Construction and Building Materials 171 (2018) 13–21

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental analysis of skeleton strength of porous asphalt mixtures

Xiaowei Wang [a], Xingyu Gu [a,b,*], Jiwang Jiang [a], Hanyu Deng [a]

[a] School of Transportation, Southeast University, Nanjing, Jiangsu Province 210096, China
[b] College of Engineering, Tibet University, Lasa, Tibet 850000, China

HIGHLIGHTS

- A skeleton penetration test was developed to evaluate the skeleton strength of porous asphalt mixtures.
- Gradation of porous asphalt mixture was optimized and recommended.
- The rutting resistance of porous asphalt mixture can be predicted by the skeleton strength test.

ARTICLE INFO

Article history:
Received 22 December 2017
Received in revised form 13 March 2018
Accepted 15 March 2018

Keywords:
Porous asphalt mixture
Skeleton strength
Rutting resistance
Skeleton penetration test
Breakdown test

ABSTRACT

The internal structure is critical to the functionality and rutting resistance of porous asphalt (PA) mixture. The objective of this paper is to develop a new test (skeleton penetration test, SPT) to directly evaluate the skeleton strength and optimize the gradation of PA mixture. The optimized diameter (50 mm) of loading head and penetration rate (2.25 mm/min) were determined for SPT to obtain a reliable skeleton strength. The influence of percent passing of 9.5 mm (P9.5) (40%, 50%, 60%, 70%, and 80%), percent passing of 4.75 mm (P4.75) (10%, 20%, and 30%), and percent passing of 2.36 mm (P2.36) (5%, 15%, and 25%) were evaluated by the SPT and breakdown test. The porosity and durability of the optimized gradation were evaluated by the volumetric determination test and Cantabro loss test, and the correlation of skeleton strength to the flow number obtained from dynamic creep test was also evaluated. Test results show that skeleton strength decreases with the increment of P2.36. P4.75 has negligible influence on the skeleton strength, and P9.5 mm has the largest impact on the skeleton strength. Based on the results, 40% and 80% are recommended as the lower limit and upper limit of P9.5. 10% and 30% are recommended as the lower and upper limit of P4.75, and 25% is recommended as the upper limit of P2.36 for PA mixture. Finally, it is observed that the optimized gradation recommended by the SPT also meets the requirements of porosity and durability of PA mixture, and skeleton strength correlates well to the rutting resistance. Therefore, SPT has a potential to improve the mixture design of PA mixture.

1. Introduction

Porous asphalt (PA) mixture contains a high percentage of air void (AV) and a high proportion of coarse aggregate, which has the advantages of reducing hydroplaning and spray, improving pavement friction, and reducing runoff [1]. These advantages are derived from the open graded skeleton structure of PA mixture. PA mixture is also termed as open graded friction course (OGFC) and permeable friction course (PFC) in the United States. The high proportion of coarse aggregates in the PA mixture provides the capability of bearing wheel loads and functionality of penetrating water. However, PA mixture has a lower rutting resistance than dense graded mixtures due to the higher AV and a less aggregate contact area [2]. In the United States and Europe, OGFC and/or PFC are predominantly used as non-structural surfacing layers and do not usually exhibit permanent deformation failures because they are placed in relatively thin layers (19–50 mm) [2,3]. However, the overloading phenomenon is serious in China and the air temperature generally above 35 °C in the hot summer. PA mixture in the field exhibited a lower rutting resistance than traditional dense graded asphalt mixtures based on field rutting measurements [4,5]. For this reason, it is important to evaluate the rutting resistance of PA mixture. Since the stiffness and cohesion of asphalt binder significantly decreases with the increasing temperature, the rutting resistance of mixture mainly depends on the aggregate skeleton strength. Therefore, the skeleton strength is critical to the high-temperature performance of asphalt mixtures [6,7]. Well-graded aggregates generally presents better rutting resistance and mechanical performance [6]. Therefore, it is

---

* Corresponding author at: 2 Sipailou Road, Nanjing 210096, China.
E-mail address: guxingyu1976@163.com (X. Gu).

https://doi.org/10.1016/j.conbuildmat.2018.03.116

essential to optimize the internal structure to improve the performance of PA mixture.

