Correlation Analysis between Viscoelastic Mechanical Properties and Volume Indicators of Asphalt Mixture

Lianfang Wang¹, Haotian Li², Zhiqiang Liu³ and Yanli Jiao⁴

¹Senior engineer, Road Structure and Material Technology Research Center of Hebei Province, NO.120 Zhenganglu, Shijiazhuang, 050091; 290285295@qq.com
²Hebei Provincial Communications Planning and Design Institute, NO.120 Zhenganglu, Shijiazhuang, 050091(corresponding author); 329401634@qq.com
³Senior engineer, Road Structure and Material Technology Research Center of Hebei Province, NO.120 Zhenganglu, Shijiazhuang, 050091
⁴Senior engineer, Road Structure and Material Technology Research Center of Hebei Province, NO.120 Zhenganglu, Shijiazhuang, 050091; 27087324@qq.com

ABSTRACT: Dynamic modulus, repeated shearing flow and indirect tension creep compliance are three typical viscoelastic properties of asphalt mixture. Deriving from the correlation between volume indicators of asphalt mixture and viscoelastic mechanical properties is of great significance. 56 common mixtures used in Hebei province were subjected to test dynamic modulus, repeated shearing flow, indirect tension creep compliance. Correlation analysis between viscoelastic properties and volume indicators were conducted under a generalized visual angle. Results show that, voids in mineral aggregate (VMA) is the generalized indicator that affects dynamic modulus yielding a negative correlation; voids filled with asphalt (VFA) is the generalized indicator that affects shearing flow slope yielding a negative correlation; VFA is the generalized indicator that affects creep compliance yielding a negative correlation. A preliminary new design frame was developed taking into account the correlation between volume indicators of asphalt mixture and viscoelastic mechanical properties.

Key words: asphalt mixture; volume indicators; mechanical properties; correlation; generalized visual angle

INTRODUCTION

NCHRP Report 465 (2002) proposed three viscoelastic mechanical properties named dynamic modulus, flow number, and flow time as the key mechanical properties of SUPERPAVE volumetric mixture design method, subsequently adopted in MEPDG (2004). Witczak (2002) confirmed that these three viscoelastic properties above correlate highly to rutting resistance in accelerated loading sections. Christensen (2004) and Roque (2002) reported low temperature indirect tensile creep compliance highly correlates to thermal cracking. Then how to design a mixture possessed a good volume indicators is urgent for industry, and deriving the correlation-ship between volume indicators of asphalt mixture and these viscoelastic mechanical properties is feasible, which was undertaken recently.

It is readily observed that Marshall stability in Marshall test is only a empirical mechanical parameters, not capable of capturing the viscoelastic properties of asphalt mixture. Critically, Marshall stability cannot correlate to field performance (2004, 2013). Summarizing the rutting resistant situations in accelerated loading test sections paved by many types of mixtures with varying volume properties, Pellinen (2004) pointed out that
the VMA and mixture dynamic modulus show a negative correlation, and low void volume dense-graded mixtures, rather than high void volume, exhibit a better field performance. Additionally, Pellinen developed a frame consisting of methods to design a rational mixture which possesses good mechanical properties. Domestic, Li Dechao (2008) investigated dynamic modulus of AC13 mixtures spanned different volume of air voids (VV), pointed VV yield a negative correlation to dynamic modulus. Wei Jincheng (2007) compared dynamic modulus test results of AC-20, AC-25, LSPM-30, FL-13, indicated mineral aggregate interlocking plays a vital role in asphalt mixture stiffness, that could not be quantified actually. Yang Ming (2007) obtained similar conclusions.

Overall, literatures for asphalt mixture mechanical properties of volume indicators were often constrained by single species, such as the type of aggregate, asphalt, mixture gradation rather than a wider sources. Given that one rational mixtures design method should employ sample sources as wide as possible, namely a generalized visual angle, it is beneficial and valuable to investigate correlations between multi-species compositions associated different volume indicators and corresponding viscoelastic mechanical properties, which was the objective of this paper.

56 common mixtures used in Hebei province were subjected to test dynamic modulus, repeated shearing flow and indirect creep compliance, including AC13, ARHM20, AC25, ATB25, SMA. Correlations between mixture volume indicators (referenced as VMA, VFA, VV, asphalt-aggregate ratio) and viscoelastic mechanical properties were developed to seek link between mixture design and likely mechanical properties, to achieve critical volume indicators under a generalized visual angle so that provide reference for improvement of asphalt mixture design method.

