

Investigation of the responses of asphalt pavement structure considering load - Poisson's ratio relation

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Abstract. Poisson's ratio is one of the important parameters that can be used to reflect the deformation characteristics of solid materials. To further understand the mechanical behaviors of materials and improve the accuracy of the finite element simulation results, the Poisson's ratio must be defined accurately. In this paper, DIC technology is employed to investigate the Poisson's ratios of asphalt mixtures under the different gradation and different compaction conditions. It is found that the Poisson's ratios of different asphalt mixture are quite different and the number of compaction had a greater influence on Poisson's ratio. It also showed that Poisson's ratio of asphalt mixture was not a constant under the 25°C temperature condition, but varied with load. The experiment data suggested that the curve of the load - Poisson's ratio could be divided into three sections through the observation of the graph and it also could be used to investigate the properties of asphalt mixtures deformation resistance. General-purpose finite element software is used to simulate the different contact pressure and Poisson's ratio under dynamic loading condition, in order to find the response of asphalt pavement structure based on the relationship between load and Poisson's ratio. It was found that the relationship of load - Poisson's ratio significantly affected the response of asphalt pavement. It meant that the relationship of load - Poisson's ratio should be considered when designing the asphalt pavement to improve the asphalt pavement service life.

1. Background

Poisson's ratio (μ) and elasticity modulus (E) are the two important parameters that characterize the material properties in the elastic theory analysis. In the design of pavement structure, the modulus values of asphalt mixture varies with temperature, however, the value of Poisson's ratio is always taken as a constant, without considering the effect of variation of Poisson's ratio on the response of asphalt pavement structure. Some researchers [1, 2] have found that Poisson's ratio increases with the rise of temperature and the content of asphalt. Therefore, it is very important to determine Poisson's ratio under different experimental conditions, such as different temperatures, different kinds of asphalt mixture, to improve the accuracy of the mechanical analysis. To achieve this purpose, the deformation of asphalt mixture should be measured accurately. In most of tests, the deformations of materials are measured by the resistance strain gage or LVDT. Such techniques require a large specimen for strain gage placement and impose tight geometry tolerances to minimize variations of strain at the gage location [3], which make it difficult to prepare the specimens, and hardly to address complex mechanical behavior with just a global stress-strain curve obtained by the classic

measurement techniques, especially for some heterogeneous materials. Asphalt mixture is a kind of heterogeneous material, wherein its fracture behavior is complicated and difficult to quantify the deformation parameters because of the difficulties of the observation of the fracture process, especially when the cracks first initiate, they are tiny and random occurrence because of the irregularly shaped and randomly oriented aggregate particles and mastic[4, 5].

To obtain more experimental information, such as microscopic information of the asphalt mixture deformation processes to improve the identification procedures for this type of material, a high resolution and full-field measurement methods are required. One of them is the Digital Image Correlation (DIC) technique [6, 7], an optical and noncontact measurement technique, which is based on a comparative analysis of digital images of the structural member captured at different deformation states. This technique has been applied successfully to various classes of mechanical and civil engineering materials and structural problems [8-11]. There are also some applications to asphalt mixture. Arasan et al.[12]quantified the morphological characteristics of coarse aggregates with digital image processing approach. Kim et al.[13]found that typical dense-graded asphalt mixtures could be characterized for their material properties with an approximate RVE size of 60 mm with the help of DIC technique. Montepara et al. [14] and Birgisson et al. [8]investigated the cracking behavior of HMA mixtures with DIC system and demonstrated the DIC technique overcome the shortcomings of traditional on-specimen strain measurement devices achieving satisfactory accuracy compared to strain gauges.

In this paper, DIC method is introduced to determinate the full-field strain produced by IDT (indirect tension test) to obtained load- Poisson's ratio relation of different asphalt mixtures, and then, the responses of asphalt pavement structure considering load- Poisson's ratio relation will be analyzed by general-purpose finite element software.

2 Materials and experiments

2.1 Materials used

2.1.1 Asphalt and grading

The basic properties of the binder used in this study as per Chinese specifications (JTJ052-2000) are shown in Table 1.

