Research on differences and correlation between tensile, compression and flexural moduli of cement stabilized macadam

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ABSTRACT. In order to reveal the differences and conversion relations between the tensile, compressive and flexural moduli of cement stabilized macadam, in this paper, we develop a new test method for measuring three moduli simultaneously. By using the materials testing system, we test three moduli of the cement stabilized macadam under different loading rates, propose a flexural modulus calculation formula which considers the shearing effect, reveal the change rules of the tensile, compression and flexural moduli with the loading rate and establish the conversion relationships between the three moduli. The results indicate that: three moduli become larger with the increase of the loading rate, showing a power function pattern; with the shear effect considered, the flexural modulus is increased by 47% approximately over that in the current test method; the tensile and compression moduli of cement stabilized macadam are significantly different. Therefore, if only the compression modulus is used as the structural design parameter of asphalt pavement, there will be a great deviation in the analysis of the load response. In order to achieve scientific design and calculation, the appropriate design parameters should be chosen based on the actual stress state at each point inside the pavement structure.

KEYWORDS. Road engineering; Cement stabilized macadam; Laboratory test; Tensile-compression-flexural modulus; Loading rate.

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INTRODUCTION

Due to high intensity and rigidity and good resistance, the cement stabilized semi-rigid base can adapt to heavy traffic and complex climate environment, making it become one of the major types of base course for high-grade highway asphalt pavement in China [1]. Restricted by economic and technological conditions, for a long period of time, semi-rigid base will still be widely applied as a major base course of pavement. Therefore, we should further understand its characteristics and improve and utilize them so as to give full play to the advantages of this semi-rigid base material [2].

The asphalt pavement design code currently in use in China is simple, in which unconfined compressive resilient modulus is used as the parameters in the structural design of asphalt mixture and semi-rigid base material [3,4], and the pavement material is similar to most of the engineering materials, showing different characteristics under different tensile and compression moduli. When the difference between the tensile and compression moduli of the material is large, it is inappropriate to use a single modulus to calculate and analyze the mechanical response [5]. Reference [6,7] studied the constitutive relations of materials with different tensile and compressive elastic moduli and the fracture mechanical responses thereof. Reference [8-11] discussed and analyzed the application of the elastic theory of different moduli like tensile and compression moduli in the theories of beam, shell and plate, established elasticity solutions to beams, shells and plates with different tensile and compression moduli under different loads, and proposed a static equilibrium equation and calculation methods for stress and displacement under external force. For the pavement material, in 1992, Changsha University of Science & Technology (formerly Changsha Communications College) proposed a calculation method when differences between tensile and compression moduli are considered for the rigid pavement [12], then analyzed the drawbacks of flexible pavement design using tensile and compression moduli as the moduli of the structural layer and deduced the basic formula and test method of the double modulus theory [13].

The semi-rigid base is formed through stratified compaction, with significant differences in its tensile and compressive moduli. Under the action of traffic load, the neutral surface of the semi-rigid base course is not at the geometric center of the structural layer; instead, it shifts towards the compressive zone. The existing asphalt pavement design method does not consider the actual stress distribution of the semi-rigid base, and performs the structural load response analysis according to the compressive elastic modulus, which will lead to the unbalance between the working state of the structural design parameter and the actual stress state, and further resulting in large deviation in calculation and analysis results. In order to achieve scientific calculation and analysis, the corresponding design parameters should be determined according to the stress state of the points inside the pavement structure. Therefore, it is necessary to set up the mechanical response analysis method for asphalt pavement structure using the double modulus theory with different tensile and compressive moduli, especially the method to obtain the corresponding material parameters.

In this paper, by using the MTS (Material Test System), we propose a new test method for measuring tensile, compression and flexural moduli simultaneously. We test three moduli of the cement stabilized macadam under different loading rates, propose a flexural modulus calculation formula which considers the shearing effect and reveal the change rules of the tensile, compression and flexural moduli with the loading rate and the differences and correlations between the three moduli so as to provide theoretical basis for the selection and optimization of material parameters in the asphalt pavement structure design.

