Study on Verification of Evaluation Indexes of Shear Resistance of Asphalt Mixtures Based on GTM Method

Chuanhai Wu¹ and Biyun Tan²

¹Guangdong Road Traffic Technology Co. Ltd, Guangzhou 510420; 731480615@qq.com
²Guangdong Construction High Vocational College, Guangzhou 510440; 787127734@qq.com

ABSTRACT: The high temperature performance of asphalt mixtures can’t be evaluated comprehensively by present widely-used rutting tests. In this paper uniaxial penetration test and GTM(Gyratory Testing Machine) method are adopted in order to test, evaluate and make correlation analysis of shear resistance performance of asphalt mixtures at high temperature. Combined with verification results of field investigation, this paper finds the shear strength in uniaxial penetration test at 60℃ and index GSF in GTM method can objectively show the shear resistance performance of asphalt mixture at high temperature and can be used to test the high-temperature stability of asphalt mixtures. Besides, there is a good linear correlation between both and the correlation coefficient R is 0.9597. For the surface or medium layer of asphalt mixture in highways, the shear strength should be no less than 0.7MPa in the uniaxial penetration test at 60℃ and the shear safety factor GSF shall be no less than 1.3 in GTM method.

Keywords: GTM; asphalt mixtures; uniaxial penetration; shear strength; index verification

0 INTRODUCTION

Rutting is one of the main diseases of asphalt pavement. To overcome the permanent deformation of asphalt mixtures become such a difficult problem that many technicians consider anti-rutting as an important research topic (Shen, 2001).

In early 1962, when AASHO Road Test was carried out by the American Association of State Highway and Transportation Officials, based on excavating surveys, Hofstra proposed that the main cause of rutting should be shear stress and he recommended high strength pavement materials. In 1987, Eisenmann put forward in a research report that on the beginning stage of rut formation, the sinkage of wheel track was larger than the volume of uplift of its two sides, which was mainly caused by the compaction of asphalt mixtures. Then he presented that after that, the sinkage of wheel track gradually balanced with the volume of uplift, which indicated that the compaction had been completed and the rutting was caused by deformation in the flow of asphalt mixtures (Eisenmann, 1987). In the 19th World roads Conference, surveys conducted on 16 countries showed that the vast majority of countries had adopted Marshall method to determine the optimum asphalt content, but they also considered that it was unreasonable to use Marshall method to estimate the high temperature performance of asphalt mixtures. It was reported that there were 8 countries using TRRL or LCPC rutting test to evaluate the anti-rutting performance of asphalt mixture (Paterson, 1987; Amy, 2001).
Rutting test is used most extensively to evaluate asphalt mixture rutting, which originated from TRRL of England and now has become the general test for most of countries in European countries, Japan, Australia and other countries. But different countries have different rutting test methods and equipment, such as Asphalt Pavement Analyzer (APA) in United States and Hamburg wheel tracking test instrument in Germany, which has a great impact on the test results that may vary under different conditions such as load or temperature. There is no fixed conversion relationship between different temperature, load, speed or standard conditions. The conversion formula of various types of asphalt and asphalt mixtures differs greatly and the conversion formula proposed by individual studies cannot be applied widely. As causes of rutting disease are complex, factors such as temperature, traffic volume, vehicle speed or load should be considered. However these factors can’t be simulated truly in the laboratory. For example, the actual vehicle tire pressure often exceeds 0.7MPa, which is often adopted in the lab standard test. And rutting test is also subjected to severe challenge (Fu, 2005).

To sum up, wheel rutting test solely can’t be adopted to evaluate the high temperature stability of asphalt mixtures comprehensively. Further study is still needed to find more scientific, accurate evaluation methods and indexes. In this paper, GTM method is adopted to evaluate the high temperature shear resistance performance of asphalt mixtures. Meanwhile, uniaxial penetration test and the verification of field works are carried out in order to propose more objective evaluation methods and indexes.

