Hindawi
Advances in Civil Engineering
Volume 2020, Article ID 8845642, 13 pages
https://doi.org/10.1155/2020/8845642

Research Article

Construction Quality Control Study of Double-Layer Continuous Paving for Large-Thickness Cement-Stabilized Base

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Received 13 September 2020; Revised 8 November 2020; Accepted 9 December 2020; Published 18 December 2020

Academic Editor: Chongchong Qi

In order to verify the interlayer bonding effect of double-layer continuous paving technology of the thick cement-stabilized base and solve the construction quality control problem of the double-layer continuous paving, based on the interlayer bonding mechanism and the evenness passing mechanism, the laboratory interlayer adhesion test, field test of evenness disturbance, and compaction test were conducted to verify the continuous paving interlayer bonding state. The effect of interval time on interlayer bonding state, evenness, and compactness was analyzed, and construction quality control measures were proposed. The test results show that the double-layer continuous paving process could significantly improve the interlayer bonding state, but there is still a gap from the ideal state (completely continuous). The pull-off strength of continuous paving specimens was 2.1 times that of the discontinuous paving specimens; the shear strength was 2.4 times that of discontinuous paving specimens. At different paving intervals, the longitudinal evenness of the upper and lower layers has little difference. The 140 kN axle load controls the transverse evenness disturbance within 3 mm, which met the requirements of the specification. Based on the evenness passing mechanism, the evenness control standard of double-layer continuous paving base was proposed. The compaction process of double-layer continuous paving base was proposed, and the feasibility was verified through the field test of compaction. The best interval time for double-layer continuous paving was also proposed; it is recommended that the best time for paving the upper layer is after the lower layer is laid for 6 hours (the final setting time of the cement). The construction quality control measures proposed in this study provide a theoretical basis for the construction of double-layer continuous paving technology with thick cement-stabilized base.

1. Introduction

Semirigid bases are widely used in high-grade highways due to high intensity and good stability. Cement-stabilized macadam bases occupy an important position in the construction of semirigid bases for low cost, simple construction process, high early strength, and short curing period [1, 2]. In the design process of high-grade highways in various countries, the thickness of the cement-stabilized macadam base is more than 30 cm, so the traditional construction method is to use a layered discontinuous paving process, that is, paving a semirigid mixture of a certain thickness and paving a layer after a long curing period [3, 4]. Engineering practice shows that this construction method is not reasonable: a long curing period; the base layer is prone to early damage; the effect of the connection between layers is weak, which affects the service life of the pavement structure.

The double-layer continuous paving technology of semirigid base, with its short construction cycle and good interlayer bonding effect, has become an innovation of traditional construction technology, and it has become the direction of many scholars' in-depth research. Germany, Netherlands, Sweden, and other countries have conducted in-depth and systematic research on the double-layer paving technology [5]. In Germany, the high-grade pavement with double-layer continuous paving technology has reached about 4 million square meters, and the pavement has a good effect. This technology has been unanimously approved by many European countries, and the technology has been introduced to Russia, Australia, and the Americas. Through economic benefit analysis, Technical University of Darmstadt proposes that the double-layer paving technology has obvious economic benefits when the paving area reaches 12400 m^2. Under the same working conditions, the double-layer paving technology can significantly save costs [6, 7]. Huszczek proposed that the "cold-welding" phenomenon in traditional construction methods can easily lead to deformation resistance of thin-layer mixtures, resulting in difficult compaction. The "hot-welding" effect achieved by double-layer paving technology can make the compaction effect close to the ideal state [8, 9]. Wang et al. studied the interlayer condition between different layers of asphalt pavement constructed by double-layer paving technology. Based on the laboratory interlayer shear test, it was proposed that the interlayer shear strength of the double-layer paving is 57.4% higher than the interlayer shear strength under traditional construction method [10, 11]. Zhang of Chang'an University has carried out laboratory tests, simulation calculations, theoretical analysis, and engineering verification on the lime-ash-stabilized crushed stone. The postponement of roller compaction, recoverability of structural strength, and feasibility of continuous construction were put forward, which provide a theoretical basis for the layered continuous construction of semirigid bases [12–14]. Wang et al. obtained the quantitative relationship between the compactness of the mixture, the temperature, and the thickness by using the Marquardt method and the DPS data processing system through the design of an indoor orthogonal test using a nonstandard Marshall's test. An equivalent conversion relationship between asphalt pavement double-layer paving and traditional paving thickness was established under the same compaction work. And it is proposed that double-layer paving of 10 cm asphalt concrete is equivalent to traditional paving of 8.8 cm [15, 16]. Zhang et al. tested the splitting, shearing, and bending performance of asphalt mixture in different paving methods under three test conditions of normal temperature, low temperature, and freezing–thawing. It was found that all pavement performance of the double-layer continuous paving asphalt mixture was better than that of the intermittent paving asphalt mixture [17, 18]. Ma of Hebei University of Technology tested the early strength of the semirigid base course mixture, using KENPAVE software to simulate the construction stress distribution of the base course. He verified the feasibility of continuous construction of the semirigid base course and proposed reasonable steps of layered continuous paving construction technology based on the test section [19, 20]. Qiao et al. used BISAR 3.0 U software to set different interlayer friction factors, calculated the bottom tensile stress distribution of each layer under different interlayer bonding states, and proposed the fatigue equation of asphalt mixture and cement-stabilized macadam mixture. The service life of the pavement using double-layer continuous paving technology was calculated, and it was proposed that the double-layer continuous paving can effectively improve the bonding effect between the semirigid base layers and increase the service life of road structure by 16.1% to 47.4% [21, 22]. By studying the evenness transmission law and the disturbance of construction vehicles on the base course with the continuous-laid double layers, Fang et al. proposed the mid or lower surface layer evenness of asphalt pavement should be controlled according to the construction standard of the upper base layer [23, 24].

At present, many scholars have conducted in-depth studies on double-layer continuous paving, but most of them focus on the service life and economic analysis of asphalt surface paving and double-layer paving, and there are few researches on the construction quality control of double-layer continuous paving highways. In this paper, through indoor interlayer bonding tests, field disturbance tests, and compaction field tests, it is proved that the continuous paving process can significantly improve the interlayer bonding based on the bonding mechanism and evenness transfer mechanism. The quality control measures from the aspects of evenness, compaction, and construction interval were also proposed, which provides a theoretical basis for the construction of large-thickness double-layer continuous paving of cement-stabilized base.

