Construction and Building Materials 122 (2016) 714–720

Contents lists available at ScienceDirect

Construction and Building Materials

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

Study on anti-freezing functional design of phase change and temperature control composite bridge decks

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HIGHLIGHTS

- An anti-freezing composite bridge deck structure was designed.
- We proved that the bridge deck structure has a good effect on melting ice and snow.
- A simulation analysis of the mechanical properties of the bridge deck was done.
- The optimal layout scheme of steel pipes was found.

ARTICLE INFO

Article history:
Received 20 May 2015
Received in revised form 31 May 2016
Accepted 14 June 2016
Available online 9 July 2016

Keywords:
Bridge deck
Anti-freezing
Construction design
Phase transition
Application

ABSTRACT

The bridge decks during the winter time usually present a poor performance of freeze resistance. Using the phase change energy-storing technology and functionally-graded materials design method, we designed and prepared a composite anti-freezing bridge deck structure. Compared with conventional bridge decks, the anti-freezing bridge deck has a phase change functional layer which consisted of high strength seamless steel pipes paved parallelly at a certain interval, and the liquid phase change materials are filled in the pipes. Through theoretical study and laboratory model tests, it has been proven that the large amount of heat given off by the new bridge deck structure during the liquid-solid phase change process has a good effect on melting ice and snow. On the other hand, in order to research the influence the heat has on the mechanical properties of the bridge deck, a simulation analysis has processed by the finite element software. The results show that: the seamless steel pipe buried in the transformation function layer has an effect on the reinforcement of the deck structure, which also greatly enhances the overall strength and stiffness. The bottom layer tensile stress and vertical displacement of the phase change functional layer are about 74% and 92% respectively of those without one. Meanwhile, the average values of tensile stress and the vertical displacement of the former are less than those of the latter. Finally, an optimal layout scheme was found through the comparative analysis of influence of pipe spacing and depth while the bridge deck was experiencing stress.

1. Introduction

The serviceability and working performance of cement concrete bridge decks play an important role in the structural function and operating efficiency. Under adverse weather, results in the decrease of the friction coefficient for pavement wearing layers, these conditions are a hazard to the safety of the vehicle. In the south of China (Hunan), where freezing rain disasters are particularly serious and heat dissipation occurs quickly, the main highway bridge freezes over rapidly during snow and rain. This can lead to the decline of the traffic capacity of the road, and even traffic accidents. Traffic along the highways of twenty three provinces were affected by varying degrees in the major snow storm that occurred in 2008 [1]. Among them, the freezing of snow and ice on the bridge was one of the most important factors of the passenger and freight traffic jam. However, these situations were mostly caused by the decrease of contingency reaction mechanisms of pavement function under extreme weather conditions.

Currently, the methods for thawing ice and snow are listed as follows [2–6]: 1) direct scavenging method including artificial scavenging and mechanical scavenging; 2) scavenging method with scattering snow-melting agent; 3) scavenging method with heating power, such as heating cable method, purge method with high temperature gas, geothermal thaw method and electro thermal deicing method with conductive concrete, etc. After

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http://dx.doi.org/10.1016/j.conbuildmat.2016.06.065
0950-0618/

analyzing the methods, it was noted that each method contains some disadvantages. In the direct scavenging method, it was found that it has a low efficiency and is a waste of manpower. Artificial scavenging, a type of direct scavenging, has a high cost while mechanical scavenging, another type of direct scavenging, is difficult to control, resulting in the ability to easily harm pavements. The second method listed (scavenging with a scattering of snow melting agent) can easily corrode pavement materials due to the snow melting agent. This has a negative influence on the pavements' structural durability as well the environment. Finally, the last method (scavenging with heating power) does not meet the current demand of energy conservation and emissions reductions. Furthermore, there are problems in the actual application of this method.

It is important to find a better technique of freeze resistance and anti-sliding that is more intelligent and has a better performance in scavenging ice and snow on bridge pavements. This study, focuses on the cement concrete bridge deck based on phase change energy storage materials [7–11] and functionally-graded design method [12–14], thus providing theoretical datum and practical base for large-scale practical engineering.

2. Materials and methods

2.1. Raw materials

2.1.1. Cement

Niuli Cement: Changsha Ping Tang Cements Limited, P·O 42.5, whose chemical compositions are shown in Table 1.