1. **Uniaxial penetration test adopted to evaluate shear resistance performance of asphalt mixture**

At present, mature methods for evaluation of shear performance of asphalt mixtures at high temperature are few, among which uniaxial penetration test is broadly adopted as it has been included in the latest revision of Design Code for Highway Asphalt Pavement (Draft). Uniaxial penetration test was proposed by Professor Sun Lijun et al from Tongji University. The mechanics state of this test was observed by establishing theoretical models based on 3D FEM and the test parameters were set by indoor experiments which can be used directly to evaluate the shear strength of asphalt mixture. The force mode of the test is in agreement with that of pavements. And the shear stress distribution in specimens in the test is similar to that of the pavement under load and both may even coincide. The diameter of penetration indenter of the test is much less than that of specimen and in the loading process the surrounding materials formulate lateral restraint on the cylinder under indenter. The damage to the specimen shows the failure of the constraint, which can accurately reflect the formation mechanism of shear strength of asphalt mixtures. Compared with three-axial test, penetration test can directly evaluate the shear strength of asphalt mixtures, and the test is also easy to operate while its data is more intuitive. Cui Peng et al proposed that φ100mm×100mm standard cylindrical specimens may be adopted for asphalt mixtures whose nominal maximum size is less than or equal to 16mm and φ150mm×150mm standard cylindrical specimens for those asphalt mixtures whose nominal maximum
size is more than 16mm. He also presented the modified formula for specimen with non-standard height (Sun 2003).

The process of uniaxial penetration test is shown in Figure 2. The test equipment is HYD-25 Cooper material testing machine. Its loading rate is 1mm / min and loading waveform is linear. The diameter of penetration indenter is 28.5mm. The size of standard specimen is 100mm * 100mm. The test temperature is 60℃. The coefficient of shear stress is $\tau=0.339$.

Figure 1. Cooper testing machine for asphalt mixture. Figure 2. Diagram of uniaxial penetration test.

In order to verify the rationality of uniaxial penetration test, this paper chose field works of two expressways as SJ and NH in Guangdong Province and on the middle and surface layers of them typical flowing ruts occurred. Uniaxial Penetration Test was carried out to the core samples of asphalt pavement. Average values of shear strength of core samples with wheel track(samples with ruts) and of road shoulder (samples without ruts) were respectively calculated. Results are shown in Table 1.

Table 1. Uniaxial Penetration Test Results of Core Samples of Asphalt Pavement in Two Expressways SJ and NH in Guangdong Province.

| Name of Expressway | Layer (Binder) | Construction Stake Number | Rut Depth under Wheel Track /mm | Shear Strength of Core Sample with Wheel Track /Mpa | Shear Strength of Core Sample of Road Shoulder /Mpa | Rate of Wheel Track Sinkage Compared with Road Shoulder /% |
|--------------------|----------------|---------------------------|---------------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------------------------------|
| SJ                 | Up-layer (Modified by Lake Asphalt) | AK15+650 9 | 0.400 | 0.759 | 47.3 |
|                    |                | AK21+870 20 | 0.463 | 0.945 | 51.0 |
|                    |                | BK17+180 22 | 0.587 | 0.682 | 13.9 |
|                    |                | BK25+330 10 | 0.648 | 0.726 | 10.7 |
|                    | Middle-layer (Modified by Lake Asphalt) | AK15+650 9 | 0.510 | 0.736 | 30.7 |
|                    |                | AK21+870 20 | 0.757 | 0.384 | -97.1 |
|                    |                | BK17+180 22 | 0.791 | 0.810 | 2.3  |
|                    |                | BK25+330 10 | 0.461 | 0.578 | 20.2 |
| NH                 | Up-layer (A level No.70) | K82+980 14 | 0.324 | 0.379 | 14.6 |
|                    |                | K91+400 24 | 0.288 | 0.564 | 49.0 |
|                    |                | K91+430 18 | 0.274 | 0.541 | 49.4 |

