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# Antifreeze asphalt mixtures design and antifreeze performances prediction based on the phase equilibrium of natural solution

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ABSTRACT

Based on the theoretical analysis and experimental study, this paper summarized and compared the frequently-used antifreeze asphalt mixtures (AFACs) design methods, i.e. mass displacement, volume displacement, and combined optimum design method. The result reveals that the combined optimum design method for AFACs is the optimal method, theoretically. Optimal asphalt content of mixtures designed by volume displacement method should be determined by additional experiments. Meanwhile, the mass displacement method is not suggested for antifreeze mixtures design. The conclusions of this research are also beneficial to asphalt mixtures replaced with binders, aggregates, fillers, or fibers. As well, engineering performances, e.g., cracking resistance at low temperature, rutting resistance at high temperature and moisture susceptibility, are measured. Additionally, a new prediction model for antifreeze performances is developed based on the phase equilibrium of liquid solution. The comparison showed a linear relationship between the present model and the previous model. The new model is supposed to match with the actual working conditions.



## 1. Introduction

Nowadays, with the economic development of the society the requirements of the public transportation system become even higher. A very important issue in recent transportation concerns is to keep the road safe for public users. The cold climates, e.g., cold winter, high attitude regions, high latitude regions, are absolutely bringing more risks for passengers and vehicles. Hence, lots of snow and ice control techniques were developed to provide a high level of service (LOS) in cold climates, associated with materials or products or chemicals, machines, environments, strategies, operations (Blackburn, 2004; Fay and Shi, 2012; Kinosita and Akitaya, 1970). It is believed that to prevent the road surface-ice bond forming is a promising solution in cold winters, where un-frozen solution layer is performed, as such, the adhesion between ice and pavement surface was believed to be reduced resulting in easily de-iced by chemicals or/or removed by machines (Dan et al., 2014; Giuliani et al., 2012; Liu et al., 2014b; Tan et al., 2013), as well as the micro-structure of pavement surface will not be damaged due to the bond between ice and pavement surface.

Antifreeze asphalt concrete (AFAC) is a special asphalt mixture containing antifreeze filler which was initially invented in Europe (Dubois, 1973) and has been widely used in Japan, USA and China (Liu et al., 2014b; NYDOT, 2003; Wang et al., 2010). To pavement materials, especially asphalt mixtures, the initial composition mainly determines the engineering performances, meanwhile the mixtures design method significantly impacts the material composition even the material-structure of asphalt mixtures (i.e. gradation). Actually, there are a lot of practices related to design methods of asphalt mixtures reported in the literature (Roberts et al., 2002). For example, New York State Department of Transportation (NYDOT) estimated the AFACs based on Surpave HMA pavement (NYDOT, 2003). The data from NYDOT showed that the antifreeze asphalt pavement dramatically improves the level of service (LOS) in winters because the ice or snow related accidents were reduced by 50% in the test section. California Pavement Preservation Center (CPPC) once evaluated the application of AFAC using Hveem method (M. Stroup-Gardiner, 2008). However, as reported, it was very difficult for researchers to determine the optimal asphalt content (OAC). They also noted that those mixture design strategies, e.g., Superpave and Gyratory methods, were not suggested for the antifreeze asphalt concretes (AFACs), except the Marshall method. In practices in China, volume displacement based on Marshall test is the most used technique (Liu et al., 2014a, 2014b), in which the mineral filler was replaced by the antifreeze filler with the iso-volume to achieve the structure unchanged AFACs. Theoretically, this treatment in engineering application should be acceptable. However, lots of practices reported that the engineering

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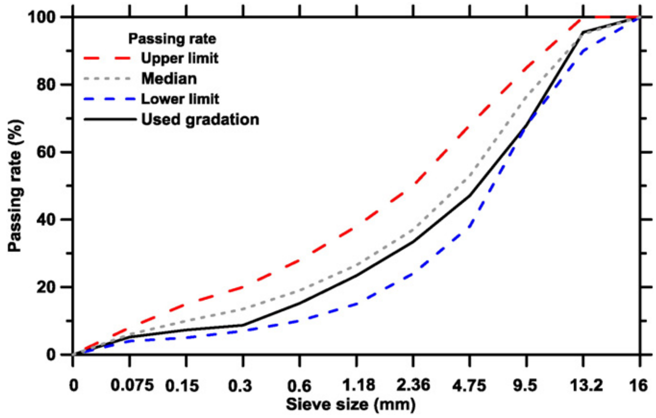


**Fig. 1.** Used asphalt mixture gradation of AC-13. It noted that the AC-13 mixture is a type of asphalt mixture used in China, whose maximum particle size is 16 mm, with a gradation determined by Marshall method.

performance of asphalt mixtures designed with volume displacement method is not as perfect as desired (Chen, 2013; Liu et al., 2014a; Zhang et al., 2010), where the optimal asphalt content (OAC) of the antifreeze asphalt mixture should be reduced. It was believed that this problem was caused by the differences in the density and gradation between mineral fillers and antifreeze fillers (Liu et al., 2014a, 2014b). The design method of asphalt mixture/concrete affects the engineering performance, as such, the properties of AFACs should link with the design technique. Up to now, few reports however are published to evaluate the mixture design method of antifreeze asphalt concretes (AFACs).