Skeleton strength is an important performance index for asphalt mixture correlating with the internal structure, and is proved to be related with the rutting resistance of mixtures [8]. Asphalt Pavement Analyzer (APA), Marshall Stability test, Wheel Tracking Test, Hamburg Wheel Tracking Tester (HWTT) were used to evaluate the rutting resistance of PA mixture [1,2,9,10]. The rutting resistance of asphalt mixture was influenced by many factors, such as skeleton strength, binder type, aging level, test temperature, AV, and et al. [11]. In order to compare and quantitatively describe the skeleton strength based on the rutting resistance, the other factors of binder type, aging level, test temperature, and AV should be invariable. Under that condition, higher rutting resistance implies a higher skeleton strength. However, factors are difficult to keep the same between different tests. So, it is hard to quantitatively describe the skeleton strength based on the rutting resistance property of asphalt mixture. With the development of imaging analysis, two-dimensional and three-dimensional imaging analyses were utilized to characterize the internal structure and rutting resistance of asphalt mixtures [12,13]. The internal structure and stone-on-stone contact condition of PFC was evaluated by the X-ray computed tomography (X-ray CT) using the indices of number of contact points and number of particles [14]. It should be noted that imaging processing were conducted based on the images of mixtures without being subjected to loading, and skeleton strength cannot be obtained from the images directly. And, it is hard to study the internal structure changing process when mixtures are subjected to loading. California Bearing Ratio (CBR) test was widely used to evaluate the bearing capacity for unbound granular materials. CBR is defined as the ratio of the unit load required to penetrate 2.5 mm of the test material and the unit load required to penetrate a standard material of well-graded crushed stone [15]. However, the penetration depth is too small to fully evaluate the skeleton strength. Discrete element method (DEM) has been explored to simulate the mechanical behavior of unbound aggregate materials under external loads. A realistic unbound aggregate model was developed by DEM to calculate the internal contact force in the specimen, and further to evaluate the influences of aggregate shape and size on the skeleton shear strength [7]. It was found that the irregular shape of aggregate is hard to be simulated properly. It can be seen that there is no standard method to evaluate and quantitatively describe the skeleton strength of asphalt mixtures currently. PA mixture consists of more than 80% coarse aggregates and contains a coarse aggregate skeleton with stone-on-stone contact. The structural performance of PA mixture mainly depends on the skeleton strength of coarse aggregates skeleton. Therefore, it is of great importance to develop a new test to evaluate the skeleton strength of asphalt mixtures.

In addition, an investigation was conducted to collect the gradations of PA mixtures used in different countries and research institutes. The representative gradations of PA mixtures with a nominal maximum aggregate size (NMAS) of 13.2 mm used in different countries and institutes were summarized in Table 1. Significant differences were found in different gradations. Therefore, it is necessary to evaluate the influence of different gradations on the skeleton strength and make a reasonable recommendation on the design of PA mixture gradation.

2. Objectives and scope

The primary objective of this study is to develop a Skeleton penetration test (SPT) to directly evaluate the skeleton strength and optimize the internal structure of PA mixture. The diameter of loading head and penetration rate were optimized to obtain a reliable skeleton strength. Ten gradations were evaluated to investigate the influence of aggregate size of 9.5 mm, 4.75 mm, and 2.36 mm on the skeleton strength. Based on the skeleton strength, the optimized gradation of PA mixtures was recommended. The optimized gradation was also validated by the volumetric determination test and Cantabro loss test, and the correlation of SPT to the rutting resistance was evaluated.

3. Materials and mixture design

Gradations used in different countries and research institutes were investigated and summarized in Table 1. Significant difference can be found in the percent passing of 9.5 mm (P9.5), percent passing of 4.75 mm (P4.75 mm), and percent passing of 2.36 mm (P2.36) among the different gradations. Other sizes have no significant difference. Aggregate fraction of passing 4.75 mm and retained on 2.36 mm (P4.75-R2.36) has been confirmed as part of coarse aggregate fraction forming the aggregate skeleton with stone-on-stone contact [22]. The breaking sieve size is 2.36 mm and the fine aggregate (smaller than 2.36 mm) has not been included in the analysis of stone-on-stone contact [14,22]. Therefore, only aggregate sizes of 9.5 mm, 4.75 mm, and 2.36 mm were investigated in this paper. Ten gradations were designed in Table 2 and cover the ranges of P9.5, P4.75, and P2.36 used in different countries. Basalt was used for PA mixtures with a NMAS of 13.2 mm (PA-13), and aggregates were sieved and separated into five groups of 13.2–16 mm, 9.5–13.2 mm, 4.75–9.5 mm, 2.36–4.75 mm, and 0–2.36 mm. Five P9.5 levels (40%, 50%, 60%, 70%, and 80%), three P4.75 levels (10%, 20%, and 30%), and three P2.36 mm levels (5%, 15%, and 25%) were investigated.

4. Skeleton penetration test

4.1. Test procedure

A total of 3000 g aggregate blend was prepared for each specimen based on the design gradation. The test mold is a rigid metal cylinder with an inside diameter of 150 mm and height of 128 mm. The blend was equally divided into three parts and placed into the mold one by one, with each layer compacted by 25 blows. After

Table 1
Gradations of PA mixture used in different countries and research institutes (% passing) [16–21].

Sieve size (mm)	China	Federal Highway Administration of US	Texas of US	Georgia of US	Nebraska of US	New York of US	Japan	Spain
16	100	100	100	100	100	100	100	100
13.2	90–100	–	–	–	–	–	90–100	–
12.5	–	85–100	80–100	80–100	95–100	95–100	–	70–100
9.5	60–80	55–75	35–60	35–60	40–80	40–56	–	50–80
4.75	12–30	10–25	1–20	10–25	15–35	20–30	11–35	15–30
2.36	10–22	5–10	1–10	5–10	5–12	6–14	10–20	10–22
1.18	6–18	–	–	–		4–12	–	–
0.075	2–6	2–4	1–4	1–4	0–3	2–5	3–7	3–6