173
According to the latest *Code for Highway Asphalt Pavement Design* (Draft), the shear strength of modified asphalt mixture is typically 0.7 ~ 1.1MPa. But in SJ Expressway, Guangdong, the shear strength of middle-layer asphalt mixtures with wheel track is lower than 0.7MPa. For road shoulder, the average value of shear strength of up-layer asphalt mixtures is a little higher while that of middle-layer asphalt mixtures is below the low limit of the range. The rut depth of K109+350, K113+260 and K99+900 in NH expressway gradually increased with the decrease of shear strength of the core samples in the surface layer and the middle layer of pavement and showed a good regularity. Field works verified that uniaxial penetration test could objectively reflect the high temperature stability of asphalt mixtures and the shear strength of asphalt mixture in the surface layer and middle layer should be no less than 0.7 MPa.

### 2. Rotary shear compaction test adopted to evaluate the shear resistance of asphalt mixture

GTM (Gyratory Testing Machine) is invented by engineers of the United States Army Corps in the 1960s in order to solve the design problem of runway for heavy bombers of air force. It maximizes the simulation of the actual effect of cars on the road and design the asphalt mixtures by reasoning based on principle of stress and strain. When asphalt concrete is designed by GTM method, the practical effect of pressure of car on the road is adopted during molding and performance parameters are tested. Meanwhile the shear strength of designed asphalt concrete is greater than the shear stress loaded on it and the loaded strain should be controlled within a proper range. The working principle is shown in Figure 3. In the 1990s, GTM method and the theory have been applied in disease prevention and design of asphalt pavements under increasing vehicle load which causes rutting, bleeding etc. At present, GTM method is adopted to design asphalt mixtures in a few northern provinces of China and success is achieved in field works.
Sg: Shear strength;  A: sectional area of the specimen; h: Height of the specimen; L: Torque of the roller; b: Torque of vertical pressure; N: Vertical pressure on experimental materials; W: Pressure on the roller;  θ : Angle of the test machine; F: Friction force on specimens.

Figure 3. Working principle diagram of GTM.

There are two core indexes in GTM test. One is GSF (Gyratory shear factor), which is the ratio of shear strength stress when asphalt mixtures are compacted to equilibrium state to the shear stress when asphalt mixture is under traffic load. It is used to test whether the shear strength of asphalt mixtures when compacted to equilibrium can reach the needed shear stress of asphalt pavement. The larger GSF is, the higher shear strength and anti-rutting performance are. The other is GSI (Gyrators stability index), which is the ratio of angle of the test machine at the end of the test to the minimum angle during the compaction process, which is the parameter to characterize degree of deformation stability of the specimen under shear force. When the asphalt mixtures are compacted to the equilibrium state, if the angle of the test machine rises and the pressure on the roller decreases, it reflects that the shear strength of the asphalt mixtures is reduced and the deformation is exacerbated, which shows the characteristics of the plastic state (Zhou, 2006).

In order to verify GTM design method and the scientific feature of main control index—shear safety factor (GSF ) which characterizes the high temperature shear resistance of asphalt mixtures, Marshall method and GTM method are adopted respectively in the design of AC-16 and AC-20 asphalt mixtures. At their individual optimal asphalt aggregate ratio, results of uniaxial penetration test to shear strength of asphalt mixture are shown in Table 2. They show that the shear strength of asphalt mixtures designed by GTM method is about twice as high as that of the asphalt mixtures designed by the Marshall method. The improvement of shear strength shows that the mixtures are more stable and can effectively avoid the emergence of rutting disease, which once again verify the advancement of the GTM design method and the rationality of its main control indexes.

