FHWA RESEARCH PROGRAM ON LIGHTWEIGHT HIGH-PERFORMANCE CONCRETE

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ABSTRACT

Using lightweight concrete in bridge decks and girders can reduce the dead load carried by the superstructure and substructure, thus allowing for longer spans and/or smaller members. There has been considerable research in recent years on the behavior of high-performance concrete (HPC) using normal weight aggregate. However, there has been considerably less research on HPC containing lightweight aggregates, especially on structural members with compressive strength in excess of 6 ksi. The limited research on lightweight HPC (LWHPC) has been focused on equilibrium densities less than 125 pcf.

This paper describes an FHWA research program focused primarily on LWHPC in the gap of equilibrium densities ranging from conventional lightweight to normal weight concrete. The purpose of the research program is to (i) investigate the performance of LWHPC produced using aggregates representative of those available in North America, (ii) investigate the transfer length, development length, and shear strength of precast/prestressed LWHPC members, (iii) study the development and splice length of mild steel reinforcement used in LWHPC, and (iv) investigate prestress losses in LWHPC girders. The result of the study will be to recommend changes to the AASHTO LRFD Bridge Design Specifications relevant to LWHPC.

Keywords: Lightweight concrete, High-performance concrete, Specified density concrete, Development length, Transfer length, Shear

INTRODUCTION

The use of lightweight concrete in bridge decks and girders can reduce the dead load carried by the superstructure and substructure, thus allowing for longer spans and/or smaller and potentially less expensive members. Additional benefits of lightweight concrete members are that they can result in reduced transportation costs and reduced erection costs due lighter members.

High-performance concrete (HPC) has been developed in the last two decades and has a more dense cement matrix resulting in improved durability and typically higher compressive strength. There has been considerable research in recent years on the behavior of HPC containing normal weight aggregate. These research efforts could expand the applicability of the AASHTO LRFD Bridge Design Specification for normal weight concrete to compressive strengths up to 18 ksi. However, there has been considerably less research on HPC containing lightweight aggregates, especially on structural members with compressive strengths in excess of 6 ksi. In addition, the limited research on lightweight HPC (LWHPC) has been focused on equilibrium densities less than 125 pcf. This leaves a gap in experimental data for concretes with equilibrium densities ranging from conventional lightweight to normal weight concrete.

This paper outlines a research program recently begun by the Federal Highway Administration (FHWA) at the Turner-Fairbank Highway Research Center (TFHRC). The purpose of the research program is to investigate the performance of LWHPC produced using aggregates representative of those available in North America. The program will investigate the transfer length, development length, and shear strength of precast/prestressed LWHPC members. Also, the development and splice length of mild steel reinforcement used in LWHPC members will be studied. The result of the study will be to recommend changes to the AASHTO LRFD Bridge Design Specifications relevant to LWHPC.

BACKGROUND

Recently completed research by the National Cooperative Highway Research Program (NCHRP) has the purpose of increasing the design concrete compressive strength utilized by the AASHTO LRFD Bridge Design Specifications to between 15 and 18 ksi. These efforts included research on flexural, axial, and shear behavior. The research also included investigating the bond between concrete and prestressing strand and the bond between concrete and mild steel reinforcement. However, this research was limited to normal weight concrete so there is a need to investigate the applicability of the proposed revisions to the AASHTO Specifications to lightweight concrete.

A review of the AASHTO Specifications to identify articles that currently address or should address lightweight concrete was recently conducted. This review resulted in a synthesis report that describes the relevant research for each article and identifies gaps where additional research is needed[1]. The current FHWA investigation into the use of lightweight concrete in highway bridges is designed to address many of the gaps in research identified by the synthesis report.

The FHWA research project will also benefit from a similar effort conducted by Virginia Tech (VT) and the Virginia Transportation Research Council (VTRC) on high-performance and high-strength lightweight concrete for bridge girders and decks as part of a National Cooperative Highway Research Program (NCHRP) project. Similar to the research effort conducted by FHWA, the VT/VTRC project will focus on the performance of lightweight concrete in bridge girders and decks. The equilibrium density for the VT/VTRC project is limited to a maximum density of 125 pcf, whereas the proposed FHWA effort will be focus on LWHPC with densities of 125 pcf and higher. As such, the experimental data from the two research programs should compliment each other and aid in the development of AASHTO provisions that are continuous between traditional LWHPC and normal weight concrete.