2. Mechanism Analysis

2.1. Adhesion Mechanism of Double-Layer Continuous Paving

2.1.1. Adhesion between Upper Base Layer and Lower Base Layer. The double-layer continuous paving technology advances the paving time of the upper base layer to the time when the lower base layer is not cured. Because the lower-layer cement has not been cemented significantly, the mixture is in a semistable state. During the compaction process of the upper layer, the aggregate of the upper layer will be embedded in the lower base layer mixture, making the interlayer bonding tighter, as shown in Figure 1 [21].

2.1.2. Cement Cementation in the Mixture. In the traditional paving process, after 7 days' curing, the contained cement in the lower base layer is almost impossible to produce the adhesion with the upper base layer, so the interlayer bonding capacity is mainly provided by the cement mortar and the cement on the bottom of the upper base layer. Double-layer continuous paving allows the cement between upper base and lower base to adhere to each other, and the interaction force between the aggregate makes the cement bond more tight.

2.1.3. Gradation of the Mixture. The coarse aggregate with large particle diameter is easy to form a large texture depth, which is convenient for the formation of the interaction force between the double-layer continuous paving layers, so the interlayer bonding effect is better.

2.2. Evenness Passing Mechanism. Evenness passing mainly refers to the process and law of upward mapping of the unevenness of the lower pavement, the unevenness of the road starts from the roadbed. Assume that an adjacent structural layer of the pavement is an upper layer and a lower layer, and the maximum sag amount when paving the lower layer is β, the slack lay thickness of the upper layer is a, then the thickness of the virtual paving at the largest depression is $a+\beta$, and the loose paving coefficients is γ, which is

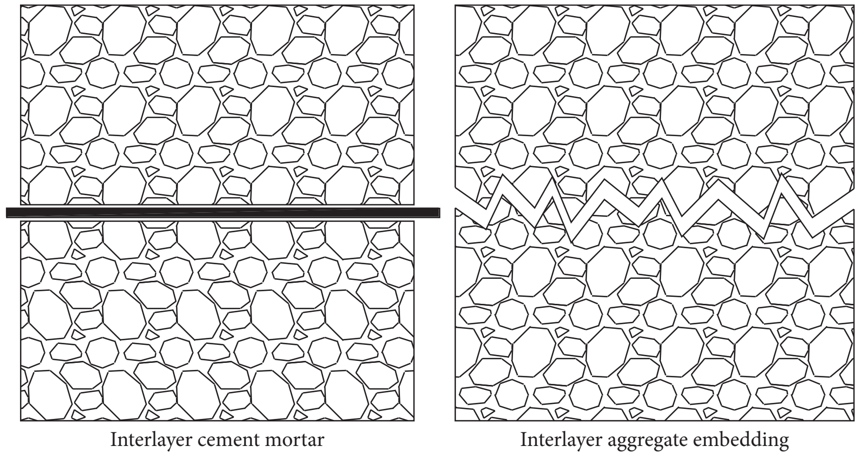

Figure 1: Interlayer adhesion schematic of traditional paving and double-layer continuous paving.

equivalent to the compacting thickness of the largest depression after compaction is $(a+\beta)\times 1/\gamma$. Then, after the compaction of the upper structure layer, the depression amount is $(1-(1/\lambda))\beta$, which is equivalent to passing the unevenness of the lower layer to the upper layer $(1-(1/\lambda))\,\beta$, as shown in Figure 2.

Assuming that the amount of uneven depression at the soil base is β, and the loose paving coefficient of each structural layer upwards is λ, the passing value of the sag amount of the paved surface can be calculated according to the following formula:

$$\beta_T = \left(1-\frac{1}{\lambda_1}\right)\left(1-\frac{1}{\lambda_2}\right)\cdots\left(1-\frac{1}{\lambda_n}\right)\beta\,(mm). \quad (1)$$

The above formula is proposed based on the ideal state, but the influencing factors need to be considered in actual construction, so the evenness formula needs to be revised. Combined with the study of related scholars [23], the influencing factor coefficient q is introduced, the guarantee rate is 1.86, and the standard deviation is 0.9 according to the normal distribution theory. The modified evenness passing formula is obtained as

$$\beta_T = (1-1.86q)^{-n}\left(1-\frac{1}{\lambda_1}\right)\left(1-\frac{1}{\lambda_2}\right)\cdots\left(1-\frac{1}{\lambda_n}\right)\beta, \quad (2)$$

where β_T is the unevenness of the current paving layer; $\lambda_1\lambda_2\cdots\lambda_n$ are the loose paving coefficients of each structural layer; β is the measured value of the unevenness of the soil foundation; and q is the influence factor coefficient.

3. Methods

3.1. Adhesion Test of Double-Layer Continuous Paving

3.1.1. Interlayer Pull-Off Strength Test. The test adopts the core-drilling method. The middle beam specimens with the size of 100 mm × 100 mm × 400 mm were prepared according to the “Testing Rules for Highway Engineering Inorganic Binding Material Stabilizing Materials” (JTGE51-2009). After the preparation process completed, the core sample was drilled with a diamond thin-walled hollow core after standard curing, and the core passed through two-layer interface penetrating into the lower layer. The top surface was polished smooth and flat with structural glue adherence to cylindrical steel block; when reaching the structural adhesive strength, pull off it with drawing instrument. Figure 3 shows the pull-off strength test of the drill core.

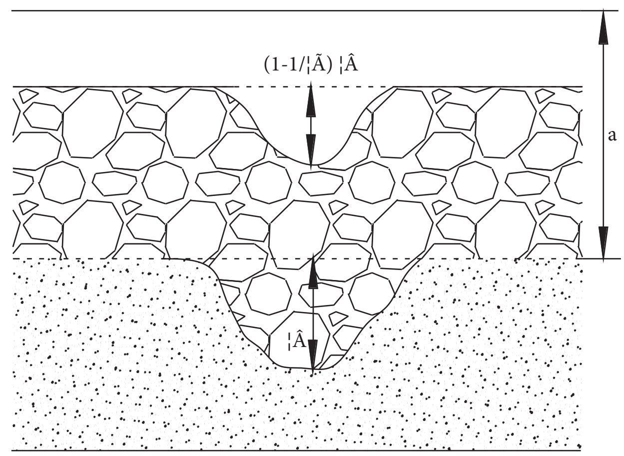

Figure 2: Schematic diagram of evenness passing.

