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Experimental study on anti-icing and deicing performance of polyurethane concrete as road surface layer

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HIGHLIGHTS

- Measured thermal properties of polyurethane concrete and asphalt concrete.
- Conducted pull-off test and inclined shear test of ice-concrete interface and ice rupture test.
- Compared ice formation time of polyurethane concrete and asphalt concrete.
- Proved polyurethane concrete having superior deicing and anti-icing performance.

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ABSTRACT

This study aims to investigate deicing and anti-icing performance of an innovative pavement surface layer that replaces asphalt binder with polyurethane using laboratory tests. The ice-mixture composite specimens were prepared using asphalt binder and polyurethane with the same aggregate type and gradation. The deicing and anti-icing performance of polyurethane concrete at different freezing time was compared to the traditional asphalt concrete. It was found that polyurethane concrete has similar thermal conductivity but much greater specific heat as compared to asphalt concrete. Compared to asphalt concrete, polyurethane concrete can significantly retard the ice-formation time. The pull-off strength and interface shear strength at the interface of ice and polyurethane concrete is about 50% and 55% of those at the interface of ice and asphalt concrete. The work of rupture to break ice layer on polyurethane concrete is about 50% of the work required on asphalt concrete with the same ice layer thickness. The findings demonstrate the potential of using polyurethane concrete on roadways in cold regions to provide better anti-icing and deicing performance and enhance traffic safety at winter seasons.

1. Introduction

The ice on pavement surface during cold seasons significantly influences traffic safety due to degradation of skid resistance at the tire-pavement interface. Previous study has indicated that the friction coefficient can decrease from 0.45 to 1 on clear and dry road surface to 0.15–0.19 on icy road surface [1]. It has been reported that roughly 15% of weather-related crashes occurred under snow and ice conditions in U.S. from 1995 to 2005 [2]. Traffic accidents can cause enormous economic losses. In November 2005, continuous snowfall in northwestern Germany resulted in more than 2000 traffic accidents and direct economic losses of 100 million Euros [3]. In January 2008, freezing rain and ice storm happened in the south-central region of China, led to economic losses of more than 20 billion dollars due to accidents [4].

In order to mitigate adverse effects of ice on roadway and enhance traffic safety in winter weather conditions, several kinds of winter operations were investigated in the past decades. These can be categorized into two types: passive methods and active methods. Passive methods entail the use of deicing chemicals (e.g. salt) or sand abrasives to road surface before snow/ice-pavement bond occurs or mechanical removal using snow plows and sweepers [5–7]. Active methods, on the other hand, use heating system embedded in pavement surface layer for melting snow or ice [8–10].

The use of common deicers including sodium chloride (salt), calcium chloride, and sodium acetate is proved to be economical and effective in winter maintenance. The anti-icing chemicals can be also applied to prevent formation of bond between ice and pavement surface by lowering the freezing point of water.

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However, the redundant deicer remains on road surface after ice storm and increases the possibility of corrosion for steel bridge components or reinforced concrete bridge deck [11]. The deicers can penetrate into asphalt surface layer and reduce adhesive strength of asphalt concrete, which lead to raveling and pothole of asphalt pavement [12]. The deicers can also cause contamination of groundwater or soil and damage to roadside vegetation [13,14]. For these reasons, alternative organic compounds, such as levulinic salts, were proposed to reduce the disadvantages of traditional deicers [15]. However, application of deicers is labor/equipment-intensive and may cause traffic delay [16].

On the other hand, proactive deicing methods have been used with pavement heating system or self-ice-melting materials. Pavement heating systems are composted of electric circuits or hydraulic pipes embedded in electrical or thermal conductive asphalt layers, which require massive reconstruction on existing pavement [17–19]. The deicing additives can be also directly added into asphalt concrete as the fillers or fine particles to produce self-ice-melting asphalt concrete. The deicing additives can be gradually released under tire rolling and capillary pressure to prevent or delay the formation of bond between ice and pavement surface [20,21]. However, the releasing rate of deicing additives is slow due to the cover of asphalt binder or mastic.

The porous polyurethane concrete (or poroelastic road surface) was developed to reduce pavement noise that consists of high contents of rubber particles and air voids [22]. Laboratory testing and field observations have proved that porous polyurethane concrete provided the superior functional performance (e.g. reduction of tire-road noise and rolling resistance) and the acceptable mechanical performance (e.g. rutting resistance, low temperature cracking resistance, and moisture resistance) [23–27]. On the other hand, recent studies have used polyurethane as the main component for preparing water-proof or anti-icing coating due to its hydrophobic and ice-phobic properties [28–30]. There is a potential of using polyurethane in pavement surface layer for better anti-icing or deicing performance.

