Construction and Building Materials 79 (2015) 420–432

Contents lists available at ScienceDirect

Construction and Building Materials

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

Design of GFRP reinforced CRCP and its behavior sensitivity to material property variations

Jeong-Hoon Choi [a],*, Hung-Liang (Roger) Chen [b]

[a] *AECOM, National Energy Technology Laboratory, U.S. Dept. of Energy, Morgantown, WV 26507, USA*
[b] *Dept. of Civil and Environmental Engineering, West Virginia University, Morgantown, WV 26506, USA*

HIGHLIGHTS

- We present design methodologies of GFRP- and steel-CRCPs constructed in WV, USA.
- We employ mechanistic and numerical methods for the CRCP designs.
- We show a very first look of design and performance of the GFRP-CRCP.
- We numerically examine the sensitivity of GFRP-CRCP behaviors to pavement properties.
- Average crack spacing and width are larger in GFRP-CRCP test section.

ARTICLE INFO

Article history:
Received 21 October 2012
Received in revised form 10 November 2014
Accepted 27 December 2014
Available online 29 January 2015

Keywords:
GFRP rebars
CRCP
Concrete shrinkage
Temperature variation
Bond-slip
Subbase
Crack spacing
Crack width

ABSTRACT

Non-corrosiveness, light weight, and high strength-to-weight ratio of Glass Fiber Reinforced Polymer (GFRP) rebars would have favorable impacts on the Continuously Reinforced Concrete Pavements (CRCPs), in terms of lowering the maintenance cost and extending the longevity of the pavement. To examine the viability of GFRP rebars as CRCP's reinforcement, the U.S.'s first GFRP-CRCP test section was constructed on Route 9 in Martinsburg, West Virginia, together with a conventional steel-CRCP test section for comparison purpose. In this paper, we introduce overall design methodology of these CRCP test sections, which involves mechanistic and numerical analyses. The reinforcement design of #7 longitudinal rebars at 6 in. (15.24 cm) spacing (1.0% ratio) is proposed to be mechanically and economically feasible for the GFRP-CRCP, when applied with 6500 psi (44.82 MPa) concrete on the cement-stabilized subbase. For the GFRP-CRCP design, shrinkage and thermal properties of concrete appear to be the most influential design parameters to the performance of the proposed GFRP-CRCP. Even though the actual field performance of the CRCP test sections shows appreciable discrepancy with its prediction, it still remains within the allowable limit for structural integrity. The properties of subbase and concrete deviating from their proposed design is presumably the cause of the discrepancy.

1. Introduction

Corrosive nature of conventional steel reinforcing rebars is a main cause for long-term degradation of concrete structures exposed to prolonged harsh environmental conditions. Continuously Reinforced Concrete Pavements (CRCPs) with steel rebars also suffer many corrosion-related distresses, such as delamination, spalling, and steel rupture, due to volume expansion and strength loss of corroded steel [1]. As a result, the pavement service life can be significantly reduced even with consistent maintenance and repair efforts, which also cost a considerable amount of expenses. Therefore, using corrosion-free Glass Fiber Reinforced Polymer (GFRP) rebars can be an answer for eliminating the adverse effects caused from corrosive steel rebars in the CRCP. Other features, such as high longitudinal strength, non-magnetic quality, light weight, and better thermal and stiffness compatibility with concrete [2], can also make the GFRP rebars attractive in their application to the CRCP.

Since 1921, conventional steel-reinforced CRCPs have been built across the United States, most recently in Illinois, North and South Dakota, Oklahoma, Oregon, Texas, and Virginia, among others. The behaviors of the steel-CRCP are well-understood by mechanistic and numerical analyses [3–7], and the design guidelines are established in the American Association of State Highway and

---

* Corresponding author. Tel.: +1 304 285 2077; fax: +1 304 285 4403.
E-mail addresses: Jeong.Choi@contr.netl.doe.gov (J.-H. Choi), Roger.Chen@mail.wvu.edu (H.-L. (Roger) Chen).

http://dx.doi.org/10.1016/j.conbuildmat.2014.12.080
0950-0618/

Transportation Officials (AASHTO) documents [8,9]. Field performance of the steel-CRCPs has also been conducted by many researchers, and the results provided better understandings of real behavior and distress of the pavement under various design and construction conditions [10–13].

The idea of applying GFRP rebars to the CRCP was initially proposed in 1999 by researchers at West Virginia University (WVU). Since then, the fundamentals of mechanical behavior and design consideration of GFRP-CRCP had been studied by researchers in the U.S. and Canada to provide applicable GFRP-CRCP designs [14–18]. The deployment of experimental GFRP-CRCP section in the U.S. was finally completed on Route 9 in Martinsburg, West Virginia in 2007 [19], following the preceding construction in Canada in 2006 [20]. The West Virginia Department of Transportation (WVDOT) allocated a 2000-foot-long (610-meter), two-lane section on Route 9 to WVU researchers as a testing ground. The experimental section incorporated two different CRCPs, GFRP-reinforced and steel-reinforced, for the purpose of comparison. Both sections were 1000 ft (305 m) long and 10 in. (25.4 cm) thick and were composed of concrete containing limestone coarse aggregate placed on a cement-stabilized subbase. The design called for #7 longitudinal GFRP rebars at 6-inch (15.24-cm) spacing for the GFRP-reinforced section and #6 longitudinal steel rebars at 6-inch (15.24-cm) spacing for the steel-reinforced section.