Table 1 The Basic Properties of Asphalts

Evaluation index	Unit	Technical requirements	Test results	Test method (JTJ052-2000)
Penetration (25°C, 100g, 5s)	0.1mm	60~80	66	T0604-2000
Softening Point ($T_{R\&B}$)	°C	≤ 55	69.2	T0606-2000
Ductility 5°C (5cm/min)	cm	≤ 30	33.9	T0605-1993
Elastic Recovery (25°C, 5cm/min, 1h)	%	≤ 65	92.7	T0662-2000
Storage Stability	°C	≥ 2.5	1.2	T0661-2000

The gradations used in this research are shown in Table 2.

Table 2 Passing percentage of mineral mixtures (%)

Sieve Sizes(mm)	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.075
AC-16	88.7	72.8	45.3	30.8	21.0	15.4	11.8	8.0	6.0
AC-13	95.9	75.3	46.0	31.5	21.0	15.4	11.8	8.0	6.0

The filler used is limestone powder passed through a 200 sieve and the specific gravity of it is 2.740. The polyester fiber (BoniFibers®) content added in the designed asphalt mixture is 0.3% by weight.

2.1.2 Mixture design

The mix design procedures for AC-16 and AC-13 in this paper are determined as per the Chinese specification JTJ052-2000 (T0703-1993). Locally available materials that meet the normal AC-16 and AC-13 specifications are used to produce the mixes. With the asphalt and gradation mentioned

above, five kinds of asphalt mixture (A, B, C, D and E) are made by gyratory compaction under the condition of optimal asphalt content to maintain consistency through the study. The results are shown in the following Table 3.

Table 3 The Category of Asphalt Mixtures

Mixture type	The number of gyratory compaction	Asphalt content (%)	Mixture ID
AC-13	90	5.2	A
	125	5.2	B
	205	5.2	C
AC-16	125	4.7	D
	205	4.7	E

2.2 Experimental part

2.2.1 Method of loading

Indirect tension test (IDT) is one of methods widely used in engineering practice to evaluate the mechanical performance of mixture samples under loading [15, 16], which is employed in this research. Laboratory specimens are prepared using Superpave Gyratory Compactor. The specimens are placed in a temperature chamber set to 25°C for 12h prior to the IDT test, and the test is done using Materials Testing System (MTS-810). The tests are conducted at 25°C temperature, 10mm/min loading rate to monitor the deformation behavior of mixes with DIC technology.

2.2.2 Method of measuring deformation

In this research, Vic-3D 2010 produced by Correlated Solutions, Inc. was employed. This system is a complete, turn-key system for measuring the shape, displacement and strain of surfaces in three dimensions [17]. The optics adopted at maximum magnification allows 0.01 per pixel resolution. The camera was set up at a distance away from the specimen so that the resulting imaging window was focused on the whole surface of specimen, where Region Of Interest (ROI) is. Once the image sequence of the fracture test has been acquired, the features on the specimen surface are tracked along the sequence to obtain image coordinates.

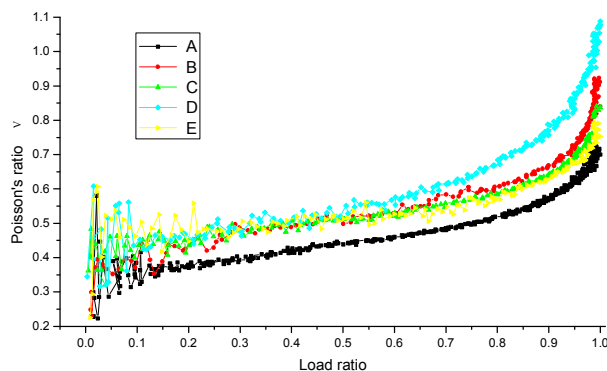
3 Results and discussion

3.1 Poisson's ratio test results and discussion

Poisson's ratio is one of the fundamental properties of any engineering material. Knowing the value of Poisson's ratio of asphalt mixture is important for evaluation and simulations.

3.1.1 Poisson's Ratio of different asphalt mixture

The ratio between transverse strain ϵ_x and longitudinal strain ϵ_y is defined as Poisson's ratio $= -\epsilon_x/\epsilon_y$. From DIC test, ϵ_x and ϵ_y can be obtained, and then the can be calculated as per above formulation. The results are shown in Fig. 1 and Fig. 2 [18].



● Load ratio= P/P_{max} .