SPECIMEN MOLDING AND TEST PREPARATION

Specimen Molding

The cement used as the raw material of cement stabilized macadam is Xing'an Hailuo ordinary portland cement PC32.5 and its information are shown as Tab.1. The aggregate is the limestone aggregate manufactured by Yangjiaqiao Crushing Plant and its information are shown as Tab.2. The test results show that the technical indexes of these raw materials meet the requirements as specified in the code.

In the basis of practical engineering, the gradation of CSM aggregate was designed to realize framework-dense structure according to the Testing Methods of Material Stabilized with Inorganic Binders for Highway Engineering [14].The mineral aggregate gradation adopted is shown in Tab. 3:

According to the mineral aggregate gradation listed in Tab. 3, we carry out the heavy compaction test on cement stabilized macadam. First, we determine the optimum water content and maximum dry density at different cement dosages, and then determine the dosage of cement that meets the requirements by performing the unconfined compressive strength test at each dose. The final test results are: the dosage of cement added into the cement stabilized macadam is 4.5%, the maximum dry density is 2.35g/cm^3 and the optimum water content is 4.5%.

Test	Results	specification
Fineness (Sieve size 80μm)	1.8	≤10%
Initial setting time (min)	302	≥180
Final setting time (min)	364	≥360
Stability (mm)	3	≤5
3 day flexural strength of cement mortar (MPa)	4.7	≥2.5
3 day compressive strength of cement mortar (MPa)	19.9	≥10

Table 1: The characterization of Xing'an Hailuo ordinary Portland cement PC32.5.

Test	Coarse aggregate	specification
Content of needle and plate particle	11.7%	≤20%
Crushing value	19.8%	≤30%
Liquid limit& Plasticity index of Particles less than 0.6mm	Liquid limit≤28%	26.5%
	Plasticity index≤9	6.2

Table 2: The characterization of the limestone aggregate.

Mesh size (mm)	Pass rate (%)
26.5	100
19	92.5
16	85.5
13.2	77.0
9.5	62.7
4.75	34.4
2.36	21.2
1.18	17.0
0.6	11.5
0.3	8.2
0.15	5.1
0.075	3.6

Table 3: Synthetic Aggregate Gradation of Cement Stabilized Macadam.

Based on the above data, according to the requirements in the test regulations [14], we make specimens for flexural strength and flexural modulus, whose size is 100mm×100mm×400mm. We use the static molding method in the specimen molding. After that, specimens are put in a standard preservation room (temperature: 20°C±2°C; humidity⩾ 95%) for 90 days of preservation.

Description of the tensile, compression and flexural test method

We use MTS (Material Test System) for modulus testing. The test principle is shown in Fig. 1, 2 and 3. The mid-span deflection is measured using a micrometer placed on the upper surface of the specimen, which is used to calculate the flexural modulus of the specimen; the compressive strain of the mid-span upper surface and the tensile strain of the lower surface are measured by the strain gauges attached to the surface, respectively, which are used to calculate the compression modulus and tensile modulus of the specimen.

In order to eliminate the friction between the load head, the support and the specimen, we use a cylindrical load head and a cylindrical support and apply butter to the load head and the support before the test. The loading rate includes 0.1mm/min, 0.4mm/min, 0.7mm/min, 1mm/min four grades.

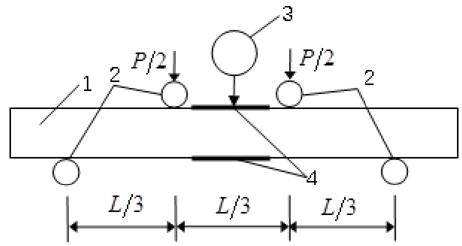


Figure 1: Testing Principle for Tensile, Compression and Flexural moduli (1-beam specimen; 2-cylindrical support; 3-micrometer; 4-strain gage).