Antifreeze performances are the most prominent characteristic of AFACs, which can evaluate the serviceability of AFAC in winter events. There are two approaches to evaluate the antifreeze performance according to current literatures (Li and Wang, 2012; Liu et al., 2015; Luo and Yang, 2015; Tan et al., 2013), in which the qualitative direction in laboratory assessment is believed to be promising and desirable, as such engineers or researchers can predict the service performance of existing mixtures or determine the mixtures composition according to their current climates, e.g. the antifreeze performances can be predicted in laboratory based on the colligative property of dilute solution (Liu et al., 2014b; Wang et al., 2010). This prediction model was developed based on the assumption that the solution on road/pavement surface in service is an ideal dilute solution because the approximate formula of colligative property just works well at low solute concentrations. Actually, the concentration of the solution on the pavement of AFAC does absolutely beyond this definition. It means that the assumption of in the previous literature is not comprehensive or incorrect. Thus, this study aims to develop a novel prediction model matching with the real situation in winter road maintenance (WRM) operation.

This paper reports a systematic study of mixture design method for antifreeze asphalt concretes (AFACs) via Marshall apparatus. Engineering performance of AFACs, containing air void, Marshall stability, flow value, cracking resistance at low temperature, rutting resistance at high temperature, and moisture susceptibility was assessed. As well, based on the phase equilibrium in real situations, a new predicting model was developed matching with the practical condition.

**Table 2**
Steps for density displacement of the case study.

| Items | Stones | Filler A | Filler B | Total (stones + fillers) | Asphalt |
|---|---|---|---|---|---|
| Original (% by volume) | 89.7 | 10.3 | 0 | 100 | 14.18 |
| After replacement (% by volume) | 89.7 | 5.15 | 5.15 | 100 | 14.18 |
| Density(g/cm$^3$) | 2.92 | 2.83 | 2.17 | – | 1.026 |
| Density × volume | 261.97 | 14.55 | 11.16 | 287.68 | 14.55 |
| After replacement (% by mass) | 91.06 | 5.06 | 3.88 | 100 | 5.06 |

The comparison and summary of design methods in this study will be beneficial to the AFAC application with which better AFACs can be achieved. The developed antifreeze performance prediction model is believed to match the practical situations, as such AFACs can be designed to fit the expected climates or the service conditions (i.e. minimum working temperatures or the longest antifreeze time etc.) that can be determined associated for the existing mixtures. It should be noted that the summarized asphalt mixture design methods in this study are not only appropriate for antifreeze asphalt mixtures (AFACs), but also useful for those whose original component will be replaced by new compositions, i.e. bitumen binders, aggregates, fillers, and reinforcing fibers.

## 2. Experimental materials and methods

### *2.1. Raw materials*

Commercial styrene-butadiene-styrene (SBS) modified asphalt produced by Xi'an Guolin SK Asphalt Company Co., Ltd.(Xi'an China), with penetration of 7.1 mm (25 °C, 100 g, 5 s), ductility of 37.6 cm (5 °C, 5 cm/min), softening point of 89.5 °C, was used as the binder in this study. Fine aggregate (specific gravity = 2.709 g/cm$^3$) and coarse aggregate (specific gravity = 2.904–2.945 g/cm$^3$) were produced with basalt stones of Qinling Mountains in northwest China. The used mineral filler (specific gravity = 2.83 g/cm$^3$) was prepared with limestone. In this study, the specific gravity of aggregates, fillers were measured following ASTM D7172-14. Antifreeze filler with a specific gravity of 2.17 g/cm$^3$ (IceBane™, Xi'an HuaBo Traffic Technology Co., Ltd., Shaanxi China) was adopted to replace the mineral filler in asphalt mixtures while the desired replacement ratio is 33.33%, 66.67%, and 100% of mineral fillers (2, 4, 6 wt.% of total aggregates). IceBane™ is a commercial chloride-based material to replace partial mineral fillers, which could self-release de-icing agent in cold winter events (e.g. snow, ice situation). The main components of IceBane™ are CaO, $Al_2O_3$, $Si_2O$, $Na_2O$, $K_2O$, $Fe_2O_3$, etc.

### *2.2. Original asphalt mixture*

A general asphalt mixture, AC-13, was adopted as the original or control sample in this research, which is mainly used as the surface layer of asphalt pavement in China. The aggregates gradation is detailed in Fig. 1. The optimal asphalt content (OAC) used in the original mixture was 4.90% by total aggregates mass (stones and fillers) and the mineral filler usage was 6% by total aggregates mass, determined by Marshall

**Table 1**
Information of the asphalt mixture for the case study.

| Items | Stones | Filler A | Filler B | Total (stones + fillers) | Asphalt |
|---|---|---|---|---|---|
| Original content (% by mass) | 90 | 10 | 0 | 100 | 5 |
| Original content (% by volume) | 89.7 | 10.3 | 0 | 100 | 14.18 |
| Targeted replacement (% by mass) | – | 5 | – | – | – |
| Density(g/cm$^3$) | 2.92 | 2.83 | 2.17 | – | 1.026 |