Fig. 1 Curve of Load ratio-Poisson's ration

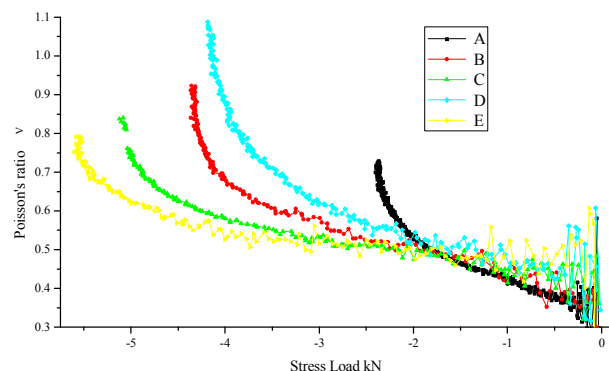


Fig. 2 Curve of Load -Poisson's ration

From Figs 1 and 2 it can be found that all the Poisson's ratio of mixture in the initial load are unstable, because of compression process; With the load increasing, Poisson's ratio tends to a stable and linear growth; When the load (or load ratio) exceed a certain point, the Poisson's ratio increases rapidly, eventually leading to destruction of the specimen. Therefore, the load - Poisson's ratio curve can be divided into three phases: initial compression phase, stable development phase and critical limit phase. It is also can be concluded from Fig. 1 and 2 that the Poisson's ration is not a constant for asphalt mixture at 25°C, it is related with the load magnitude.

From Fig. 1 and 2, it can be found that gyratory compaction time has a great influence on Poisson's ration. The fewer gyratory compaction times, the shorter second phase of the load - Poisson's ratio curve and the higher growth rate; it is adverse to mixture performance.

3.1.2 Modeling Poisson's Ratio of different asphalt mixture

It can be known that the Poisson's ration is not a constant from the above result, to improve the computer simulations results, the relationship between Poisson's ration and load should be investigated. In this research, Burges model $y=1/[1/a+x/m+1/b*(1-\exp(-x*b/n))]$ is employed to evaluate the relationship of them, the curves are fitted by Origin® 8.1 software. To eliminate the negative effects of the first phase, the fitting starts at -0.5kN. The results are shown in Table 4.

Table 4 Fitting results

Asphalt mixture type	Fitting Function: $y=1/[1/a+x/m+1/b*(1-\exp(-x*b/n))]$				R^2
	Fitting Parameter				
	a	m	b	n	
A	3.0159	-11.0824	-4085034.05	-728566.80	0.99
B	2.5961	-16.9402	-123754201.91	-31285823.93	0.98
C	2.3988	-26.9984	-1151465.34	-480636.92	0.99
D	2.5207	-13.8309	-1467960.42	-466329.25	0.99
E	2.28933	-36.8260	-1765410.79	-778828.82	0.98

It is can be found that Burges model can fit load - Poisson's ratio curve well, and correlation coefficients are all above 0.98.

3.2 Finite element simulation results and discussion

To further investigate the effect of load - Poisson's ratio on the responses of asphalt pavement structure, general-purpose finite element software is employed in this part.

3.2.1 The establishment of finite element model

3.2.1.1 Establishment of the model

Studies have shown when the size of the pavement structure model is greater than 5m × 5m × 5m, structural size has little effect on the calculation results. In this paper, the model size is 6m×5m×5m. The structure of pavement is shown in Table 5.

Table 5 Structure of pavement

Thickness	Possition	Material parameters
4cm	AC-16	E=1200Mpa,
6cm	AC-20	E=1200Mpa
8cm	AC-25	E=1100Mpa, $\mu=0.35$
36cm	Cement-stabilized crushed stones	E=1500Mpa, $\mu=0.25$
20cm	Cement-stabilized gravel	E=2000Mpa, $\mu=0.30$
--	Subgrade	E=50Mpa, $\mu=0.40$

All materials are considered as the elastic material, each structural layer of the pavement is completely continuous contact; the model around boundary is restricted to generate Longitudinal, horizontal and normal displacement, but it can rotate about the normal axis, the bottom cannot move vertically. The element type of FEM model is reduced integrated quadratic three dimensional octahedrons (C3D8R). Then apply more seeds on the area of wheel loading and asphalt mix layers.