The strain gages are foil resistance strain gages, with a grid length of 80mm and a resistance of 120Ω. Due to the rough beam surface of the cement stabilized macadam specimen, it is necessary to put cement paste on the upper and lower surfaces to fill the gaps in areas where strain gages will be put on one week before the test. While attaching 4 strain gages on the upper and lower surfaces respectively, i.e. 8 strain gages in total, we measure the compressive and tensile strains of the test beam (as shown in Fig. 1 and Fig. 2). At the same time, considering the edge effect of strain, the center of the most marginal strain gage should be 20mm away from the edge of the beam. The strain gage pasting method and test device are shown in Fig. 2 and Fig. 3. The center of the most marginal strain gage is 20mm away from the edge of the beam. The way the strain gage is pasted and the test device are shown in Fig. 2 and Fig. 3.

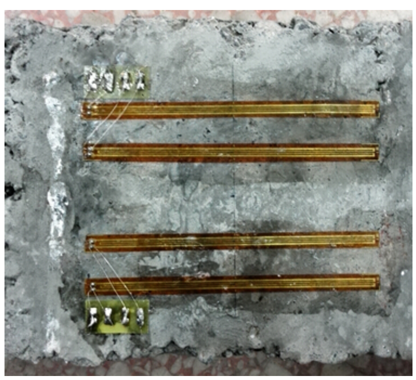


Figure 2: Schematic of Strain Gauges Pasted

Figure 3: Installation Drawing of Modulus Test

DERIVATION OF THE TENSILE, COMPRESSION AND FLEXURAL MODULI CALCULATION FORMULAS

Traditional flexural modulus calculation formula

When the length of the bar l is much greater than the cross-sectional height h, i.e. $l>5h$, the analytical formula for pure bending can be used. The current test procedure calculates the flexural modulus without considering the shear effect [14]. The calculation and derivation process is as follows:

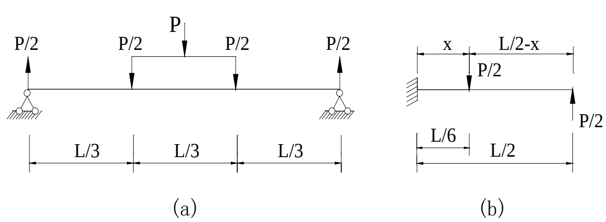


Figure 4: Force Analysis Diagram of Specimen

Fig. 4(a) shows the simplified force diagram of the specimen. (b) shows the equivalent force diagram for the right part of the specimen. The approximate differential line of deflection equation for the beam can be expressed by section as follows:
When 0≤x≤L/6:

$$E_f I\omega'' = \frac{PL}{6} \tag{1}$$

When L/6≤x≤L/2:

$$E_f I\omega'' = \frac{PL}{4} - \frac{Px}{2} \tag{2}$$

Where, E_f is the traditional flexural modulus; I is the inertia moment; w is the mid-span deflection; P is the load applied; L is the specimen span.
By integrating Formula (1) and (2) twice respectively, based on the boundary conditions and continuity conditions, we will know that when L/6≤x≤L/2,

$$E_f I\omega = \frac{PLx^2}{8} - \frac{Px^3}{12} - \frac{PL^2x}{144} + \frac{PL^3}{2592} \tag{3}$$

When x=L/2, by substituting the inertia moment $I=bh^3/12$ into Formla (3), we obtain the flexural modulus calculation formula:

$$E_f = \frac{23PL^3}{108bh^3\omega} \tag{4}$$

Where, h is the mid-span sectional height; b is the cross section width of the specimen; other symbols are the same meanings as above.