The test was carried out according to Table 1 in which there were 5 test pieces in each group. Pull-off strength is calculated according to the following formula:

$$f_n = \frac{P}{A} = \frac{4P}{\left(\pi D^2\right)}, \quad (3)$$

where f_n is the pull strength of the drill core (MPa); P is the pull force used to break the core sample (N); A is the cross-sectional area of the core sample (mm^2); and D is the core sample diameter (mm).

3.1.2. Interlayer Shear Performance Test. The ordinary surface shear tester can only cut 10 cm specimens. Design and process a shear mold to test the two specimens in Table 2. The shear mold is shown in Figure 4, and the

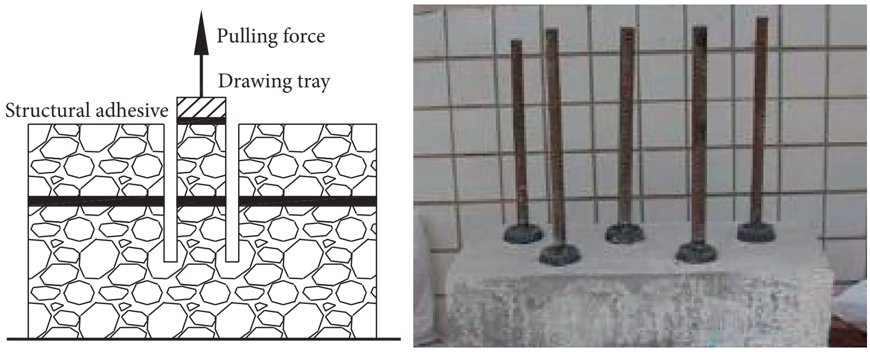

Figure 3: Pull-off strength test.

Table 1: Design of pulling strength test of core sample.

Test group		Control group
Simulate layered discontinuous paving	Simulate layered continuous paving	
Compact a 100 mm × 100 mm × 200 mm test piece in a 100 mm × 100 mm × 400 mm mid-beam test mold, demold, then standard curing for 7 days, and then put back into the test mold. The cement slurry was applied on the top of the test piece, and then the mold was filled to prepare the 100 mm × 100 mm × 400 mm test piece, and then the whole test piece was demolded, taking the standard curing for 90 days.	Compact a 100 mm × 100 mm × 200 mm test piece in a 100 mm × 100 mm × 400 mm mid-beam test mold, and then fill the mold with the mixture to prepare a 100 mm × 100 mm × 400 mm test piece, demold, and then standard curing for 90 days.	Compact a 100 mm × 100 mm × 200 mm test piece in a 100 mm × 100 mm × 400 mm mid-beam test mold, demold, and then standard curing for 90 days.

Table 2: Design of pull strength test of core sample.

Simulate layered discontinuous paving	Simulate layered continuous paving
In accordance with the "Testing Rules for Highway Engineering Inorganic Binder Stabilizing Materials" (JTG E51-2009), the test pieces with the size of Φ150 mm × 150 mm were molded.	
Weigh half of the mixture to make a test piece. After being demolded, the test piece was cured for 7 days. After that, put the test piece back into the test mold, spread a layer of cement paste on the surface, and then pour the other half of the same quality mixture, compact and curing for 7 d.	Weigh half of the mixture and pour it into the test mold, put into a pad for compaction, remove the pad after 1 hour, and pour the remained mixture into the mold, compact and curing for 7 d.

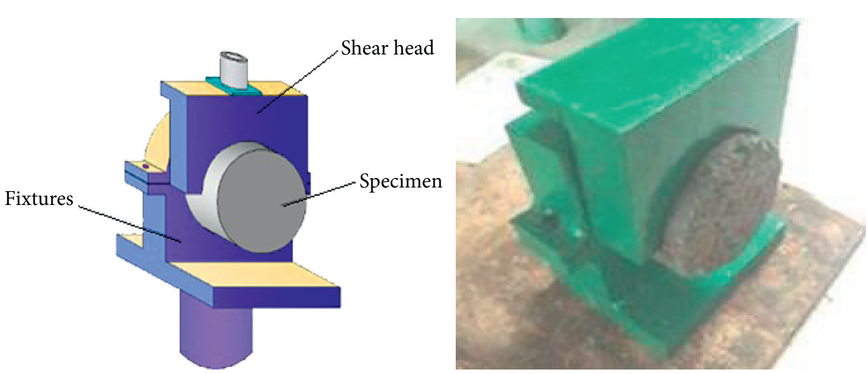

Figure 4: Shear test.

specimen is fixed in the mold after curing. Align the interlayer position with the test specimen jaw, and then place the mold together with the test specimen on the shear instrument to detect the maximum pressure when the test specimen breaks. The shear strength is calculated as follows:

$$\tau = \frac{F}{A}, \tag{4}$$

where τ is the shear strength (MPa); F is the failure load (N); and A is the cross-sectional area of the test piece (mm^2).

The interlayer shear test was carried out according to Table 2. There were 5 test specimens in each group.

3.1.3. Double-Layer Compaction Test. A double-layer compaction test was used to simulate the effect of different paving periods on the interlayer embedding depth. According to the "Testing Rules for Asphalt and Asphalt Mixtures of Highway Engineering" (JTG E20-2011), the large Marshall specimens were formed in two layers, one layer was 40 mm depth and another was 55.3 mm (the test mold size was Φ152.4 mm × 95.3 mm). Firstly, put part of the mixture in proportion, then compact 112 times to simulate the compaction process (make sure that the thickness after compacted is 40 mm), and then put the test specimen into the standard curing room for curing. Three test specimens were taken out at each time after curing for 0, 3, 6, and 24 hours. Secondly, a thin paper was inserted in the test mold, and then the remaining mixture was poured in, compact 112 times. Finally, measure the interlayer insertion depth of the two-layer specimen by the micrometer ruler.

3.2. Field Test of Evenness Disturbance. In the reconstruction project of S203 highway from K130 + 120 to K130 + 420 in Inner Mongolia, the two-layer continuous paving test section of cement stabilized base was carried out. The thickness of the base layer was 16 cm + 16 cm, and the maximum axle weight of the transport vehicle was 140 kN. Among them, from K130 + 120 to K130 + 220, the upper base was paved after the lower base was laid down for 3 hours (test section 1). From K130 + 220 to K130 + 320, the upper base was paved after the lower base was laid down for 6 hours (test section 2). From K130 + 320 to K130 + 420, the upper base was paved after the lower base was laid down for 24 hours (test section 3).