**EXPERIMENTAL PREPARATION**

56 common mixtures presented overall were from Pavement Engineering Qualification Testing Laboratory of Hebei, which issued a number of highways mixture design and verification testing reports, aggregate sampled from different suppliers in Hebei, as well the bitumen. Aggregates and bitumen met the requirements of Technical Specifications for Construction of Highway Asphalt Pavements, the results of which were shown in reference (2016). Common mixture gradations used in Hebei are listed on Fig. 1.

![Figure 1. Common Mixture Gradations Used in Hebei.](image)

In accordance with the design information provided in the mixtures design report, testing specimens were fabricated according to the reference (2011). In order to span as large ranges of volume indicators, each mixture fabricated three gradations with three
asphalt-aggregate ratios each. In Hebei, SMA, as well as ARHM20 mixtures are designed by Marshall design method, AC13, AC25, and ATB25 mixtures are designed by GTM method. For SMA and AC13, the PG76-22 SBS modified asphalt was employed, as the rubber modified asphalt for ARHM20, Pen-70 asphalt for AC25 and ATB25. Specimens information are shown in Table 1. Dynamic modulus specimens were 150 mm-tall ×100 mm-diameter, testing temperature was selected as 20°C, load frequency as 10 Hz. Repeated shearing flow test specimens were the same as dynamic modulus, testing temperature was selected as 55°C, deviator stress as 0.7 MPa, confining pressure as 138 KPa. Indirect tensile creep testing specimens were cut from SGC specimens, 40 mm-thickness ×150 mm-diameter, testing temperature was selected as 5°C, 10°C, 15°C, vertical pressure 1400 N, creep time 1000s, the creep compliance under -10°C were calculated from master curve developed by time-temperature superposition principle.

Table 1. Specimens Information.

| Gradation Type | Asphalt-Aggregate Ratio | Replicate Specimens |
|----------------|-------------------------|---------------------|
| Optimum        | Optimum                 | 7                   |
| Coarse         | Optimum - 0.3%          | 7                   |
| Fine           | Optimum + 0.3%          | 7                   |

Note: Of 7 replicate specimens, 4 are subjected to dynamic modulus testing, 2 to repeated shearing flow testing, 1 to indirect tension creep testing.

VV, VFA, VMA, as well as asphalt-aggregate ratio of mixtures versus corresponding dynamic modulus, shearing flow parameters, respectively, indirect tensile creep compliance were plotted, non-linear fittings were conducted to determine correlation coefficient. As defined, the indicator possessed the biggest correlation coefficient captures the impact on corresponding viscoelastic mechanical properties of mixtures under a generalized visual angle.

Volume indicators and dynamic modulus standard deviation (Stdev.) of the mixtures employed are shown in Table 2. A little larger Stdev. are obtained due to the wide sampled sources, and it is the wide sampled sources on which this paper focus to obtain the key indicators captured corresponding mechanical properties under a generalized visual angle.

Table 2. Volume Indicators and Modulus Standard Deviations Information.

| Gradation Type | VV(%) | Asphalt-Aggregate Ratio | Stdev.(MPa) |
|----------------|-------|-------------------------|-------------|
| AC13           | 0.1~7.5 | 4.0~4.9                | 1792        |
| ARHM20         | 0.1~8.9 | 4.2~5.0                | 1998        |
| AC25           | 2.0~10.1 | 3.3~3.9                | 2954        |
| ATB25          | 0.2~5.4 | 3.0~3.6                | 1916        |
| SMA            | 2.5~12.6 | 5.3~6.3                | 1465        |
RESULTS AND DISCUSSIONS

Indicators captured the impact on dynamic modulus

Dynamic modulus testing results of different types mixtures versus corresponding mixture volume indicators were plotted respectively, non-linear fittings were conducted, and correlation coefficients were determined. Only slightly higher correlation coefficient analysis results were presented in Figures 2 and 3. Other results were presented in reference (2016).

Comparing correlation analysis results of VV, VMA, VFA, asphalt-aggregate ratio versus dynamic modulus respectively, following conclusions can be found:

1. VV yields a negative correlation to dynamic modulus, the greater the VV is, the smaller dynamic modulus tend to become; VFA yields a positive correlation to dynamic modulus, the greater the VFA is, the bigger dynamic modulus tend to become; and, VMA yields a negative correlation to dynamic modulus, the greater the VMA is, the smaller dynamic modulus tend to become;

2. Degree of association between the dynamic modulus and VV, VFA, VMA appeared to enhance as the nominal particle size increase.

3. For overall mixtures, correlation coefficient of dynamic modulus with asphalt-aggregate ratio are very poor, the largest is of 0.28, and the rest are of 0.1 or less.