Flexural modulus calculation correction formula considering the shear effect

When the span height of the beam is greater than 5, the positive stress formula for pure bending can be applied to the positive stress calculation for transverse bending. However, for a deep beam with a span height of less than 5, if we use the pure bending theory and assumptions for slender beam in material mechanics, the error will increase rapidly with the decreasing depth-span ratio [15]. In the current inorganic binder test regulation for flexural modulus, the span height ratio L/h used is 3, but it did not consider the shear effect on the beam deflection, so the result is inconsistent with the actual situation [14]. Therefore, this paper deduces the flexural modulus calculation correction formula considering the shear effect. (the flexural modulus mentioned later is the result considering the shear effect).

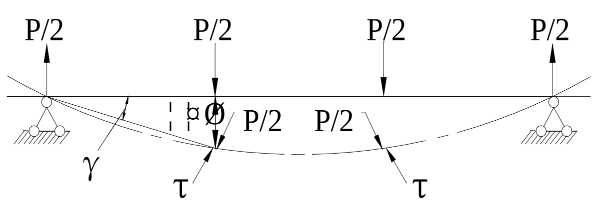


Figure 5: Force Analysis Diagram of Specimen Considering the Shear Effect

As shown in Fig. 5, let the additional deflection caused by the shear effect be $\Delta\omega$. Then:

$$\Delta\omega = \gamma \cdot \frac{L}{3} \tag{5}$$

Where, $\gamma = \frac{\tau}{G}$ is the shear strain; is the shear stress; $\tau = \frac{T}{A}$ is the shear force; $T = \frac{P}{2}$ is the sectional area; $G = \frac{E_f}{2(1+\mu)}$ is the shear modulus; μ is Poisson's ratio. We substitute this into Formula (5) and obtain $\Delta\omega = \frac{2(1+\mu)PL}{3E_f bh}$.
The deflection ω' under the mutual action of moment and shear can be expressed as: $\omega' = \omega + \Delta\omega$. By substituting the above equations, we obtain:

$$\omega' = \frac{23PL^3}{108E_f bh^3} + \frac{2(1+\mu)PL}{3E_f bh} \tag{6}$$

Then the flexural modulus E_f' considering the shear effect can be expressed as:

$$E_f' = \frac{23PL^3}{108bh^3\omega'} + \frac{2(1+\mu)PL}{3bh\omega'} \tag{7}$$

If we compare the flexural modulus formula (7) considering the shear effect and formula (4) without considering the shear effect, the change ratio of the two is: $\frac{E_f' - E_f}{E_f} = \frac{216(1+\mu)h^2}{69L^2}$. As the required span height ratio L/h of the cement stabilized macadam beam specimen is 3, we know that with the shear effect taken into account, the flexural modulus is increased by about 47% (Poisson's ratio μ is 0.25).

Derivation of tensile modulus calculation formula based on flexural test
The tensile and compressive stress distribution of the mid-span section is shown in Fig. 6(b).

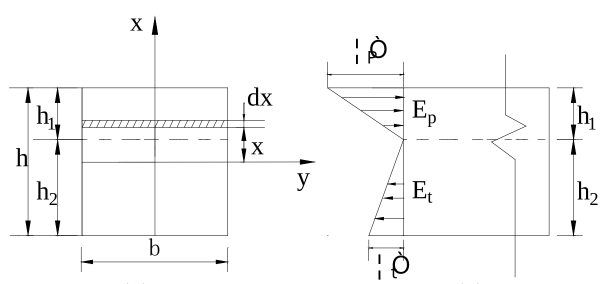


Figure 6: Stress Distribution of Specimen Mid-Span Section

Let the micro-area unit parallel to the neutral axis (as shown in Fig. 6(a)) $dA = bdx$. For the mid-span section, the bending moment M caused by the internal force can be expressed as follows:

$$M = \int_0^{h_1} \frac{\sigma_p}{h_1} bx^2 dx + \int_{-h_2}^{0} \frac{\sigma_t}{h_2} bx^2 dx \tag{8}$$

