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Laboratory study on the adhesive properties of ice to the asphalt pavement of highway

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ABSTRACT

Currently, there are few quantitative studies on the adhesion of ice to the asphalt pavement surface. In this paper, a large-scale freezing laboratory is employed to simulate the low-temperature and wet environment, and a full-scale asphalt pavement model is constructed in the freezing laboratory. The experimental schemes are developed to measure the magnitudes of the normal and horizontal adhesive force of ice to the rough asphalt pavement surface. Then, the normal and horizontal adhesive strength of ice is evaluated to quantify the adhesive force per unit rough area, and the effects of ice temperature as well as the mean texture depth of asphalt pavement on the ice adhesive strength are taken into consideration. Based on the test and evaluation results, it is found that the normal and horizontal ice adhesive strength increases with the ice temperature decrease. The adhesive strength in the normal direction exhibits a logarithmic relation to the ice temperature whereas that in the horizontal direction shows a linear relation. The adhesive strength of ice to the asphalt pavement with higher mean texture depth (0.65 mm) is stronger than that with the lower mean texture depth case (0.50 mm).

1. Introduction

The adhesion of ice to variable materials is a significant concern in civil, power grid facilities and aeronautical structures exposed to low-temperature environments (Laforte and Beisswenger, 2005; Loughborough, 1946; Petrenko, 1998). The icing formed on the surface of civil structures exerts adverse impacts on the engineering construction and normal use (Hanbali, 1994). It is well known that the wet asphalt pavement is more likely to be frozen in the low-temperature environment especially in a moist mountain area. Thereinto, the area in western China often suffers from the freezing rain during the winter; and the ice on the asphalt pavement reduces the pavement skid-resistance and subsequently endangers the traffic safety (Gustafson, 1982; Zhu et al., 2012). Accordingly, the techniques (e.g., anti-freezing coating, deicing products and mechanical deicing) were developed and applied to reduce this kind of adverse impact (Croutch and Harttey, 1992; Petrenko, 1999; Sarkar and Farzaneh, 2009). The adhesion strength of ice directly affects the difficulty and effectiveness of deicing, and indirectly affects the choice of deicing techniques (Oksanen, 1983; Tan, 2008). So far, there are few researches which quantify the ice adhesion to the asphalt pavement surface under different cold conditions. Nonetheless, relatively more investigations have been presented to measure and calculate the adhesion of ice to the certain materials in the other research fields (Andrews and Lockington, 1983; Raraty and Tabor, 1958; Ryzhkin and Petrenko, 1997).

Raraty and Tabor (1958) studied the adhesion and strength properties of ice to variable solid surfaces and compared the differences of the adhesion of ice to polymeric materials and metals. Ryzhkin and Petrenko (1997) studied an electrostatic model of ice adhesion based on the existence of the surface states of protonic charge carriers on the surface of ice. Their work provides an understanding of the time- and temperature-dependent phenomena that explain the difference between the adhesive properties of ice and water. Andrews and Lockington (1983) developed a test method to study the properties of ice adhering to the substrates of stainless steel, titanium and anodized aluminum under different low temperatures. Laforte et al. (2002) presented the adhesion reduction efficiency of seven solid ice phobic coatings. The results were analyzed in terms of ice density, hydrophobic properties of the coatings, and roughness surface characteristics. Dotan et al. (2009) carried out the ice adhesion tests and measured the contact angle to establish the relationship between water wetting and ice adhesion. Yang and Jin (2002) reviewed the ice adhesion phenomenon under sub-freezing temperature in terms of the freezing condition, adhesive properties, the method and technology to reduce the adhesion of ice. Based on the experimental data for the adhesion stress of ice to the surface of metal and non-metal materials, the freezing adhesion stress is independent of the contact area and ice thickness. In

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addition, some researchers reported the adhesion force of ice to the structure surfaces (Baker et al., 1962; Chu and Scavuzzo, 1991; Hassan et al., 2010; Maeno, 2004; Matsumoto and Kobayashi, 2007; Yang et al., 2004); however, most of these studies are restricted to the field of material engineering and sporadic or even no concern has been raised in pavement engineering. The asphalt pavement is porous with a rough surface which is different from other materials (e.g., the metal, plastics, polymeric material and other materials with a smooth surface). It is understandable that the freezing mechanism of ice on the electric wires, airplane wings and some metal materials is largely different from that on the asphalt pavement surface due to their distinct material properties. Consequently, the study method cannot be directly applied, and the relevant conclusions may be different in the pavement engineering. Therefore, the specific and targeted fundamental experimental studies are needed.

For the asphalt pavement frozen in low temperature and wet environment, the adhesive strength of ice to the pavement is generated. It includes normal (perpendicular to the interface) and horizontal (parallel to the interface) adhesive strength which characterizes the strong and weak of adhesive force per unit rough contact area. In this paper, a large-scale freezing laboratory is employed to simulate the low-temperature and wet environment, and a full-scale asphalt pavement model is constructed in the freezing laboratory. Experimental schemes are developed to measure the ice adhesion and quantificationally analyze the effects of ice temperature and pavement surface texture on the adhesive strength of ice to the asphalt pavement surface.