Calling subroutine written by FORTRAN through Dload port Abaqus to apply dual-wheeled uniform moving load on model. To eliminate the edge effect and shorten the computation time, the longitudinal end of model on both sides of 0.5m is not applied load, only applying load on the middle of model. The region of load is shown in Fig. 3.

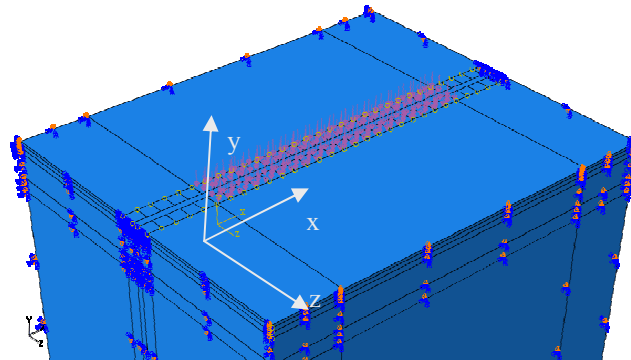


Fig. 3 The region of load

3.2.1.2 Study cases

To study the effect of load- Poisson's ratio relation on the responses of asphalt pavement structure qualitatively, according to the above test results, six cases are determined, they are shown in Table 6 and Table 7.

Table 6 Load and material parameters in different cases

Case		1	2	3	4	5	6
Pressure (Mpa)		0.7	0.9	0.9	1.1	1.1	0.7
Poisson's ratio	Top surface	0.35	0.35	0.40	0.45	0.35	0.40
	Mid surface	0.35	0.35	0.38	0.40	0.35	0.38

Table 7 Material parameters in other layers

Materials	Lower surface	Top base	Lower base	Earth subgrade
Poisson's ratio	0.35	0.25	0.30	0.40

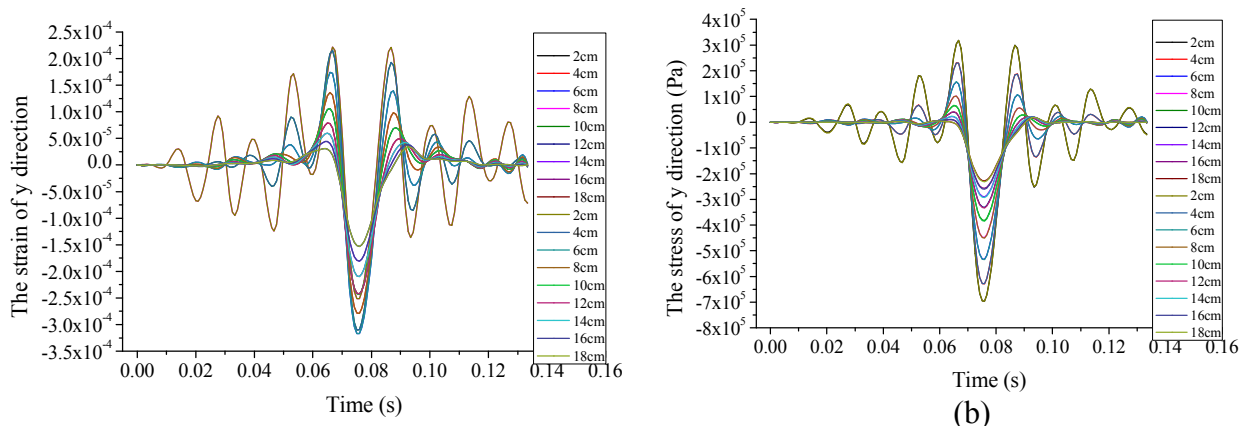
3.2.1.3 Determination of observation position

Studies have shown that the point directly below the wheel load is the most adverse point under static loads. So in this paper, the stress and strain of this point are investigated.

3.2.2 Results and analysis

3.2.2.1 The structural response in various pressures and Poisson's ratio

In this section, Case 1 and Case 6 are selected. The simulation results are shown in Fig. 4.