Where, M is the bending moment; σ_p is the compressive stress of the upper surface; σ_t is the tensile stress of the lower surface; h_1 is the vertical distance between the upper surface of the specimen and the neutral axis moved up; h_2 is the vertical distance between the lower surface of the specimen and the neutral axis; other symbols have the same meanings as above.
By integrating this formula, we obtain:

$$M = \sigma_p bh_1^2 / 3 + \sigma_t bh_2^2 / 3 \tag{9}$$

That is:

$$M = E_p \varepsilon_p b h_1^{\ 2} / 3 + E_t \varepsilon_t b h_2^{\ 2} / 3 \tag{10}$$

The plane hypothesis:

$$\varepsilon_t / h_2 = \varepsilon_p / h_1 \tag{11}$$

Where, ε_p is the compressive strain of the upper surface; ε_t is the tensile strain of the lower surface; other symbols have the same meanings as above.
Equilibrium condition:

$$\int_0^{h_1} \frac{\sigma_p}{h_1} b x dx = \int_{-h_2}^{0} \frac{\sigma_t}{h_2} b x dx \Rightarrow \sigma_p h_1 = \sigma_t h_2 \tag{12}$$

As the tensile modulus $E_t = \sigma_t / \varepsilon_t$ and the compression modulus $E_p = \sigma_p / \varepsilon_p$, by combining Formula (10), (11) and (12), we obtain:

$$E_t = 3M(\varepsilon_p + \varepsilon_t) / b \varepsilon_t^{\ 2} h^2 \tag{13}$$

$$E_p = 3M(\varepsilon_p + \varepsilon_t) / b \varepsilon_p^{\ 2} h^2 \tag{14}$$

Where, E_t is the tensile modulus; E_p is the compression modulus.
Therefore, the tensile - compression modulus ratio is:

$$\frac{E_t}{E_p} = \frac{\varepsilon_p^2}{\varepsilon_t^2} = \frac{h_1^2}{h_2^2} \tag{15}$$

The mid-span bending moment of the specimen:

$$M = PL / 6 \tag{16}$$

By substituting Eq. (16) into Formula (13) and Formula (14), we obtain the tensile and compression modulus calculation formulas as follows:

$$E_t = \frac{pL(\varepsilon_{\mathrm{t}} + \varepsilon_{\mathrm{p}})}{2bh^2 \varepsilon_{\mathrm{t}}^{\ 2}} \tag{17}$$

$$E_p = \frac{pL(\varepsilon_{\mathrm{t}} + \varepsilon_{\mathrm{p}})}{2bh^2 \varepsilon_{\mathrm{p}}^{\ 2}} \tag{18}$$

ANALYSIS ON TENSILE, COMPRESSION AND FLEXURAL MODULI TEST RESULTS

Analysis on the change rules of the three moduli with the loading rate

According to the deduced tensile, compressive and flexural modulus calculation formulas, we use the triple mean variance to eliminate the abnormal test results and calculate the test mean value of 9 groups of specimens. The test results of the three moduli under different loading rates are shown in Tab. 2.

Loading rate ν /(mm/min)	Flexural modulus E_f'/MPa	tensile modulus E_t/MPa	compression modulus E_p/MPa
0.1	2341.94	9304.05	15949.03
0.4	2515.55	9492.45	16872.67
0.7	2617.37	9565.97	17355.81
1	2660.74	9645.57	17401.38

Table 2: Tensile, Compression and Flexural Modulus Test Results under Different Loading Rates.