4. Compared with the dense-graded AC13, SMA with a dense skeleton structure yields high correlation coefficient of dynamic modulus with volume indicators. Considering gradation characteristics of AC25, ATB25 mixtures (coarse aggregates are easier to form a skeleton), that the skeleton-type gradation yields more significant correlation between dynamic modulus and volume indicators.

Comparison of various types mixtures correlation coefficient of VV, VFA and VMA with dynamic modulus shows that VFA is the least, VV is the highest, and VMA is medium. Consequently, VMA is recommended as the indicator captured the impact on dynamic modulus under a generalized visual angle, after all VMA contains information of both VFA and VV. Taking into account the practice of engineering, VV can be the candidate indicators.
Indicators captured the impact on repeated shearing flow deformations

Different term characterizations of repeated shearing flow testing were investigated in literatures, on ease, herein selected the slope of accumulative plastic deformations in second phase (referred to as the shearing flow slope b) as a maintained indicator of investigation. The shearing flow slope b of different mixtures versus corresponding mixture volume indicators were plotted respectively, non-linear fittings were conducted, and correlation coefficients were determined. It should be noted that only slightly higher correlation coefficient analysis results were presented in Figures 4. Other results were presented in reference (2016).

The results show that both the correlation coefficient between asphalt film thickness, powder cement ratio and shearing flow slope b are poor, as less than 0.1. Either high or low correlation maybe established between other four indicators and the shearing flow slope b, while correlation of asphalt-aggregate ratio is the worst.

VV, VMA, VFA analysis results show that:

1. Compared with VV, either VFA or VMA is capable of establishing a better relationship with the shearing flow slope b, the highest correlation coefficient is of 0.5 or more.
2. Correlation between SMA mixtures VV and shearing flow slope is poor, which may be attributed to the SMA mixture constitute. Methylcellulose with asphalt mastic form a high resistance to permanent deformation, and shearing flow slope distributes from 0.26 to 0.29 in a narrow range.
3. Correlation between rubber asphalt mixtures VV and shearing flow slope is poor, which may be attributed to different sources of bitumen production process, causing the asphalt-aggregate interface strength different.
4. VFA yields a negative correlation to shearing flow slope, the greater the VFA is, the higher degree of filling the voids, and the lower the risk of high-temperature mixture flow deformation becomes. VMA yields a positive correlation with shearing flow slope, the greater the VMA is, the lower degree of filling the voids, and the higher the risk of high-temperature mixture flow deformation becomes.

Generally, VFA, VMA are capable of establishing link between mix design and resistance to permanent deformation. VFA is recommended to capture the impact on mixture resistant to permanent deformation. But VFA must be limited to a controllable range, namely bitumen content cannot increase indefinitely, due to the fact that unlimited increase will result in a lower VV, asphalt mix will play a role as lubrication, which faces flowing risk.

Indicators captured the impact on indirect tension creep compliance

Indirect tensile creep compliance under low temperature highly correlates to thermal cracking. The creep compliance under -10℃ was determined to establish correlative relationship, only slightly higher correlation coefficient are shown in Figure 5. Other results of the analysis were presented in reference (2016).

Data shows that, VFA has an obvious effect on the creep compliance. Correlation coefficient is of 0.5 or more. Creep compliance decreases as VFA increases. Reasons may be, as higher VFA, the more gap is filled, the greater stiffness is, then more risk of cracking. On the contrary, if the VFA is low, the remaining gaps unfilled would dissipate positive temperature shrinkage caused by temperature stress, also slack off more temperature shrinkage deformation without cracking.
In contrast, the creep compliance cannot establish correlation with VMA, correlation coefficient is of 0.2 only. Correlation between the creep compliance and VV still reach about 0.4, as VV increases. Creep compliance increases which confirms that the effective gap helps to dissipate temperature shrinkage stress. Creep compliance with the aggregate ratio is not capable of establishing any correlation.

In the mixture of pavement surface layer, the use of SBS modified asphalt, high asphalt-aggregate ratio, contributions to low bending strain, high temperature properties of the specimen should be more favorable, but in fact relatively high creep compliance is not necessarily high in a high asphalt-aggregate ratio. It is believed that VFA is able to capture the impact on low temperature creep compliance.

Figure 4. VFA vs. Shearing Flow Slope b.

Figure 5. Creep Compliance vs. VFA.
A preliminary new mix design frame

Given that VMA captures the impact on dynamic modulus under a generalized visual angle yields a negative correlation. Repeated shearing flow test simulates the mechanism of rutting in suit, VFA captures the impact on the shearing flow slope b determined from second phase of accumulative plastic deformations, yields a negative correlation, while shearing flow slope b itself yields a positive correlation with rutting in suit, in turn VFA yields a negative correlation with rutting in suit can be concluded; Meanwhile, indirect tension creep compliance simulates the mechanism of thermal cracks in suit, VFA captures the impact on it, yields a negative correlation, while indirect tension creep compliance itself yields a negative correlation with thermal cracking, in turn VFA yields a negative correlation with thermal cracking in suit can be concluded.