In this paper, design philosophy and methodology of the West Virginia's GFRP-CRCP are introduced. CRCP8, a simplified one-dimensional mechanistic CRCP analysis program developed by researchers at the University of Texas [21], was utilized for the GFRP-CRCP design. Even though the program had been developed for the steel-CRCP and constantly improved by incorporating field test data from the steel-CRCPs, its simplicity and respectable accuracy, already proven in predicting the performance of steel-CRCP, made it a feasible tool to provide a proto-type GFRP-CRCP design in this study. The design, first determined by the mechanistic analysis, was then confirmed by Finite Element (FE) modeling. The anticipated performance of the GFRP-CRCP proposed was evaluated mainly on the basis of AASHTO Guide for Design of Pavement Structures [8] and ACI 440 Guide for the Design and Construction of Concrete Reinforced with FRP Bars [2]. The criteria applied for the performance pre-evaluation are: (1) 3.5 ft (1.067 m) $\leqslant$ crack spacing $\leqslant$ 8 ft (2.438 m), (2) crack width $\leqslant$0.04 in. (1 mm) at the top surface of the pavement, and (3) tensile stress in GFRP reinforcement $\leqslant$20% of the ultimate tensile strength of GFRP rebar used (against $\leqslant$75% of the ultimate tensile strength of steel rebar). The similar design and performance pre-evaluation approaches were also adopted for the steel-CRCP test section constructed next to the GFRP-CRCP section.

The sensitivity of the GFRP-CRCP performance pertaining to the material and design parameters was investigated to foresee the magnitude of behavior changes of the proposed GFRP-CRCP due to possible variation of material properties and construction conditions in the field. In addition, as a complementary effort for CRCP design verification, we also adopted the most recent AASHTO Interim Mechanistic-Empirical Pavement Design Guide (MEPDG) limiting criteria [9] during the CRCP performance evaluation particularly with the FE modeling results, where the crack width at the depth of reinforcement is available. In contrast to the previous AASHTO guide [8], the AASHTO interim MEPDG [9] utilizes the depth of reinforcement as a reference point to define the crack width of a CRCP, and applies more strict limiting criteria, such as crack spacing $\leqslant$6 ft (1.829 m) and crack width $\leqslant$0.02 in. (0.5 mm) at the depth of reinforcement. Finally, the short-term performance of both the steel- and GFRP-CRCP sections is introduced in terms of crack spacing and width induced at 38 days after concrete placement, and compared with its predictions made during the CRCP design process.

2. CRCP designs

2.1. Design parameters considered for GFRP- and steel-CRCPs

The mechanistic analysis program, CRCP8, was used to determine a feasible design for each of 10-inch-thick (25.4 cm) GFRP- and steel-reinforced CRCP test sections on Route 9, Martinsburg, WV. For the mechanistic analysis, the design parameters, such as reinforcement ratio, concrete properties, reinforcement properties, underlying support properties, and external/environmental load characteristics, are needed as inputs, and shown in Tables 1 and 2 are those to be examined for the CRCP design. The input values, especially concrete material properties and environmental characteristics, were selected after a careful consideration of given construction conditions, because they have great influences on the outcome of mechanistic analysis.

In northern states, where more severe weather occurs with greater temperature differentials, a steel reinforcement ratio of about 0.7% has generally been used for steel-reinforced CRCPs [22]. Therefore, a steel longitudinal reinforcement design of #6 rebars spaced at 6 in. (15.24 cm) with a reinforcement ratio of 0.733% was selected for the steel-CRCP section. Due to low Young's modulus of GFRP rebar (about one-fifth of that of steel rebar), the reinforcement amount for a GFRP-CRCP section would need about five times of that for steel-CRCP section to obtain equivalent stiffness. However, for the reason of economy, an optimum reinforcement amount for GFRP-CRCP section had to be proposed, minimizing the quantity of reinforcement without violating the limiting criteria for CRCP, especially the crack width criterion ($\leqslant$0.04 in. (1 mm), [8]). Therefore, in addition to 0.733% (#6 rebars at 6 in.), two GFRP percent reinforcement ratios, 1.000% (#7 rebars at 6 in.) and 1.317% (#8 rebars at 6 in.), which are merely about two times that of the steel-CRCP section at maximum, were considered in the CRCP8 design analysis, and one of them was to be selected as the optimum for the GFRP-CRCP section, on the basis of material properties and load characteristics considered (Tables 1 and 2).

WVDOT specification [23] requires the pavement concrete to have a minimum compressive strength of 3000 psi (20.70 MPa) at 28 days. In general, the concrete having about 3000–4000 psi (20.70–27.58 MPa) strength is used for the pavement, and therefore, a similar compressive strength of 4500 psi (31.03 MPa) was considered for a CRCP8 design simulation. Another compressive strength of 6500 psi (44.82 MPa) was also adopted for the simulation, representing the upper bound of concrete strength for the concrete pavement. The 28-day concrete compressive strength and maturity were used as reference properties to calculate other concrete properties.

Considered in the simulation was a limestone-coarse-aggregate concrete, which can easily be procured from local ready-mix-concrete companies. According to the AASHTO Guide for Design of Pavement Structures [8], limestone concrete has the lowest coefficient of thermal expansion (CTE), about 3.8 $\mu\varepsilon$/°F (6.84 $\mu\varepsilon$/°C), as compared to the other concrete with different aggregates. It can be expected that with a lower CTE, tensile concrete stress developed by a temperature drop under restrained condition will be lower, leading to a larger crack spacing in the CRCP. The CRCPs with limestone concrete may need more restraints from reinforcement and/or subbase in order to have comparable crack spacing. On the other hand, if the limestone CRCP were controlled to have the crack spacing comparable to that of the CRCP with other aggregate type, its crack width would certainly be narrower. The narrower crack width can then secure better aggregate interlock at the crack, reducing the possibility of punch-out failure as well as spalling failure. Since the most influential factor of the concrete CTE appears to be the