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Mechanical properties of a waterproofing adhesive layer used on concrete bridges under heavy traffic and temperature loading

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ABSTRACT

Based on the data collected from a concrete box girder bridge in Shanghai-Hangzhou Expressway Widening and Rebuilding Project, the laboratory tests, on-site temperature monitoring, and finite element method were conducted to study the adhesive behavior of a waterproof adhesive layer (WAL) that is used between a concrete-bridge deck and an asphalt mixture pavement. Firstly, styrene-butadiene-styrene (SBS) modified asphalt, SBS modified emulsified asphalt, rubberized asphalt, and FYT-1 bridge waterproof coating were used respectively as the material of a waterproof adhesive layer, and their shear strength and tensile strength were tested and compared. Then, the sensors were applied to monitor the temperature of pavement. At last, a finite element model of the bridge was developed to analyze the interfacial shear stress and tensile stress in response to vehicle and temperature loading. Results indicate that SBS modified asphalt and rubber asphalt SAMI can be considered as the material of waterproof adhesive layer. The maximum tensile stress appears when the loads move on the pavement surface above the quarter-span, and the maximum shear stress appears when the loads move on the pavement surface at the center of a span. The safety factor (strength/stress) decreases significantly with increasing environmental temperatures. The effects of environmental temperature, spraying quantity of WAL material, and surface roughness on the adhesive strengths were examined. The influences of pavement and WAL thicknesses, and the interface friction were calculated.

1. Introduction

In the transportation industry, asphalt mixture pavement is commonly used as a wearing course constructed on concrete bridge decks. Pavement debonding occurs when the shear stress and/or normal tensile stress exceed the interfacial shear strength and/or pull-off strength. To prevent this, a waterproofing adhesive layer (WAL) can be placed as an interlayer between the bridge deck and the asphalt mixture pavement to prevent permeation of water and enhance interface adhesion.

Laboratory and field tests for evaluating the engineering properties of WALs have been carried out by the National Cooperative Highway Research Program (NCHRP) in the United States [1,2]. The engineering properties tested for WALs included tensile strength, durability, toughness, elasticity, water impermeability, puncture resistance, temperature susceptibility, etc. Laboratory test methods for evaluating material properties and repairing techniques in field construction were comprehensively investigated in UK [3–5]. The importance and technical requirements of the WAL on concrete bridges were put forward by the Danish Road Institute in Denmark [6]. The influences of temperature, shear speed, different interlayer interfaces and surface texture depth on the interface adhesive strength of the WAL on concrete bridges were discussed in China [7–9]. However, the primary performance criterion to assess the benefits of WALs is the interface adhesive strength.

Due to the complicated multi-state loading conditions applied on bridges and the membrane structure of WALs as an interlayer, it is very difficult to effectively measure the interface shear and normal tensile stresses between WAL and bridge deck or pavement. Therefore, it would be very meaningful to capture these critical stresses by using numerical modeling. There are some researches focused on the structural modeling and stress analysis in China [10–12]. The finite element models of concrete bridges with and without WAL were established to calculate the stress state of WAL. The effects of load, pavement thickness and modulus, and interface friction on the mechanical response of WAL were analyzed. The temperature gradient, which caused by the temperature variation at different depth of pavement, leads to the temperature stress. Very little attention has been paid to the influence of pavement temperature gradient on the mechanical response of WALs so far. Therefore, studies on the influences of pavement temperature gradient on the mechanical behaviors of WALs are considered essential in order to design more reliable materials and structures.

Accordingly, this paper aims to describe the adhesive behavior of WALs used on the concrete bridge deck. Four different materials were tested to study the shear strength and tensile strength of the WAL

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under three different environmental temperatures, and one of them would be recommended. The influences of the amount of WAL and surface roughness (SR) on the adhesive behavior of WAL were studied. The mechanical response of WAL considering temperature gradient was analyzed using field monitoring and finite-element (FE) modeling technique, and the effects of pavement thickness, interface friction, and WAL thickness on the stress state of WAL were analyzed. Based on research results, designs of materials and structures were also discussed.

2. Experimental programs

2.1. Description of structure and materials

A simply supported prestressed concrete box-girder bridge in Shanghai-Hangzhou Expressway Widening and Rebuilding Project in China is taken as the engineering background. The bridge with each standard span of 30 m has a nine-cell cross-section. Transverse diaphragms are located at each of the two ending supports of each span. The pavement structure under investigation consists of an 8 cm-thick steel reinforced concrete bridge deck placed on the box-girder, a 3 mm-thick WAL bonded to bridge deck and a 10 cm-thick Stone Matrix Asphalt (SMA) pavement placed on the WAL, as displayed in Fig. 1.