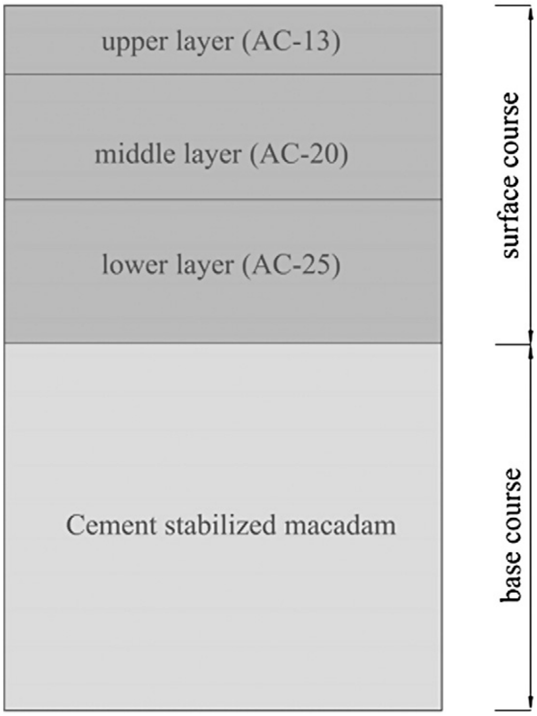

Fig. 1. Schematic diagram of the pavement structure.

2. Experimental

2.1. Introduction to large-scale freezing laboratory

2.1.1. Experimental environment simulation

The ice is essentially formed in a wet and low temperature environment. The large-scale freezing laboratory is constructed for simulating this kind of environment. The air temperature, rainfall, wind speed and pavement temperature can be controlled. The technical parameters of the laboratory with respect to the environment are listed in Table 1.

2.1.2. Pavement structure and test model

The pavement structure is shown in Fig. 1 and the experimental model is filled with building materials (asphalt mixture) (Fig. 2). The experimental model is constructed in the freezing laboratory and subjected to low temperature and wet condition. Platinum sensors are buried in the upper surface course and put on the pavement top surface to detect temperature variation during the temperature drop in the laboratory.

2.2. Test instruments and specimens

2.2.1. Normal adhesion test

The normal adhesion of ice to the asphalt mixture can be weighed by the adhesive force at the irregular interfaces. It is much difficult, if not impossible, to directly pull out the ice from the pavement surface because of the difficult operation. In this paper, we adopt the cylinder specimen (standard Marshall specimen with diameter 102.2 mm and height 63.5 mm) casted with the asphalt mixture which is the same as the material of the pavement surface course (Fig. 3). The cylinder specimen is laid on the pavement surface, and the water between specimen and pavement surface can be frozen under a low temperature condition. If an instrument can be utilized to pull the specimen upward till the specimen separates from the pavement surface, the force obtained by the instrument should be regarded as the adhesive force at the interface of ice and asphalt mixture, no matter the interface is at the ice and pavement surface or the ice and specimen.

To facilitate the test, the combination specimen consists of the cylinder specimen and metal block which is fixed on the specimen with screws to connect to the pull-off tester. The pull-off tester can pull out the specimen from the freezing pavement surface (Fig. 4 shows the schematic diagram for testing the normal ice adhesive force to the asphalt pavement surface.).

2.2.2. Horizontal adhesion test

The specimen for the horizontal adhesion test is also the standard Marshall specimen (Fig. 3) without connecting the metal block. The device to provide a push force is named push-off tester and the schematic diagram is shown in Fig. 5. It can provide about 100 kN maximum push force with an accuracy of 0.01 kN. The push-off tester can record the peak value of the push force when the specimen is pushed away from the pavement surface.

2.2.3. Mean texture depth (MTD) of asphalt pavement and specimen

Texture is a surface characteristic which influences the pavement functional quality significantly (e.g., skid resistance performance) (Flintsch et al., 2007; Zou et al., 2011). Surface macrotexture is a predominant contributor to pavement roughness and skid resistance (Ahammed and Tighe, 2011; Ongel et al., 2009). In this paper, the mean texture depth (MTD) is selected for characterizing the surface roughness of asphalt pavement. After the asphalt pavement being paved, the MTD (macrotexture) is measured through sand patch

Table 1
Environment technical parameters of the large-scale freezing laboratory.

Internal spatial dimension (m)	Air temperature (°C)	Pavement temperature (°C)	Humidity	Rain flow (Th^{-1})	Wind speed (ms^{-1})
3 × 9 × 2.7(W × D × H)	−10–60	−10–60	<100%	<25	1.0–17