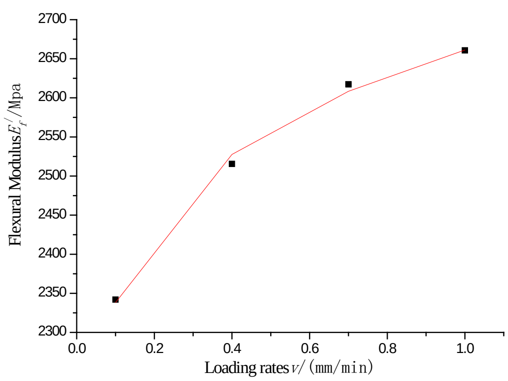
According to the change rules of the three moduli with the loading rate, we use a power function (19) to fit the data:

$$E = a \cdot v^b \tag{19}$$

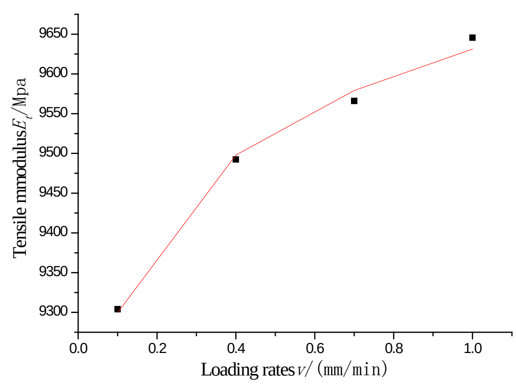
The fitting results are shown in Tab. 3 and Fig. 7.

	Fitting parameters		Correlation coefficient R^2
	a	b	
Flexural modulus	2661.22	0.056	0.996
tensile modulus	9631.25	0.015	0.993
compression modulus	17493.15	0.039	0.985

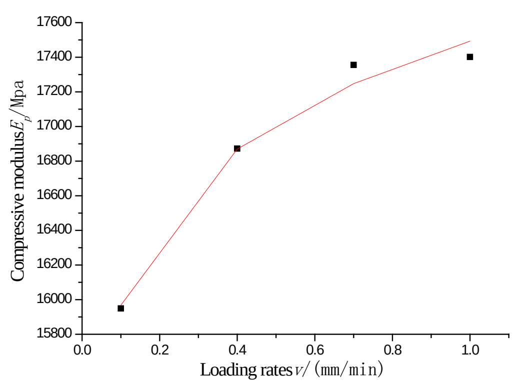
Table 3: Summary of Three Modulus Fitting Results under Different Loading Rates.



(a) Flexural Modulus



(b) Tensile Modulus



(c) Compression Modulus

Figure 7: Change Rules of the Three Moduli with the Loading Rates.

From the above fitting results, it can be seen that the tensile modulus, compression modulus and flexural modulus increase with the increase of the loading rate, showing a good power function relationship. It has been proved in the existing research that when the loading rate increases, the stress state inside the specimen is not exactly one-dimensional stress state, but rather a mechanical response characteristic towards the one-dimensional strain state. In particular, in the middle part of the specimen, under a higher loading rate, due to the inertia of the material, the lateral strain of the specimen is restricted, and the higher the strain rate is, the more obvious the restriction will be, showing an obvious strain ratio effect, which causes the material modulus and strength to increase with the growth of loading rate [16]. The modulus and strength of asphalt mixture has a similar change pattern [17-20]. In the same way, in this paper, the change rule that the modulus of the cement stabilized macadam material changes with the loading rate also proves this conclusion.

Comparison and analysis of the three moduli

According to the test results in Tab. 2, we get to know:
(1) Under different loading rates, the ratio between the compression and tensile moduli is 1.71, 1.78, 1.81 and 1.80, with an average value of 1.78. The cement stabilized macadam material shows significant differences between the tensile and compression moduli, and the compression modulus is greater than the tensile modulus, it proved the differences between the tensile and compressive modulus of cement stabilized macadam material.
(2) The tensile modulus is respectively about 3.97, 3.77, 3.65 and 3.63 times the flexural modulus, with a mean value of 3.76; the compression modulus is about 6.81, 6.71, 6.63 and 6.54 times the flexural modulus, respectively, with a mean of 6.68. In other words, the tensile and compression moduli are much greater than the flexural modulus. It can be seen that, regardless of the stress state inside the cement stabilized macadam semi-rigid base structure, it is obviously inappropriate to simply use the unconfined compressive resilient modulus to calculate the structural load response. As the compressive resilient modulus is the largest among the three moduli, the structural deformation response calculated based on this modulus will be the smallest. As a result, the asphalt pavement structure, which takes the surface deflection as the indicator, will be thin and unsafe, and the road pavement is likely to be damaged at an early stage.
(3) Under different loading rates, the ratios between each two of the tensile, compressive and flexural moduli, are stable, showing that even the loading rate has direct impact on the moduli of cement stabilized macadam material, but it does not affect the ratio relationship between the three moduli[19]. This provides basis and convenience for the conversion between the three moduli.