The evenness detection of the base layer includes the detection of lower layer and upper layer. The lower layer was tested 3 times, and the first test is performed immediately after the compaction of lower layer is completed. The three-meter straight ruler was used to continuously measure 6 metrics in the longitudinal direction in the middle of three lanes to determine the evenness quality of the lower layer. For the second time, before the upper layer paving process, take three cross sections, use the three-meter straight ruler, and perform a continuous 4-metric horizontal detection before the transport vehicle acts. The position of the third detection is the same as the second detection. After the transportation vehicle acts, perform a continuous 4-metric detection on the traveled track. The upper layer inspection was performed after the upper layer compaction completed, and a continuous 6-metric inspection should be carried out in the longitudinal direction at the middle position of the three lanes to determine the overall evenness of the double-layer continuous paving. The evenness detection is shown in Figures 5 and 6.

3.3. Field Test of Degree of Compaction. Test section K130 + 120~K130 + 420 was selected for field observation test of compaction. In order to ensure the compaction quality, the following compaction process was proposed: for the lower base layer, during recompression process, strong vibration compaction was performed multiple times to ensure that the lower layer has been well compacted, and then one time weak vibration compaction and three times strong vibration compaction was performed, of which the speed was controlled at 1.8~2.0 km/h. For the upper base, during recompression process, the times of strong vibration should be reduced as much as possible, and the compactness quality of the upper layer was ensured through multiple weak vibrations and reduced rolling speed. One time weak vibration, one time strong vibrations, and then three times weak vibrations were performed. The compaction speed was controlled at 1.5~1.8 km/h. The sand replacement method (T0921) in "Field Test code of Subgrade and Pavement for Highway Engineering" (JTG E60-2008) was used to test the compaction of the upper and lower layers respectively, as shown in Figure 7.

4. Results and Discussion

4.1. Interlayer Adhesion Properties

4.1.1. Interlayer Pull-Off Properties. Use formula (3) to calculate the pull-off strength of interface bonding. The core diameter must be measured with a vernier caliper. In this test, D = 60.0 mm. The test results obtained after excluding the maximum and minimum values are shown in Table 3.

As can be seen from Table 3, the pull strength of the double-layer discontinuous paving test piece is very weak, and the interlayer bonding force is almost 0. The pull strength of double-layer continuous paving test piece is 2.1 times that of the discontinuous paving test piece, which shows that compared with discontinuous paving, continuous paving can effectively improve the bonding status between layers. The pull strength of the continuous paving test piece is 47.5% compared to that of the control group, which indicates that although the continuous paving can significantly improve the bonding state between layers, there is still a large gap from the ideal bonding state (fully continuous).

4.1.2. Interlayer Shear Properties. The shear test was conducted on both conventional and continuous layered paving test specimens. After excluding the maximum and minimum values, the average value of the remaining data was taken as the shear strength. The test results are shown in Table 4.

It can be seen from Table 4 that the shear strength of discontinuous paving specimen was very weak, and the

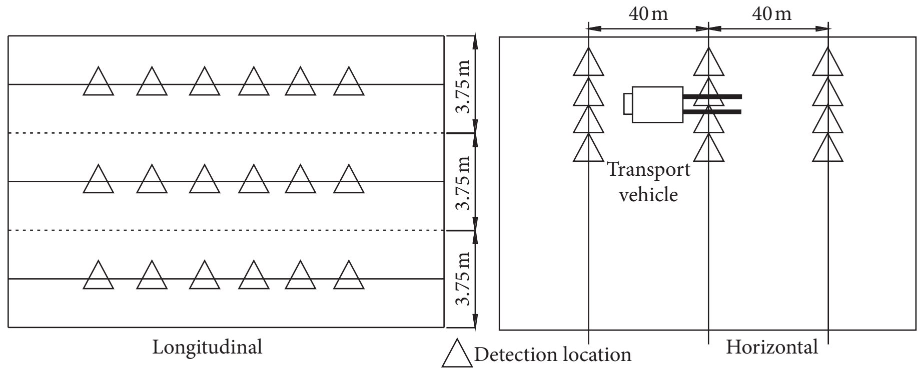

Figure 5: Schematic diagram of evenness detection.

Figure 6: Longitudinal and horizontal evenness detection.

Figure 7: Base compacting and compaction quality detection.

Table 3: Pull test results of interlayer bonding.

Simulation type	Specimen number	Ultimate pull-off force (kN)	Pull-off strength (MPa)	Strength average value (MPa)
Double-layer discontinuous paving	#1	0.3	0.11	0.09
	#2	0.2	0.07	
	#3	0.3	0.11	
Double-layer continuous paving	#4	0.5	0.18	0.19
	#5	0.5	0.18	
	#6	0.6	0.21	
Control group	#7	1.1	0.39	0.4
	#8	1.2	0.42	
	#9	1.1	0.39	

Table 4: Results of double-sided shear test between layers.

Type of specimen	Shear strength (MPa)			Average (MPa)
Layered continuous paving	0.263	0.198	0.179	0.213
Layered discontinuous paving	0.066	0.057	0.060	0.061

interlayer bonding force was almost 0. The shear strength of continuous paving specimens is 3.49 times that of discontinuous paving specimen, which showed that compared with the discontinuous paving, continuous paving could effectively improve the bonding state between layers. The damage of both specimens occurred at the interface. The damaged interface of discontinuous paving specimen was smooth, and the failure was generated along the interface. The interlayer bonding force was all provided by the cement paste, while the damaged interface of continuous paving specimen was relatively rough, which indicated that the interlayer bonding partly came from the adhesion generated by interfacial aggregate.

4.1.3. Double-Layer Compaction Test. The exposure diagrams of the interlayer bonding surface of double-layer compaction test specimens are shown in Figure 8, and the test results (average value) are shown in Table 5.

It can be known from Figure 8 and Table 5 that with the increase of curing time, the embedding depth between the two-layer paving gradually decreased. When the curing time increased from 3 hours to 24 hours, the embedded depth between the layers decreased from 3.3 mm to 0.8 mm, which was reduced by 71.4%.

4.2. Field Test of Evenness Disturbance. The test results of longitudinal and transverse evenness of each test section are shown in Tables 6 and 7.

The test results of longitudinal evenness are shown in Figure 9.

