Construction and Building Materials 161 (2018) 124–131

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of bell-shaped loading and haversine loading on the dynamic modulus and resilient modulus of asphalt mixtures

Li Ruan [a,b,c], Rong Luo [a,c], Xiaodi Hu [b,*], Pan Pan [b]

[a] School of Transportation, Wuhan University of Technology, 1178 Heping Avenue, Wuhan, Hubei 430063, China
[b] School of Resource and Civil Engineering, Wuhan Institute of Technology, 693 Xiongchu Avenue, Wuhan, Hubei 430073, China
[c] Hubei Highway Engineering Research Center, 1178 Heping Avenue, Wuhan, Hubei 430063, China

HIGHLIGHTS

- Bell-shaped loading wave was developed to measure the dynamic modulus and resilient modulus of asphalt mixture.
- The dynamic modulus and resilient modulus master curves were generated by generalized logistic sigmoidal function.
- The effect of bell-shaped loading on the dynamic modulus and resilient modulus were investigated.
- Bell-shaped loading was recommended to measure the dynamic modulus and resilient modulus.

ARTICLE INFO

Article history:
Received 23 May 2017
Received in revised form 1 October 2017
Accepted 10 November 2017

Keywords:
Asphalt mixture
Dynamic modulus
Resilient modulus
Bell-shaped loading
Haversine loading

ABSTRACT

The vertical compressive stress pulse distributions at various asphalt pavement depths can be represented as square loading, haversine loading and bell-shaped loading. This study aims in comparing the effects of bell-shaped loading and haversine loading on the dynamic modulus and resilient modulus of asphalt mixtures. Dynamic modulus test for AC-13, AC-16, AC-20, AC-25 and SUP-25 asphalt mixtures were conducted by applying haversine loading and bell-shaped loading. On the other hand, the resilient modulus test for these asphalt mixtures were measured by applying square loading, haversine loading and bell-shaped loading on specimens. The results indicated that the dynamic modulus under haversine loading were greater than those under bell-shaped loading. The resilient modulus under bell-shaped loading was the greatest, followed by that under haversine loading and square loading, respectively. It also revealed that the effects of bell-shaped loading on the dynamic modulus and resilient modulus of asphalt mixture increased with increasing nominal maximum aggregate size. Finally, linear relations were proposed for dynamic modulus under different loading waveforms, and as well as resilient modulus.

1. Introduction

The dynamic modulus and resilient modulus are critical parameters for analyzing the mechanical behavior of asphalt pavement. The analytic results can be used for calculating reasonable pavement thickness using calculation functions [1,2] and for evaluating the long-term performance characteristics of asphalt pavement, such as fatigue life, permanent deformation and thermal cracking of asphalt pavement [3–5].

During the dynamic modulus and resilient modulus tests, haversine loading was applied on asphalt mixture specimens at various frequencies and temperatures. Test results illustrated that the values of these parameters decreased with increasing temperature. On the other hand, they exhibited an increasing trend as the loading frequency increased [6,7]. In addition, loading waveform is another parameter that can influence the dynamic modulus and resilient modulus of asphalt mixture [8].

Loading waveforms can represent the vertical compressive stress pulse created by vehicles travelling on asphalt pavement [9]. Several researchers proposed multifarious relations and methods to determine loading waveform distributions at various asphalt pavement depths [10–12]. They concluded that square loading has better representation of the vertical compressive stress distribution in the top 2.5 cm asphalt pavement [13]. At intermediate depths, the vertical compressive stress pulse is similar to haversine loading wave [14]. Shafabakhsh et al. compared resilient modulus under haversine loading and square loading. The results

* Corresponding author.
E-mail address: huxiaodi@wit.edu.cn (X. Hu).

https://doi.org/10.1016/j.conbuildmat.2017.11.038
0950-0618/

revealed that resilient modulus under haversine loading were greater than that under square loading at the same stress level. Moreover, the value difference of resilient modulus between haversine loading and square loading become significant while the test temperature increased [15].

However, when the depth of asphalt pavement was higher than 10 cm, square loading and haversine loading were not feasible to simulate the vertical compressive stress pulse [14]. Loulizi investigated the vertical compressive stress pulse in Virginia smart road. The field test results revealed that bell-shaped loading wave was a good representation of the vertical compressive stress pulse at the bottom layer of asphalt pavement [16]. In order to incorporate asphalt mixture dynamic modulus and resilient modulus at the depths higher than 10 cm, the effect of bell-shaped loading should be investigated. Furthermore, the dynamic modulus and resilient modulus of asphalt mixture are also influenced by the gradation of asphalt mixture [17,18]. Therefore, asphalt mixture gradation should be taken into account for investigating the effect of bell-shaped loading on dynamic modulus and resilient modulus.

The aim of this study is to compare the effect of bell-shaped loading and haversine loading on dynamic modulus and resilient modulus of asphalt mixture. For this purpose, five types of asphalt mixtures (AC-13, AC-16, AC-20, AC-25 and SUP-25) were employed in this research. Based on experimental results, the dynamic modulus and resilient modulus master curves were generated for these asphalt mixtures under each loading waveform. The effect of bell-shaped loading on dynamic modulus and resilient modulus of the asphalt mixtures was compared with the effect of haversine loading. Moreover, some linear relations were introduced for the results of dynamic modulus and resilient modulus under different loading waveforms, respectively.