Table 2. Results of Shear Strength of Asphalt Mixture Designed by Different Methods.

| Design method | Shear strength/MPa |
|---------------|--------------------|
|               | AC-16 asphalt mixture | AC-20 asphalt mixture |
| Marshall method | 0.65 | 0.58 |
| GTM method     | 0.7  | 1.13 |
|                | 0.8  | 1.27 |
| Vertical pressure/MPa | 0.9  | 1.34 |
|                |      | 1.30 |
3. Verification of evaluation indexes of shear resistance performance of asphalt mixtures based on GTM method

GTM method is relatively independent and its theoretical system is more perfect. Asphalt mixtures designed by traditional GTM design method are more stable with good high temperature stability and are in an ultimate density state. So problems such as water seepage, decline of anti-sliding ability will be avoided, for the designed asphalt mixtures have good durability and don’t need other performance verification. At present, design methods with volume index (such as void ratio) have already taken the dominant position. Therefore, to examine and judge the rationality and superiority of GTM design parameters from different angles is to be further studied by technicians. The two indicators GSF, GSI in GTM design method are calculated based on mechanical reasoning, and their correlation with the stress and strain of the shaped specimen becomes a breakthrough in the study.

Because GSF is the ratio of real-time data in GTM method and specific values of shear strength of asphalt mixtures can’t be gained in the test, uniaxial penetration test is adopted to verify shear strength of asphalt mixtures. Four specimens formed by GTM method were tested by the test at five different asphalt aggregate ratios. The test results will be discussed as follows.

(1) Analysis of correlation between GSI and vertical deformation

Vertical deformation in uniaxial penetration test in Table 3 and GSI values in GTM rotational shear compaction test are both plotted in Figure 4. It is easy to find that the changes of two indexes are quite different. Vertical deformation in the uniaxial penetration test fluctuates strongly, showing no regularity while GSI increases along with asphalt aggregate ratio. So it can be concluded that there is no obvious correlation between both since vertical deformation in the uniaxial penetration test is a single displacement value while GSI is the ratio of the maximum rotation angle to the minimum one in the process of the experiment which is dimensionless. What’s more, test conditions and the calculation methods for both are obviously different.

| Table 3. Test Results of Asphalt Mixture with Different Asphalt-aggregate Ratio in GTM Test and Uniaxial Penetration Test. |
|---|---|---|---|---|
| Asphalt-aggregate Ratio (%) | Test results of uniaxial penetration test | Test results of GTM test |
| | Deformation/mm | Peak pressure/KN | Shear strength/MPa | GSI | GSF |
| 3.5 | 1.25 | 2.65 | 1.41 | 1.00 | 1.52 |
| 3.8 | 4.96 | 2.80 | 1.51 | 1.60 | 1.56 |
| 4.1 | 1.47 | 3.77 | 2.01 | 1.03 | 1.71 |
| 4.4 | 1.90 | 3.89 | 2.07 | 1.07 | 1.73 |
| 4.7 | 2.35 | 3.47 | 1.84 | 1.11 | 1.80 |
(2) Correlation analysis of shear strength and GSF

The shear strength in uniaxial penetration test and GSF values in GTM rotary shear compaction test are plotted in FIG. 5. It is obvious that the regularity of changes of two indexes are basically consistent and both fluctuate along with the asphalt aggregate ratio. In FIG. 6, the correlation diagram of shear strength $\sigma$ and GSF value in GTM gyratory shear compaction test is plotted, which shows there is a good linear correlation between them and the correlation coefficient R reached 0.9597.

Based on the principle of GTM design, GSF is the ratio of the shear strength to the shear stress of specimens. Only if GSF is greater than 1, shear failure of the pavement is ensured to be avoided. When the vertical pressure and other parameters are set, the shear stress which the specimens need to be achieved is also determined. Index GSF is used to test whether shear strength of the material can reach that shear stress. It is sure that the larger shear strength of the material and the more it exceeds the permissible shearing force show the material is with higher safety factor. With increase of dosage of asphalt, asphalt film thickness also increases while the structure of asphalt does not. When the structure of asphalt increases to a certain extent, too much free asphalt will play the role of lubrication under load, which leads to the decrease of shear strength that shows the safety factor of shear failure reduces accordingly.