In the "Highway Engineering Quality Inspection and Evaluation Standards"(JTG F80/1-2017), the specified values for the evenness of the stable granule base course and the subbase of highway or first-grade highway are 8 mm and 12 mm. It can be known from Tables 6 and 7 that the longitudinal and transverse evenness of the upper and lower layers met the requirements when the double-layer continuous paving was carried out using a vehicle with 140 kN maximum load. The test results of transverse evenness of different test sections are shown in Figure 10. It can be seen from Figure 10 that the evenness disturbances of test section 1 are 2.2 mm, 2.6 mm, and 2.4 mm, respectively, those of test section 2 are 1.8 mm, 2.0 mm, and 2.1 mm, respectively, and those of test section 3 are 1.7 mm, 1.9 mm, and 2.0 mm, respectively. At the different paving intervals, the longitudinal evenness of the upper and lower layers was little different, and the control range of the transverse evenness disturbance amount of 140 kN axle load was controlled within 3 mm, which met the requirements of the specification. Different paving intervals have little effect on the longitudinal evenness of the upper and lower layers, but have a certain effect on the disturbance of the transverse evenness.

According to the evenness passing mechanism of Section 2.2, in the double-layer continuous paving construction, the unqualified evenness of the lower base would be transmitted to the upper layer, increasing the roughness of the upper base layer and even making the evenness of the upper base not in compliance with the specification requirements. According to the 95% guarantee rate of evenness detection in the "Highway Engineering Quality Inspection and Evaluation Standards," the longitudinal evenness disturbance field detection data was subjected to reliability processing. The fitting results are $q = 0.4229$ and $n = 1$. Substituting into formula (2), the following formula is obtained:

$$\beta_T = (1 - 1.86q)^{-1}\left(1 - \frac{1}{\lambda}\right)\beta_{\text{lower}}\,(mm). \tag{5}$$

Then,

$$\beta_{\text{lower}} = \frac{\beta_T\,(1 - 1.86q)\lambda}{\lambda - 1}. \tag{6}$$

The specification stipulates that β_T is 12 mm and λ is 1.25. Substituting into formula (6), β_{lower} was calculated as 13 mm. In the continuous paving process of 16 cm + 16 cm double-layer subbase, considering the construction load on longitudinal evenness disturbance, the limit of evenness quality control standard of the lower layer is 13 mm. Therefore, the following principles were proposed for the evenness control standard of continuous paving. The evenness control of the upper layer of the continuous pavement layer should be controlled by the evenness construction standard of the next layer, and the other layers should be controlled according to the traditional paving construction standards. The specific control standards can be seen in Table 8.

According to the above analysis, in order to ensure that the evenness of the double-layer continuous pavement of the cement-stabilized base course meets the requirements, U-turns, emergency starts, and emergency braking of the transport vehicle should be prohibited when driving on the newly paved base course. The speed of the vehicle should be kept as low as possible to prevent longitudinal forces between the tire and the road, causing lateral movement of the paved base. The mixture should be added, and small compaction equipment should be used to recompact at the position where wheel disturbance exists. The lower layer of double-layer continuous paving should be strictly controlled according to the standards in the table above.

4.3. Field Test of Compaction. The results of the compaction tests are shown in Table 9.

It can be known from Table 9 that the double-layer continuous paving compaction process used in the compaction field test can ensure that the compactness of top and bottom layer can meet the requirements of "Technical Specifications for Highway Pavement Base Construction." In

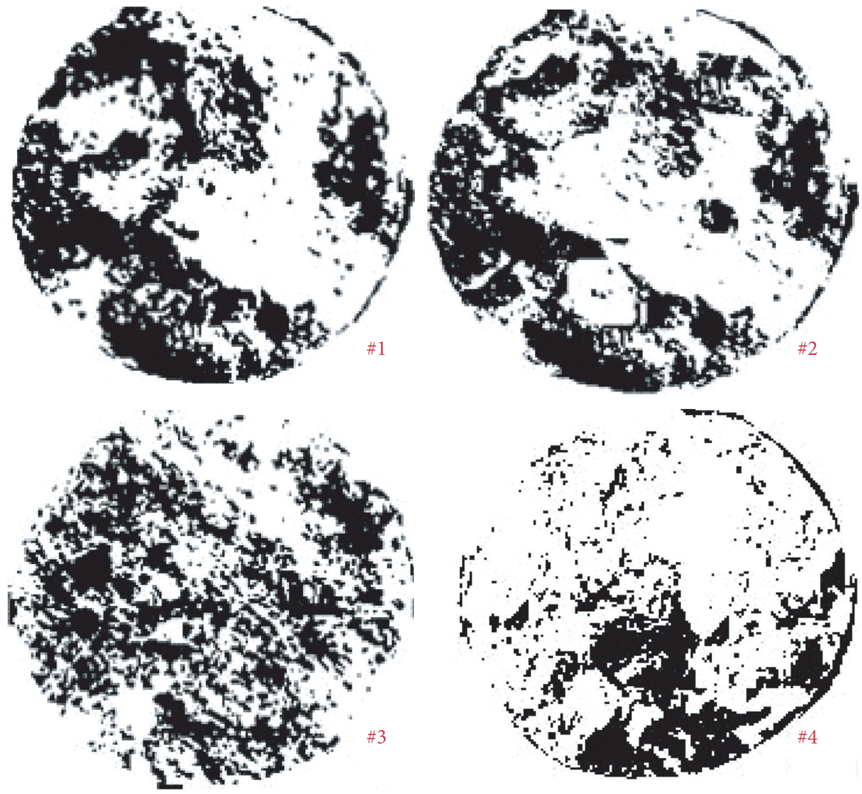

Figure 8: Schematic diagram of embedding depth of specimen aggregate.

Table 5: Test results of embedding depth under different curing times.

Number	Curing time (h)	Test results (mm)			Average value (mm)
#1	0	4.1	3.8	4.3	4.1
#2	3	2.9	3.4	3.6	3.3
#3	6	2.5	3.2	2.6	2.8
#4	24	0.5	0.2	0.6	0.8

Table 6: Test results of longitudinal evenness (mm).