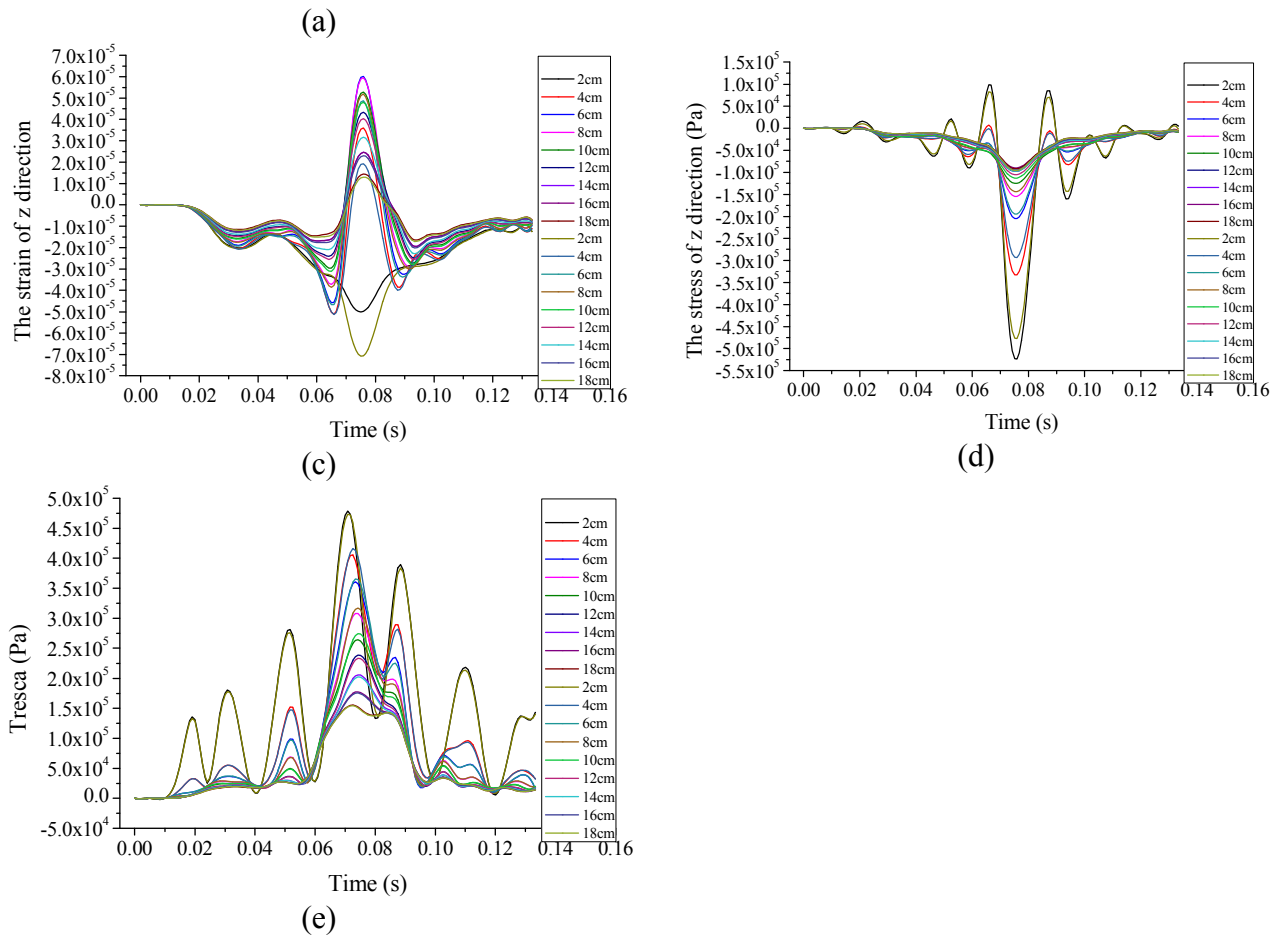


Fig. 4 The simulation results of Case 1 and Case 5

It can be inferred from Fig. 4 that with the load close to the observation point there is a slight stress and strain response; and when the load on the observation point, the response amplitude of structure is max. The stress-strain responses of different depths have the same trend, but different amplitude. From Fig. 4-a and Fig. 4-b it can be found that when the load moves to the observation points, the state of these points are not only the process of compressive stress (compressive strain) formation and dissipation; these points subject to tensile stress before the compressive stress (compressive strain). It means that when load passing, the pavement will subject the compression and shear process. From Fig. 4-c it can be found that when the load on the observation point, there is tensile strain in the direction of z. It also can be inferred from Fig. 4 that when Poisson's ratio changed, the amplitude of responses will be effect, but the laws of responses will be the same.

