194.10 | 7.50  |
|                     | Dry shrinkage coefficient /µε/%                 | 50.04              | 55.77         | 57.86                 | 52.61                | 49.01  | 48.76  | 52.34  | 7.23  |
|                     | Water losing rate /%                            | 3.82               | 3.77          | 3.69                  | 3.47                 | 3.87   | 3.65   | 3.71   | 3.86  |
| 4                   | Dry shrinkage strain /µε                        | 198.56             | 187.23        | 181.14                | 178.45               | 205.79 | 210.66 | 193.64 | 6.89  |
|                     | Dry shrinkage coefficient /µε/%                 | 54.70              | 50.33         | 50.60                 | 46.11                | 56.07  | 53.74  | 51.93  | 7.01  |
|                     | Water losing rate /%                            | 3.63               | 3.72          | 3.58                  | 3.87                 | 3.67   | 3.92   | 3.67   | 3.43  |

It can be seen from Table 5 that the maximum water lossing rate of each group decreases with the increase of vibration intensity. The vibration mixing has a certain effect on the water lossing rate of the molded specimens. At the same time, the average dry shrinkage strain and the average dry shrinkage coefficient of the mixture under all vibration intensities are lower than the conventional forced mixing. It shows that the vibration mixing can improve the dry shrinkage performance of cement stabilized
macadam. Compared with the conventional forced mixing, the dry shrinkage coefficient decreased by 5.39%, 10.03%, 13.21% and 13.89% respectively with the increase of vibration intensity. The variation coefficient of water lossing rate, dry shrinkage strain and dry shrinkage coefficient is also given in Table 5. It can be seen from the test results that the variation of water lossing rate and dry shrinkage strain between the conventional forced mixing specimens is greater, which indicates that the material shrinkage difference between the conventional forced mixing specimens is greater. The uneven shrinkage of dry shrinkage is an important cause of cracks in the pavement of cement stabilized macadam [15]. The smaller variability of the water-sinking rate and the dry-shrinkage strain of the vibration-stirred mixture indicates that the difference in the shrinkage between the materials is small, which is favorable for reducing the occurrence of road surface cracks.

When the other conditions are constant, the dry shrinkage strain of the mixture is directly related to the loss of moisture in the mixture, and the dry shrinkage stress is changed by the combination of capillary tension, adsorbed water and intermolecular force and the contraction force of interlayer water at different stages of water loss [7]. Figure 3 is each group of samples continuous 7d water lossing rate with time change chart, Figure 4 is each group of samples continuous 7d average dry shrinkage coefficient with time change chart. The water lost from the mixture in the early stage of shrinkage is free water. Figure 3 shows that the water lossing rates of the test specimens in each group are not significantly different. However, from Figure 4 it can be seen that the shrinkage coefficient of the cement stabilized macadam with conventional forced mixing in the early stage of shrinkage rapidly increases. Because there are a large number of undamaged cement aggregates in the mixture of conventional forced mixing. During the curing process, the cement hydration in the cement slurry is not sufficient and uneven, the unhydrated cement continues to hydrate in the hydration-hardened cement stone to generate greater compressive stress. At the same time, the hydration of the cement causes the relatively rapid reduction of the free water around the cement mass to accelerate the local shrinkage process, causes the shrinkage factor to increase rapidly. In the post-shrinkage specimens, the main loss of water is the capillary water and adsorbed water. It can be seen from Fig. 3 that the water lossing rate of the mixture of conventional forced mixing at the post stage of shrinkage is higher than that vibratory mixing of various kinds of vibration intensity, it shows that the water lossing rate of the specimens is accelerating during this period. The cement slurry produced by conventional forced mixing has loose microstructure, many voids, large and uneven pore diameters, and the capillary water and the adsorbed water are easily lost quickly, which is detrimental to drying shrinkage. cement stabilized macadam of vibratory mixing is well-hydrated in the early-stage curing, the hydration of the cement in the gelled slurry is homogeneous with a dense microstructure. The porosity is small and has a dense microstructure and a uniform distribution of closed pores. The capillary water and the adsorbed water dissipate slowly. This change is also beneficial for dry shrinkage.

Figure 3. Change of water lossing rate for 7 days
For different vibration intensity, the coefficient of shrinkage is always decreasing as the vibration intensity increases compared with the shrinkage coefficient of the conventional forced mixing materials. It can be seen from Fig. 4 that the change of the shrinkage coefficient of the vibration-mixing specimen during the entire test period is relatively uniform, and the larger the vibration intensity is, the smaller the change rate of the shrinkage coefficient is. It shows that under the different levels of vibration intensity that have been tested, the greater the vibration intensity of the specimen, the more stable the shrinkage process, and the lower the shrinkage coefficient, the more favorable it is to improve the crack resistance of the cement stabilized macadam.

4. Conclusions
1) Vibratory mixing can significantly improve the strength of cement stabilized macadam and reduce the variation level of strength. With the increase of vibration intensity, the increase range of specimen strength increases first and then decreases, when the vibration intensity D = 2 ~ 3, the strength increase is the largest, considering the mechanical reliability factors, It is reasonable to increase the strength of the material when the vibration intensity is D=2 ~ 3.

2) Vibration mixing can improve the dry shrinkage performance of cement stabilized macadam, with the increase of vibration intensity the shrinkage coefficient decreases by 5.39%, 10.03%, 13.21% and 13.89% respectively. The results of measuring the water lossing rate and shrinkage coefficient of the specimens for 7 days showed that the vibration mixing reduces the water lossing rate of the specimen at the later stage of shrinkage, with the increase of vibration intensity, the variation of dry shrinkage coefficient becomes smaller and process of dry shrinkage becomes smoother during shrinkage period. It is proved that the greater the vibration intensity, the better the dry shrinkage performance of cement stabilized macadam.

3) The test results show that vibration mixing can improve the mechanical properties and cracking resistance of cement stabilized macadam simultaneously, it is an ideal solution for the preparation of high-performance cement stabilized macadam, and it has a wide application prospect in the construction of cement stabilized macadam roadbase.

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