Test section	Position	Lower layer							Upper layer						
		Detection value						Average	Detection value						Average
1	Lane 1	2.5	4.4	3.9	2.7	4.6	3.3	3.6	2.9	2.2	4.5	3.3	3.6	3.2	3.3
	Lane 2	4.2	3.3	3.5	3.2	2.0	4.3	3.4	3.8	3.5	2.9	4.2	2.8	4.6	3.6
	Lane 3	4.7	4.2	3.0	3.7	2.2	2.6	3.4	2.8	4.3	4.5	3.0	2.8	2.8	3.4
2	Lane 1	2.8	4.4	3.5	3.0	4.0	3.3	3.5	2.9	2.4	3.8	2.7	3.8	2.6	3.1
	Lane 2	4.0	2.7	3.7	3.8	2.5	3.6	3.4	3.6	3.0	2.5	3.8	3.0	4.1	3.3
	Lane 3	4.3	4.0	2.8	4.1	2.8	2.8	3.5	2.9	3.8	3.9	2.8	2.6	2.3	3.1
3	Lane 1	3.0	4.4	3.9	2.4	4.6	2.7	3.5	2.5	2.0	3.5	2.5	3.5	2.5	2.8
	Lane 2	3.9	2.9	3.7	3.9	2.9	3.9	3.5	3.5	3.0	2.5	3.5	2.5	4.0	3.2
	Lane 3	5.0	4.2	3.0	3.7	2.1	2.1	3.4	2.5	3.5	3.5	2.5	2.5	2.0	2.8

order to ensure the quality of double-layer continuous paving construction, the evenness control requirements of the lower base should be ensured. According to the compaction test results, the compaction process shown in Table 10 is proposed. Under the premise of not affecting the construction progress, the rolling speed should be taken as low as possible in Table 10.

5. Optimal Interval Time for Double-Layer Continuous Paving

5.1. Effect of Interval Time on Bonding Status between Layers. According to the test results of the embedding depth of the upper layer aggregate under different curing times in Section

Table 7: Test results of the horizontal evenness of the lower layer (mm).

Test section	Position	Before the disturbance					After the disturbance				
		Detection value				Average	Detection value				Average
1	Cross section 1	2.0	2.5	2.5	3.5	2.6	4.5	4.0	5.5	5.0	4.8
	Cross section 2	3.0	4.0	3.5	2.5	3.3	5.5	7.5	6.5	4.0	5.9
	Cross section 3	4.0	2.5	3.5	3.0	3.3	4.5	5.0	6.5	6.5	5.7
2	Cross section 1	2.1	2.6	2.5	3.6	2.7	4.3	3.8	5.4	4.8	4.5
	Cross section 2	3.1	4.0	3.6	2.6	3.3	4.9	6.8	6.0	3.6	5.3
	Cross section 3	4.0	2.6	3.6	3.1	3.3	4.2	4.9	6.2	6.4	5.4
3	Cross section 1	2.1	2.7	2.7	3.6	2.8	4.4	3.8	5.3	4.8	4.5
	Cross section 2	3.1	4.1	3.7	2.6	3.4	4.8	6.8	6.0	3.6	5.3
	Cross section 3	4.2	2.7	3.6	3.1	3.4	4.1	4.8	6.3	6.3	5.4

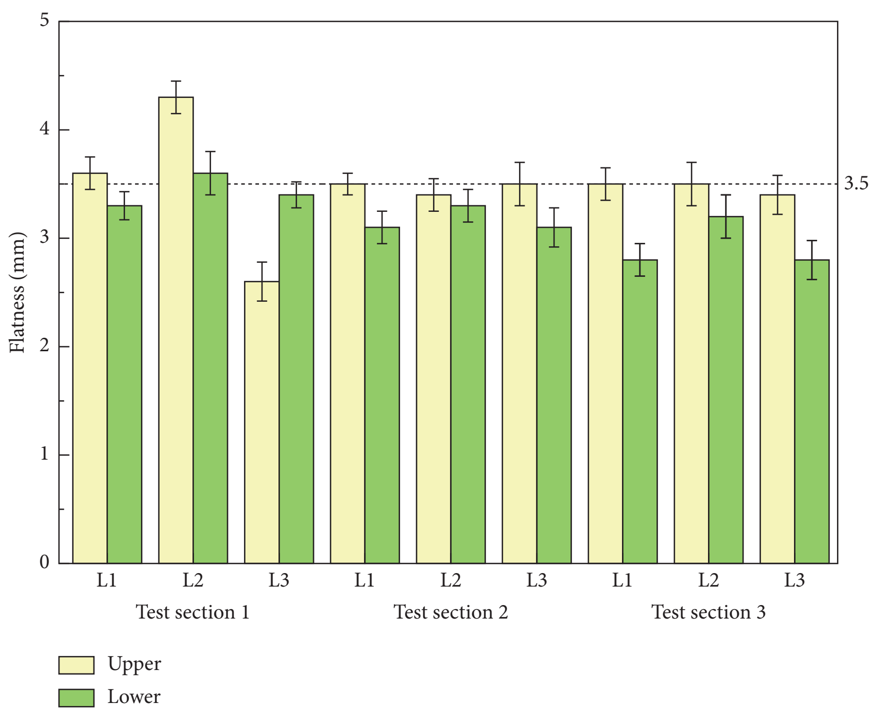

Figure 9: Longitudinal evenness test results.

4.1.3, it is possible to obtain the variation of aggregate embedding depth with curing time, as shown in Figure 11.

It can be seen from Figure 11 that with the increase of curing time, the embedding depth of upper-layer mixture and lower-layer mixture continuously decreased. This was mainly because the strength of the lower layer increased with the increase of the curing time, which made it more and more difficult for the upper-layer aggregate to be embedded in the lower layer. This showed that with the increase of the paving interval, the bonding effect between base layers continuously declined.

5.2. Effect of Interval Time on Evenness. From the results of the evenness field test in Section 4.2, it was known that the evenness disturbances of cross section 1 were 2.2 mm, 1.8 mm, and 1.7 mm at different paving time intervals; the evenness disturbances of cross section 2 were 2.6 mm, 2.0 mm, and 1.9 mm; the evenness disturbances of cross section 3 were 2.4 mm, 2.1 mm, and 2.0 mm, respectively. The relationship between paving time intervals and evenness disturbance was obtained, as shown in Figure 12.