Based on field works verification of several highways such as SJ, NH in Guangdong Province, when the shear strength of surface and middle layer of asphalt pavement is lower than 0.7MPa in uniaxial penetration test at the temperature of 60°C,
there is a greater risk of rutting in the pavement. In Figure 6, the correlation between GSF and shear strength $\sigma$ in uniaxial penetration test is $\text{GSF} = 0.299 \sigma + 1.093$, which shows when shear strength $\sigma$ is required to be no less than 0.7 MPa, the value of GSF should not be less than 1.3092, which is amazingly consistent with the opinion at home and abroad that GSF value of stable asphalt mixture should generally be not less than 1.3.

It is great to find that there is a good correlation between GSF value in GTM gyratory shearing and compacting test and shear strength in uniaxial penetration test, which explains why asphalt mixtures with good high temperature stability can be designed by GTM test system. The find paves the way of usage of GTM method in asphalt mixture design and provides a sufficient basis for the adaption of Gyratory Testing Machine (GTM) to test the high temperature stability of asphalt mixture from a scientific point of view.

4. CONCLUSIONS
Shear resistance performance of asphalt mixture at high temperature is tested and evaluated by Gyratory Testing Machine (GTM) and uniaxial penetration test. Correlation analysis is carried out to deal with the test results, which are also verified by field works. Therefore the following main conclusions can be drawn.

(1) Results in uniaxial penetration test at the temperature of 60 $^\circ$C can objectively reflect the shear resistance performance of asphalt mixtures at high temperature. For the up-layer asphalt mixture in highways, when its shear strength is less than 0.7 MPa, there is a great risk of rutting in the pavement.

(2) Control indexes of high temperature stability of asphalt mixtures in GTM design method is more reasonable and the shear strength of the designed asphalt mixture in uniaxial penetration test at the temperature of 60 $^\circ$C is mainly more than 1.0MPa, which is twice as high as that of the asphalt mixtures designed by Marshall method.

(3) With the variation of asphalt aggregate ratio, the changing regularity of vertical deformation of asphalt mixture in uniaxial penetration test and GSI in GTM gyratory shear compaction test seems no consistent and there is no obvious correlation between both.

(4) There is a good linear correlation between GSF in GTM rotational shear compaction test and shear strength in uniaxial penetration test at the temperature of 60 $^\circ$C, whose correlation coefficient reaches 0.9597, indicating that GSF based on GTM test can act as the testing indexes of high-temperature shear performance of asphalt mixture. For surface and middle layer of asphalt in highways, the GSF value should not be less than 1.3.

REFERENCES
[1] Amy L. Simpson. Measurement of Rutting in Asphalt Pavements [D]. The University of Texas at Austin, 2001.
[2] Eisenmann J, et al. Influence of wheel load and inflation pressure on the rutting
effect at for pavement-experiment bland theoretical investigations. proceedings, the 6th International Conference on the structural design of asphalt Pavements. Michigan Ann Arbor, 1987.

[3] Fu Zhiyong. Test Methods of High Temperature Performance of Asphalt Mixture [D]. Changsha: Changsha University of Science and Technology, 2005.

[4] Paterson W D O. Road deterioration and maintenance effects: models for planning and management, The Highway Design and Maintenance Standard Series. Published for The World Bank, The John Hopkins University Press, Baltimore, 1987.

[5] Shen Jinan. Road Performance of Asphalt and Asphalt Mixture [M]. Beijing: China Communications Press, 2001:300-305.

[6] Sun Lijun, et al. Theory of Structural Behavior of Asphalt Pavement [M]. Shanghai: Tongji University press, 2003:143-145.

[7] Zhou Weifeng. Research on Design Method of Asphalt Mixture based on GTM [D]. Xi'an: Chang'an University, 2006.