Conversion relations between the three moduli

With the loading rate as the intermediate variable, according to Formula (19) and the fitting results in Tab. 3, we can establish the conversion relations between the three moduli.
(1) Conversion relation between the tensile modulus and the flexural modulus:

$$E_t = 1164.79 {E'_f}^{0.27} \tag{20}$$

(2) Conversion relation between the compression modulus and the flexural modulus:

$$E_p = 72.04 {E'_f}^{0.7} \tag{21}$$

(3) Conversion relation between the tensile modulus and the compression modulus:

$$E_t = 224.81 {E_p}^{0.39} \tag{22}$$

According to the conversion relations between the three moduli in Formula (20), (21) and (22), as long as we can get one modulus value, we can easily calculate the other two modulus, which facilitates the selection of modulus design parameters based on the stress state inside the pavement structure.

CONCLUSIONS

(1) When the shear effect is considered, the flexural modulus of the beam specimen of cement stabilized macadam will be greatly increased. Therefore, when measuring the modulus of the indoor middle beam made of semi-rigid material, we should consider the shear effect.

(2) The tensile, compression and flexural moduli of the cement stabilized macadam increase with the increase of the loading rate, showing a power function growth pattern.
(3) The tensile and compression moduli of cement stabilized macadam are significantly different. If only the compression modulus is used as the structural design parameter of asphalt pavement, there will be unbalance between the working state of the structural design parameter and the actual stress state, and further resulting in large deviation in load response analysis and affecting the safety of the design results. In order to improve the accuracy of the design calculation, we should select the corresponding design parameters according to the stress state of the points inside the pavement structure.
(4) This paper reveals the differences between the tensile, compression and flexural moduli of cement stabilized macadam and their conversion relations, but it does not consider the impacts of different mineral aggregate gradations, which, however, are rather significant on the moduli of cement stabilized macadam. In order to improve the resistance of the semi-rigid base material against load damages, the gradation optimization will be one of the focuses in our future research.

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NOMENCLATURE

L	Test beam span
P	Test load applied
ω	Mid-span deflection of the specimen under pure bending
h	Mid-span sectional height of the specimen
b	Mid-span sectional width of the specimen
E	Resilient modulus of the specimen
I	Mid-span sectional inertia moment of the specimen
E_f	Flexural modulus without the shear effect taken into account
$\Delta\omega$	Change in the mid-span deflection of the specimen caused by the shear effect
γ	Shear strain
τ	Shear stress
T	Shear force
A	Mid-span sectional area of the specimen
G	Shear modulus
μ	Poisson's ratio
ω'	Mid-span deflection of the specimen under the mutual action of moment and shear
E_f'	Flexural modulus with the shear effect considered
h_1	Vertical distance from the upper surface of the specimen to the neutral axis
h_2	Vertical distance from the lower surface of the specimen to the neutral axis
σ_p	Compressive stress of the upper surface of the specimen
σ_t	Tensile stress of the lower surface of the specimen
ε_p	Compressive strain of the upper surface of the specimen
ε_t	Tensile strain of the lower surface of the specimen
E_p	Compression modulus
E_t	Tensile modulus
M	Mid-span bending moment of the specimen
v	Loading rate
R^2	Correlation coefficient