There is the same law between Case 2 and Case 3 and between Case 4 and Case 5, whose results are not shown in this paper.

3.2.2.2 The asphalt pavement structural response considering load- Poisson's ratio relation

To study the effect of load- Poisson's ratio relation on pavement structural response, the strain of z direction at the depth of 6cm in Case 1, 2, 3, 4 and 5 are plotted in Fig. 5.

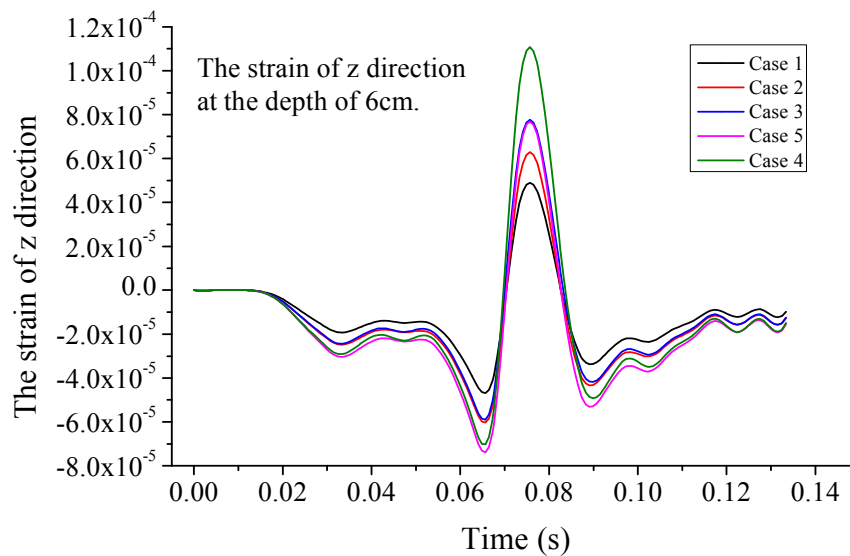


Fig. 5 The strain of z direction under different Cases.

From Fig. 5 it can be found that whether or not to consider the load- Poisson's ratio relation, the strain of z direction at the depth of 6cm will be increased varied with the increase of the load. When without considering the load- Poisson's ratio relation, the increase of transverse deformation is 29.5% when the load increases from 0.7Mpa to 0.9Mpa; when the load increases from 0.7Mpa to 1.1Mpa, the increase of transverse deformation is 57.6%. However, when considering the load- Poisson's ratio relation, the increase of transverse deformation is 59.6% when the load increases from 0.7Mpa to 0.9Mpa; when the load increases from 0.7Mpa to 1.1Mpa, the increase of transverse deformation is 127.5%. It means that the load- Poisson's ratio relation has the significant effect on the transverse deformation of asphalt pavement. The greater load, the more significant effect.

Excessive transverse deformation would lead to transverse flow, which is one of the reasons that lead to rut. Therefore, the load- Poisson's ratio relation should be considered when designing the asphalt pavement, especially in heavy-load and overload pavement, to ensure the pavement life.

4 Conclusions

Based on the testing and analysis presented herein, the conclusions of the study are summarized as follows:

(1) The load - Poisson's ratio curve can be divided into three phases and the Poisson's ratio is not a constant for asphalt mixture at 25°C, it is related with the load magnitude; The number of gyratory compaction has the great effect on the deformation properties of asphalt mixture, the more number of gyratory compaction, the better deformation resistance.

(2) When load passing, the pavement will subject the compression and shear process. When the load is on the observation point, there is tensile strain in the direction of z. It also can be inferred from Fig. 6 that when Poisson's ratio changed, the amplitude of responses will be effect, but the laws of responses will be the same.

(3) Whether or not to consider the load- Poisson's ratio relation, the strain of z direction at the depth of 6cm will be increased varied with the increase of the load, but the load- Poisson's ratio relation has the significant effect on the transverse deformation of asphalt pavement. The greater load, the more significant effect.

(4) Excessive transverse deformation would lead to transverse flow, which is one of the reasons that lead to rut. Therefore, the load- Poisson's ratio relation should be considered when designing the asphalt pavement, especially in heavy-load and overload pavement, to ensure the pavement life.

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