2.1.2. Aggregate

(1) Fine aggregate: river sand from Xiang River of Hunan Province, fine aggregate parameters are shown in Table 2.
(2) Coarse aggregate: continuous grading macadam size from 5 mm to 20 mm, coarse aggregate parameters are shown in Table 3.
(3) Super fine skeleton aggregate Quartz sand: mix the 24–50 mesh with 50–80 mesh by the ratio of 1:1.

2.1.3. Mineral additive

(1) Mineral powder

Produced by Wuhan iron and steel factory, specific surface area: 420 m^2/kg;

(2) Fly ash

The first class fly ash (FA I) produced by Hunan Xiangtan power plant, specific surface area: 450 m^2/kg;

2.1.4. Additive and fiber components

(1) Super plasticizer: FDN, Naphthalene;
(2) Shrinkage reducing agent: prepared by ourselves, decrease the shrinkage by reducing the surface tension of capillary.

2.1.5. Phase change material (also called "PCM")

Composite organic polyol

Density: 0.82 g/cm^3, Phase change latent heat: 240.5 J/g, Liquid-solid phase transition temperature: 4.53 °C.

Table 1
Chemical composition of cement.

Chemical composition (mass/%)					
Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3
0.08	2.32	4.98	22.6	0.06	2.31
K_2O	CaO	TiO_2	MnO	SrO	BaO
0.75	61.6	0.31	0.07	0.16	0.15

Table 2
Parameters of fine aggregate.

Parameters of fine aggregate		
Mud content	Clay lump content	Fineness modulus
1.0%	0.5%	2.5

Table 3
Parameters of coarse aggregate.

Parameters of coarse aggregate		
Mud content	Acicular content	Crushing index
1.5%	4.5%	2.5

2.2. Experimental methods

Design principles of gradient-material and phase change energy storage materials system are introduced to the design the anti-freezing and wear-resistance concrete bridge deck. The design result is shown in Fig. 1.

As shown in Fig. 3, the cement concrete bridge deck that is temperature controlled consists of four layers, in down-top order, namely, main concrete structural layer, thermal insulation mortar layer, high strength seamless steel pipe layer with phase change energy storage material and wearable concrete surface course. The thickness of main concrete structural layer is 1/2–2/3 of that of the whole pavement bridge deck, and its performance is similar to ordinary concrete with compressive strength of C35 or above. The seamless steel pipe layer with phase change material is 30–50 mm away from the pavement surface, and the outside diameter of the hollow steel pipe is between 40 mm and 60 mm. In order to fill the PCM easily, the steel pipes have a type L design, closed at one end while the other end is set as an open structure, as shown in Fig. 2.

According to the materials and the design principle of the bridge deck structure, which were mentioned above, the indoor simulation test was carried out. In order to ensure its objectivity and accuracy, the model was processed with a cube of 500 mm × 400 mm × 80 mm, as shown in Fig. 3. Then, according to the material ratio and preparation processes, the composite concrete bridge deck model is constructed, as shown in Fig. 4. The composition and properties of pavement concrete deck are shown in Table 4.

3. Results and discussion

3.1. Analysis of effect of ice melting

The concrete bridge deck was prepared following the moisture retention maintenance methods of construction standards [14–17]. After being cured for 24 h and demoulded and injected with PCM, the simulation test was carried out in low temperatures. Refer to Fig.5 for a depiction of the process.

The spiral design of steel pipe ports provides convenience for injecting the PCM from the side. After injecting the PCM and sealing, ice was scattered evenly on the surface of the model to simulate snowy and icy conditions on a bridge deck surface. Two hours later, the thawing status on the surface where the steel pipes were laid was evaluated. Its thawing status was better than the section without steel pipes. Meanwhile, the temperature inside and outside the steel pipes was tested before and after the experiment, the results show that the inside temperature of the PCM dropped from 10 °C to 3.5 °C and that the liquid-solid phase change was carried out. The temperature of the concrete surface paving steel pipes increases from 0 °C to 1.8 °C, showing that it absorbed some heat. The model was put into the constant temperature and humidity curing room of 10 °C and relative humidity 60 ± 4%. As shown in Fig. 5, the PCM becomes a solid state and latent heat has been released, transferring from the steel pipe to the bridge deck surface, and the bridge's performance of anti-freezing is improving.

3.2. Effect of packaging steel pipes on workability of bridge deck

A two-dimensional mathematical model is set up by the finite element software ABAQUS. Mesh generation adopts secondary