Dynamic Modulus mainly represents the dynamic stress-strain response of asphalt mixture pavement, while shearing flow slope represents the rutting, low-temperature tensile creep compliance represents the thermal cracking in conjunction. These three parameters form a new design frame taking account for the correlation between volume indicators of asphalt mixture and viscoelastic mechanical properties, as shown in Figure 6.

![Figure 6. A Preliminary New Mix Design Frame.](image)

Taking the volume indicators as the maintained design parameters, both shearing flow slope and indirect tensile creep compliance are related to VFA. These two relationship curves form an intersection (in Figure 6 shown as a Star).

In pavement design procedure, it’s anticipated that pavement materials possess a high resistance to rutting, the corresponding shearing flow slope should be greater than a certain value corresponds VFA be limited to a rational range. In balance, pavement materials should possess high resistance to thermal cracking, the corresponding creep compliance should be lower than a certain value corresponds VFA to be greater than a rational range. The dialectical relationship is concentrated in Figure 6, which requires VFA in a specific range, the upper limit of which is controlled by the shearing flow rate, while the lower limit the indirect tensile creep compliance is. When VFA is set within the range, mix design will have an acceptable high temperature resistance to permanent deformation capability and resistance to low temperature thermal cracking.

In addition, design mixture anticipate dynamic modulus to be within a certain range, in order to have reasonable response characteristics of pavement under vehicle load and
temperature effects. According to dynamic modulus and VMA relationship, VMA should be limited within a corresponding range during the mixtures design to obtain an acceptable dynamic response.

CONCLUSIONS

(1) Both VMA and VV are highly correlated to dynamic modulus, VMA integrated contains VV and VFA double, captures the impact on dynamic modulus under a generalized visual angle, yields a negative correlation.

(2) VFA is highly correlated to shearing flow slope, captures the impact on repeated loading shearing flow under a generalized visual angle, yields a negative correlation.

(3) VFA is highly correlated to indirect tensile creep compliance, captures the impact on thermal cracking under a generalized visual angle, yields a negative correlation.

(4) Considering the correlation between volume indicators of asphalt mixture and viscoelastic mechanical properties, a preliminary index frame has been developed to serve the asphalt mixture design system.

REFERENCES

Witczak, M.W., Kaloush, K., Pellinen, T., et al. (2002). "Simple Performance Test for Superpave Mix Design". NCHRP Report 465, National Cooperative Highway Research Program, Washington, D.C.

ARA, Inc., ERES Consultants Division (2004). "Guide for Mechanistic–Empirical Design of New and Rehabilitated Pavement Structures". Ilians: NCHRP 1-37A Final Report.

D. W. Christensen, R. F. Bonaquist (2004). "Evaluation of Indirect Tensile Test(IDT) Procedures for Low-Temperature Performance of Hot Mix Asphalt". NCHRP Report 530, National Cooperative Highway Research Program, Washington, D.C.

Reynaldo Roque, Bjorn Birgisson, etc. (2002). "Implementation of Sharp Indirect Tension Tester to Mitigate Cracking in Asphalt Pavements and Overlays". University of Florida.

Yang Yang, Li Yuxin, Zhang Zhengqi, Cao Dongwei (2013). "Evaluation on Asphalt SPT Simple Performance Test and Parameters". Foreign Highway, 2013(2): 262-267.

T. K. Pellinen (2004). "Conceptual Performance Criteria for Asphalt Mixtures". Journal of the Association of Asphalt Paving Technologists, 2004(73): 337-366.

Li Dechao (2008). "Test and Study on Dynamic Modulus of Asphalt Mixture". Highway, 2008(1): 134-140.

Wei Jincheng, Cui Shiping, Hu Jiabo (2007). "Research on Dynamic Modulus of Asphalt Mixtures". Journal Of Building Materials, 2007(12): 657–661.

Yang Ming (2007). "Research on the Dynamic Modulus of Asphalt Mixture". Changsha University of Science & Technology Master Thesis.

Hebei Provincial Communications Planning and Design Institute (2016). "Research on Asphalt Pavement Structure Design Parameters and Performance Evaluation of Asphalt Mixture Based on AMPT". Hebei Province Department of Transportation.

JTG E20-2011 T (2011). "Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering". Beijing: China Communications Press.