It can be seen from Figure 12 that with the increase of the paving interval, the evenness disturbance of the lower layer gradually decreased. The interval time increased from 3 hours to 6 hours, and the decrease of the evenness disturbance was much larger than that of the increase of the interval time from 6 hours to 24 hours. This is mainly because the initial setting time of the cement used in the test section is 4 hours, the final setting time is 7 hours, and the delay time of the base layer paving is 1 hour. Therefore, the initial setting time of the cement was advanced to 3 hours, and the final setting time was advanced to 6 hours after the lower layer was paved. When paving the upper layer, the cement in the lower layer had a certain lubricating effect, which caused the paved layer to be easily deformed under

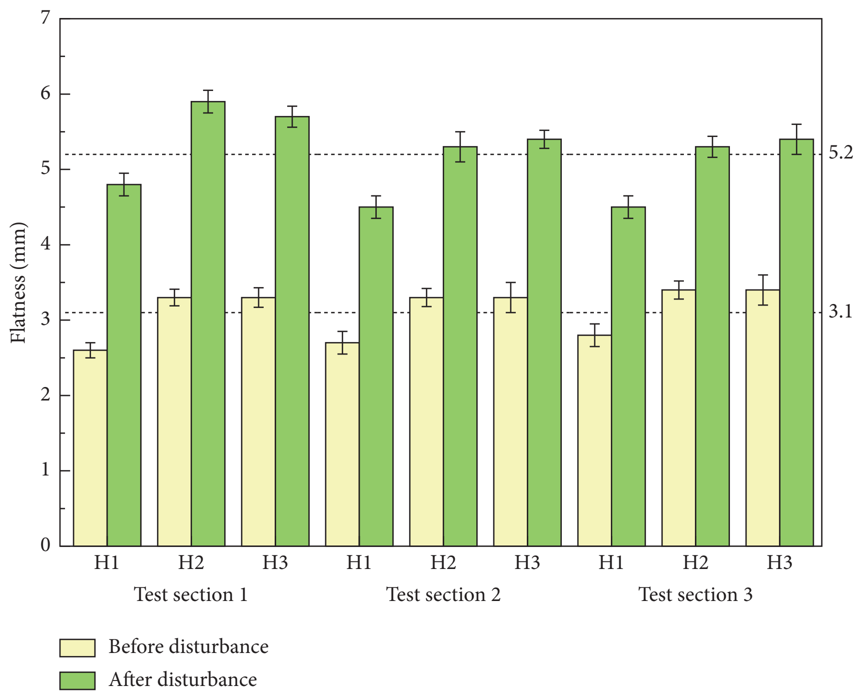

Figure 10: Transverse evenness test results.

Table 8: Quality control standards considering evenness disturbance.

Double-layer paving of subbase	Evenness control standard	Double-layer paving of base course	Evenness control standard (mm)
Upper base	12	Upper base	8
Lower base	13	Lower base	9

Table 9: Field test results of compaction degree in test section 1.

Measuring point	#1	#2	#3	#4	#5	#6	
Test section 1	K130 + 130	K130 + 130	K130 + 150	K130 + 150	K130 + 170	K130 + 170	Average value
Lower layer	99.2	99.7	100.1	99.6	99.7	98.9	99.5
Upper layer	95.7	96.3	97.1	96.0	96.6	96.2	96.3
Test section 2	K130 + 230	K130 + 230	K130 + 250	K130 + 250	K130 + 270	K130 + 270	Average value
Lower layer	98.6	99.1	99.3	99.0	99.2	98.3	98.9
Upper layer	96.9	97.5	98.3	97.2	97.8	97.4	97.5
Test section 3	K130 + 330	K130 + 330	K130 + 350	K130 + 350	K130 + 370	K130 + 370	Average value
Lower layer	98.2	98.7	99.1	98.6	98.7	97.9	98.5
Upper layer	97.8	98.4	99.2	98.1	98.7	98.3	98.4

Table 10: Compaction process of double-layer continuous paving base.

Position	Usage	Compaction method	Rolling speed (km/h)
Lower base	Initial pressure	Static compaction 1 time	1.5~1.7
	Repress	One weak and three strong	1.8~2.0
	Final pressure	Rubber wheel 1 time	2.0~2.5
Upper base	Initial pressure	Static compaction 1 time	1.5~1.7
	Repress	One weak, one strong, and three weak	1.5~1.8
	Final pressure	Rubber wheel 1 time	2.0~2.5

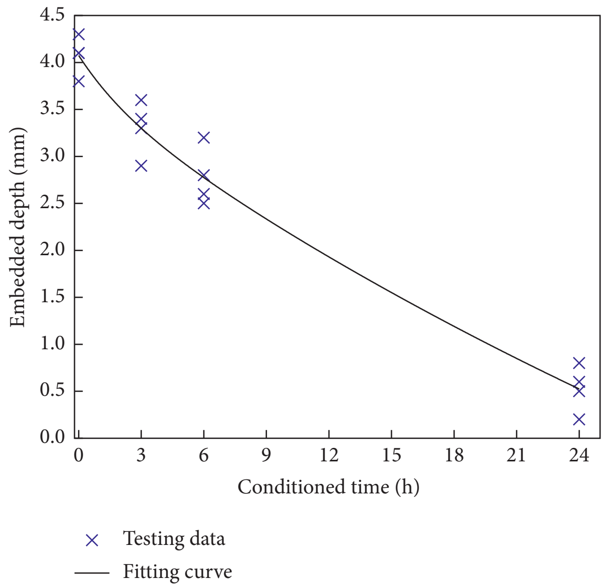

Figure 11: Variation of embedding depth with curing time.

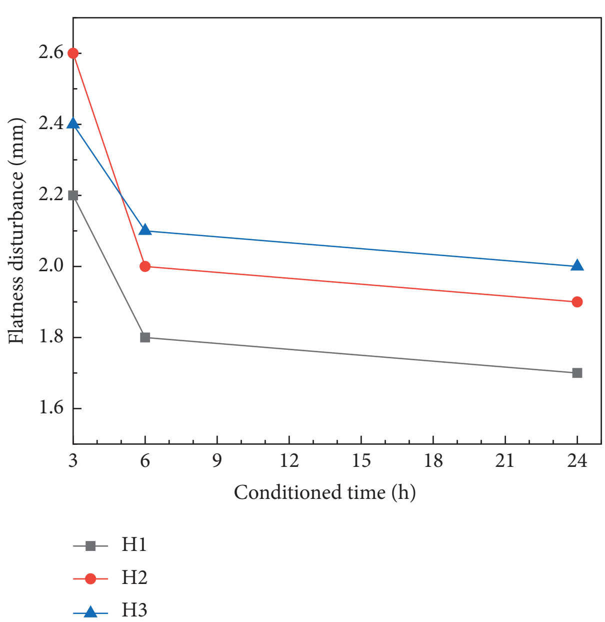

Figure 12: Variation of evenness disturbance with interval time.

the action of the transport vehicle. With the increase of time, this lubrication effect gradually weakened, and the deformation of the paved layer under vehicles gradually decreased. When the cement reached the final setting time, the lubrication effect of the cement had little effect, so the deformation of the lower layer tended to be stable.