Laboratory tests have been used to evaluate de-icing performance of different materials. Ice melting test, ice penetration test, and ice undercutting test were introduced for performance evaluation of chemical deicers [31]. The impact load test was used to evaluate ice-melting performance of mixtures in terms of the number of impact required to completely remove ice [32]. The rupture test and pull-off test of ice layer have been used to measure the adhesive strength between ice and asphalt concrete [33]. Similarly, the normal and horizontal adhesive forces of ice to asphalt pavement surface were measured considering the variations in surface texture depths and the temperature of ice [34]. The previous studies mainly focused on ice-melting characteristics and adhesive strength between ice and pavement surface material; while the anti-icing performance (e.g. the time delay for ice formation) should be further studied.

2. Objective and scope

This study aims to investigate deicing and anti-icing performance of an innovative pavement surface layer that replaces asphalt binder with polyurethane using laboratory tests. The ice-mixture composite specimens were prepared using asphalt binder and polyurethane with the same aggregate type and gradation. The de-icing performance was evaluated using pull-off strength test, inclined shear test, and ice rupture test. The thermal properties including heat conductivity and specific heat of polyurethane concrete and asphalt concrete were measured. The anti-icing performance was evaluated using the ice-formation time with different ice layer thicknesses. The deicing and anti-icing performance of polyurethane concrete at different freezing time was compared to the traditional asphalt concrete.

3. Test materials and methods

3.1. Preparation of test specimen

The dense-graded polyurethane concrete with the nominal maximum aggregate size of 13.2 mm (PC-13) was used in this study. The polyurethane binder is two-component polyurethane (A and B). The polyurethane is two-component system (A and B). Polyether polyol was mixed with pentaerythritol to prepare the B component. Then, the isocyanate (A component) was mixed with the B component to form polyurethane. If needed, catalyst (stannous iso caprylate) can be added into the polyurethane immediately to adjust the curing time. Based on recommendations from the provider of polyurethane, if the curing time is required within 15 min after mixing, 2‰ catalyst is usually used; the fewer amount of catalyst is recommended when a longer curing time is required. The mass ratio of A and B component used in this study is 32:68, which is determined by hydroxyl value of polyether polyol. The polyurethane is transparent yellow liquid at room temperature, as shown in Fig. 1(a). The basic properties of polyurethane are shown in Table 1.

The traditional asphalt concrete (AC-13) was designed using the Marshall mix design method. The aggregate is limestone and the asphalt binder is 70# base asphalt with basic properties shown in Table 2. The aggregate gradation, binder content, and air void content of AC-13 and PC-13 specimens are shown in Table 3. To compare the performance of PC-13 and AC-13, PC-13 was prepared using the same aggregate gradation and the same source of limestone as AC-13. Because there is not standard mix design method for polyurethane concrete available, the polyurethane content of PC-13 was determined from the asphalt binder content in AC-13 based on the equivalent volume.

The asphalt and polyurethane were mixed with the graded aggregates for 30–50 s at 160 °C and room temperature, respectively, to prepare loose mixtures. After that, the Marshall specimens (101.6 mm in diameter and 65 mm in height) of AC-13 and PC-13 were prepared after the compaction of 75 times on each side of the specimen, respectively. The curing time is 24 h and demolding was taken 2 h after curing to avoid damage due to demolding.

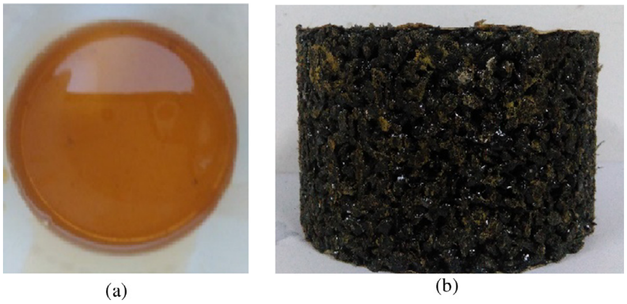
(a) (b)

Fig. 1. Illustration of (a) polyurethane binder and (b) Marshall specimen of polyurethane concrete.

Table 1
Basic properties of polyurethane binder.

Index	Density (g/cm^3)	Curing time (min)	pH value
Value	1.003	5–1200	6.7