2. Materials and methods

2.1. Materials and mixture design

The softening point, ductility and penetration values for the AH-70 asphalt binder were 48.6 °C, 147 cm (5 cm/min, 15 °C) and 66 (deci-millimetre, 25 °C, 100 g, 5 s), respectively. Crushed limestone and limestone filler obtained from Xiaogan City, Hubei Province, China. The physical properties of the aggregates are presented in Table 1. Marshall method was adopted to design AC-13, AC-16, AC-20 and AC-25 asphalt mixtures while Superpave method was use to design SUP-25 asphalt mixture in this research. The aggregate gradation curves of all the asphalt mixture are presented in Fig. 1. The optimum asphalt contents (OAC) of AC-13, AC-16, AC-20, AC-25 and SUP-25 asphalt mixtures were 4.9%, 4.4%, 4.0%, 3.8% and 3.7% by weight of asphalt mixture, respectively, which was determined by mechanical and volumetric properties (e.g. air void, voids in mineral aggregate, voids filled with asphalt).

2.2. Specimen preparation

Three replicates of AC-13, AC-16, AC-20, AC-25 and SUP-25 asphalt mixtures were prepared for dynamic modulus test and resilient modulus test under each loading waveform. The cylindrical specimens were compacted by Superpave gyratory compactor (SGC). The specimens were 170 mm in height and 150 mm in diameter. Then, the specimen was cored and cut into a specimen with a height of 150 mm and a diameter of 100 mm. The target air voids for the test specimens were 7 ± 0.5%.

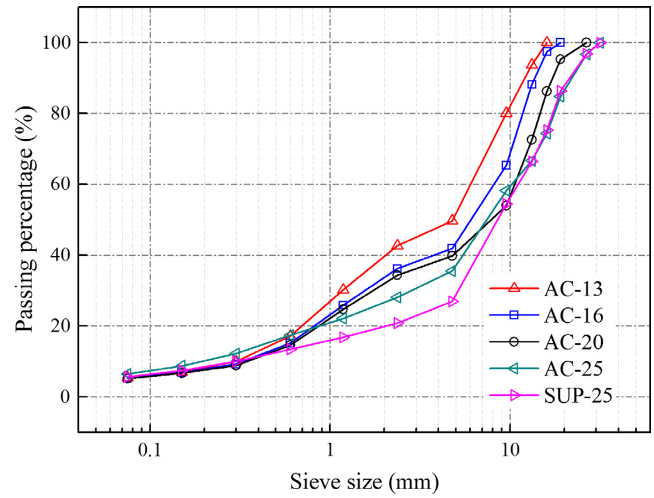

Fig. 1. Gradation curves of aggregates.

2.3. Bell-shaped loading data file developed on universal testing machine (UTM)

There are numerous extant loading wave data files in the UTM, which can be directly invoked by the software on it, such as universal testing software 019 (UTS 019). However, the bell-shaped loading wave data file was not in the range of those data files. Therefore, bell-shaped loading wave data file was needed to be developed on the UTM. The requirement for loading wave data file on UTM is that the file contains 512 data points, which can express a whole period of loading wave. The value of first, maximum and last data points must be 0, 65,535 and 0, respectively [19]. The process for generating the bell-shaped loading wave data file was as follows:

(i) The maximum value of bell-shaped loading wave function is obtained from Eq. (1) [16].

$$\text{Bell-shaped loading wave equation}: y = e^{-t^2/s^2} \tag{1}$$

where t is the time (s) and s is the parameter of bell-shaped loading wave equation, which can be expressed by Eq. (2) [16]. The duration of bell-shaped loading wave is shown in Eq. (3) [16].

$$s = 0.633\,v^{-1.0439} \tag{2}$$

$$d = 2.558\,v^{-0.9032} \tag{3}$$

where v is the truck speed (km/h). The truck speed was selected as 72 km/h according to the field test conducted on Virginia smart road [16].

(ii) According to Eqs. (1)–(3), y values are obtained for various values of t from $-d/2$ to $d/2$ at increments of $d/511$.

(iii) The values of 512 data points are multiplied by the result of 65, 535/max. Then, these data are saved in FWF format and placed in "Shapes" folder. Consequently, UTS019 can invoke the bell-shaped loading wave data file.

2.4. Loading waveforms

Haversine loading wave, square loading wave and the developed bell-shaped loading wave were used in this research. The applied peak stress was 150–1700 kPa for lower temperatures (−10, 4.4 and 21.1 °C) and 15–200 kPa for higher temperatures (37.8 and 54.4 °C). The shapes of the three types of loading waveforms are presented in Fig. 2. The areas under the three types of curves were not equal. As shown in Fig. 2, the area under the square loading wave was the largest, followed by the area under the haversine loading wave, and the area under the bell-shaped loading wave.

Table 1
Physical properties of the aggregates.

Fraction	Standard	Specific gravity (g/cm^3)		Water absorption (%)
		Apparent	Bulk	
Coarse aggregate (>2.36 mm)	ASTM-C127	2.673	2.590	1.2
Fine aggregate (0.075–2.36 mm)	ASTM-C128	2.676	2.573	1.5
Filler (<0.075 mm)	ASTM-D854	–	2.678	–