In this study, styrene–butadiene–styrene (SBS) modified asphalt, SBS modified emulsified asphalt, rubberized asphalt, and FYT-1 bridge waterproof coating were chosen as the alternative materials for waterproofing adhesive layer. SBS modified asphalt is found by modifying asphalt with SBS, and SBS modified emulsified asphalt is produced by modifying emulsified asphalt with SBS. Rubberized asphalt consists of regular asphalt paving mixed with “crumb rubber”. Used tires are processed by separating the casings, fabric and steel. FYT-1 bridge waterproof coating is made of high quality asphalt as base, emulsion, and waterborne coatings modified with a variety of special polymer materials. Laboratory tests, including the direct-shear and pull-off tests, were conducted to measure the interfacial adhesive strengths of WALs used on the concrete-bridge deck. The lab test temperatures were selected according to the monitoring air temperature, those being 3, 27 and 40 °C.

2.2. Skew-shear test

The skew-shear test was designed to determine the interfacial shear strength using Universal Testing Machine (UTM) [13], as shown in Fig. 2. In this test, a concrete slab and asphalt mixture slab both measuring 70 mm (width) by 50 mm (length) by 50 mm (height) were prepared. The WAL material was heated and adhered to the top of the PCC slab. Likewise, the asphalt mixture slab was heated and then compacted on the WAL. Consequently, the asphalt mixture slab was fixed by a steel box, to which a compressive force was applied on the top and a shear force was applied on the side. The shear rate of 50 mm/min was applied [10].

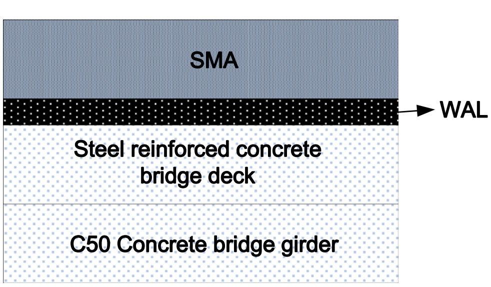

Fig. 1. Pavement on concrete bridge.

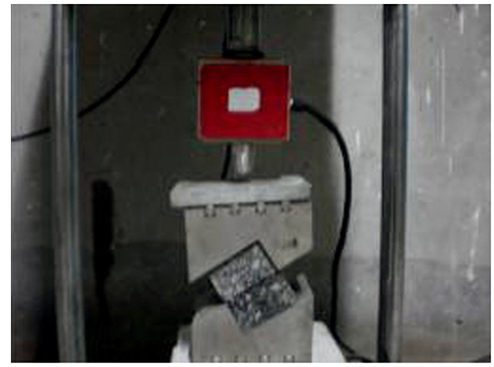

Fig. 2. Skew-shear adhesion test.

Fig. 3. Pull-off adhesion test.

2.3. Pull-off test

The pull-off test was designed to determine the interface pull-off strength, as depicted in Fig. 3. The test samples included a concrete cylinder and asphalt mixture cylinder with a diameter of 100 mm and a height of 80 mm. The concrete and asphalt mixture cylinder were bonded with a WAL as an interlayer, using the same method as explained for the shear adhesion test. The drawing rate of 100–200 N/s was applied [14].

2.4. Test results

2.4.1. Effect of environmental temperature

For discussing the effect of the environmental temperature on interfacial shear strength and tensile strength, the aforementioned four materials with the spraying quantity of 1.0 L/m^2 was sprayed on bridge deck surface, which has been roughened along single direction.

Tests results show that the environmental temperature has significant effect on the shear strength. As illustrated in Table 1, the shear strength obviously decreases with increasing environmental temperature. For instance, the shear strength decreases 90.74% when temperature increases from 3 to 40 °C as for SBS modified asphalt. This trend was also observed in the tests on other three materials. Asphalt is a viscoelastic material and its mechanical behavior is dependent on temperature; thus the shear modulus of asphalt decreases with increasing temperature. As a result, interfacial shear strength decreases.

In addition, it is also found that the environmental temperature has pronounced effect on the tensile strength. As illustrated in Table 2, the tensile strength decreases dramatically with increasing