5.3. Effect of Interval Time on Compaction. The relationship between the paving time and the compactness could be obtained from the results of field test of compaction in Section 4.3, as shown in Figure 13.

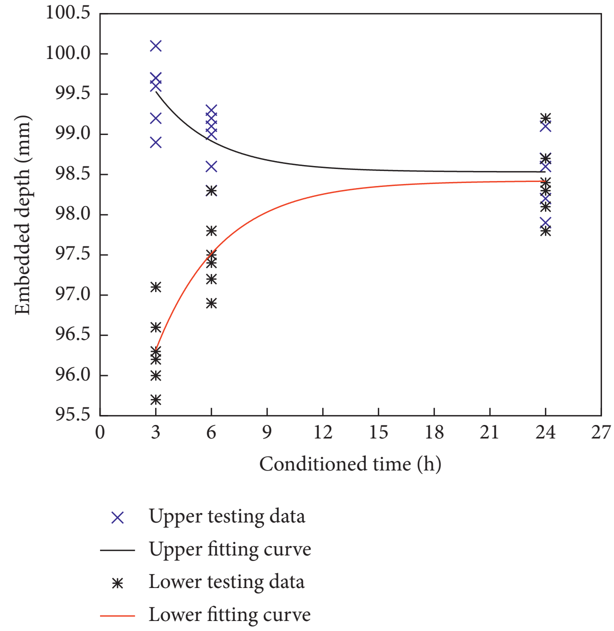

Figure 13: Variation of compactness with interval time.

As can be seen from Figure 13, as the interval time increased, the compactness of lower layer gradually decreased, while the compactness of upper layer continuously increased, and the compactness gap between the upper and lower layer gradually decreased. The interval time increased from 3 hours to 6 hours, and the compactness change of the upper and lower layers was much larger than that of the change from 6 hours to 24 hours. This was mainly because the cement has a certain lubricating effect with no curing. During the compaction process of upper layer, the aggregates in lower layer would continue to be squeezed into each other, and the compactness would be further improved. With the increase of interval time, the lubricating effect of cement continued to weaken, and the recompaction effect on the lower layer was continuously weakened. The higher the strength of the lower base layer was, the easier the upper layer was compacted. As time goes on, the strength of the lower base layer gradually increased, which resulted in the upper base layer becoming tighter, and the compaction degree gradually increased. Therefore, as the interval time increased, the strength of the lower layer continued to increase, and the compactness of the upper layer also increased.

5.4. Determination of the Optimal Interval Time. Conclusions can be drawn from the above research. With the increase of the interval time, the evenness of the lower layer and the compaction of the upper layer were getting better and better, while the solidity of the lower layer and the bonding state between the layers were continuously worsening. The evenness of the lower layer, the compactness of the upper layer, and the state between the layers are the three most concerned aspects of the double-layer continuous paving technology. According to the research results, onesided pursuit of the best quality in one area will lead to the decline of quality in the other. Therefore, in order to give consideration to the construction quality of the double-layer continuous paving base and the combination state between the base layers, it is recommended that the best time for paving the upper layer is after the lower layer is laid for 6 hours (the final setting time of the cement). At this time, the evenness disturbance of the upper layer is the smallest, and the effect of the solidity of the upper layer is ideal. At the same time, the interlayer bonding could be ensured. Therefore, the upper layer should be paved when the lower paved concrete reaches the final setting time during the construction organization arrangement, which can ensure both construction quality and good interlayer bonding.

6. Conclusions

Based on the adhesion mechanism of double-layer continuous paving and evenness passing mechanism, it is proved that the continuous paving process could significantly improve the interlayer bonding status, and quality control measures for double-layer continuous paving were proposed through interlayer adhesion test, evenness disturbance field test, and compaction field test. Some conclusions can be obtained.

(1) Through laboratory interlayer adhesion properties test, it is proved that the double-layer continuous paving technology can significantly improve the interlayer bonding state, but there is still a gap from the ideal state (fully continuous). The pull-off strength of continuous paving is 2.1 times that of discontinuous paving, and the shear strength is 2.4 times that of discontinuous paving.

(2) Through the field test of evenness disturbance, it is proposed that the longitudinal and transverse evenness of the upper and lower layers of double-layer continuous paving base meet the requirements of the specification. The interval time has little effect on the longitudinal evenness, but with the increase of the paving interval, the transverse evenness disturbance of the lower layer gradually decreases. Based on the evenness passing mechanism, evenness control standard for double-layer continuous paving is proposed, and evenness disturbance control measures are proposed based on the analysis of the test results.

(3) The compaction process of double-layer continuous paving technology is proposed, and field tests of compaction have verified that the proposed process can ensure that the compactness of upper and lower layers meets the requirements of the specification. The compaction control measures proposed are based on the analysis of the test results.

(4) The influence of interval time on interlayer bonding state, evenness, and the degree of compaction was analyzed, and the optimal interval time of double-layer continuous paving was proposed. It was recommended that the optimal time of the upper layer paving should be 6 hours after the lower layer was paved (the final setting time of the cement).

(5) In this paper, the double-layer continuous paving technology is studied and analyzed from the aspects of interlayer bonding, evenness, compaction, and interval time, and construction quality control measures are proposed, which provide a theoretical basis for the double-layer continuous paving construction of large-thickness cement-stabilized base. Mechanical calculation and the maximum load that affect the evenness passing will be further studied in the next step.

Data Availability

The test data are included within the article and can be made freely available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Authors' Contributions

X. W. conceived and designed the experiments; T. H. performed the experiments; M. Z. and J. M. contributed with reagents/materials/analysis tools; L. D. analyzed the data and wrote the paper.

Acknowledgments

Thanks are due to all those who have provided guidance and assistance for this article. This work was supported by Inner Mongolia Autonomous Region Transportation Science and Technology Project of China (NJ-2018-23 and NJ-2013-37).

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