NEED FOR RESEARCH

Research has shown that the use of lightweight concrete in many components of highway bridges has economic benefits. Other research has been conducted to increase the design compressive strength in the AASHTO Specifications for normal weight concrete. The present research is needed to verify and/or recommend modifications to existing provisions relating to lightweight concrete and also to address other gaps in the research on lightweight concrete.

BENEFITS OF LWHPC IN HIGHWAY BRIDGES

Use of lightweight concrete in bridge decks was recently investigated[2,3] and found to have many benefits. These benefits include: reduced dead loads allowing longer spans, reduced size and cost of substructure, reduced transportation costs, and potentially reduced cracking.

LWHPC reduces the weight of long span girders so that special permits may not be required to transport them. A recent study showed that the transportation costs of girders with spans between 125 and 155 ft would benefit from the use of lightweight concrete[4]. The span length of simply supported high strength girders can also be increased by using lightweight concrete.

Designers of the 22-span Benicia-Martinez Bridge in the San Francisco Bay area chose a cast-in-place cantilever lightweight concrete segmental bridge over steel box-girder, steel-truss, and concrete cable-stayed alternative due to its the reduced initial cost[5]. A more detailed list of the economic benefits of lightweight concrete is given by ACI 213R-03[6].

LACK OF LWHPC RESEARCH

The most economic use of lightweight concrete in bridge girders and decks is limited by the lack of LWHPC research. Most of the research on lightweight concrete before the 1990s dealt with concrete strengths below 6000 psi. Research on high strength concrete, which typically utilizes additional cementitious material and admixtures to create an increased density in the concrete matrix, became more common in the late 1980s. Some of this research utilized lightweight aggregate; however, the bulk of the data on the performance of lightweight concrete is based on traditional mix designs. As such, test data that represents the performance modern mix proportions for lightweight concrete is lacking.

GAP IN SPECIFIED DENSITY CONCRETE RESEARCH

The current AASHTO Specifications define normal weight concrete as having a unit weight between 135 pcf and 155 pcf and lightweight concrete with a unit weight of 120 pcf or less. Concrete with densities between normal weight and lightweight are commonly referred to as specified density concrete. Most specifications that include modifications for lightweight concrete do not present the modifications in terms of unit weight, thus leaving a gap in the specified density range that the specifications do not address.

MAJOR THRUST AREAS OF THE RESEARCH

The FHWA research program will investigate several areas where improved understanding in LWHPC is assumed to have the most benefit. These areas are the transfer length and development length of prestressing strand in LWHPC girders, the time-dependant prestress losses, and shear strength of precast/prestressed LWHPC girders. The development length and splice length of mild steel reinforcement used girders and decks made with LWHPC will also be investigated.

An important aspect of the study will be using LWHPC produced from aggregates representative of those available in North America. This means selecting lightweight aggregates from a geographically distributed region. This is important because the mechanical properties of one type of lightweight aggregate (i.e. clay, shale, or slate) can vary from different sources. The mechanical properties of the lightweight aggregate are mostly responsible for the differences between concrete made from normal weight and lightweight aggregate.

The aggregate in lightweight concrete is commonly manufactured in a rotary kiln process, producing a lower density particle with a cellular pore system. Two main differences in mechanical properties of concrete made from normal weight and lightweight aggregates are reductions in the tensile strength and the modulus of elasticity, with these differences being related to the cellular pore system in the aggregate.

The reduced modulus of elasticity has a detrimental effect on deflection and prestress losses, and also increases the transfer length of prestressing strands. However, the reduced modulus can benefit a structure in terms of improved durability[7].

The reduced tensile strength of the aggregate causes a reduction in the concrete splitting tensile strength and the concrete modulus of rupture. It can also reduce the bond strength and the shear capacity of members without web reinforcement[6].

TRANSFER LENGTH OF PRESTRESSING STRANDS

The transfer length of prestressing strands is defined as the embedment length required to transfer the effective prestressing force in the strands to the surrounding concrete. An accurate estimation of the transfer length is important for several reasons: calculation of the concrete stresses at transfer and under service loads, design of anchorage zone reinforcement for strut-and-tie models, and design of shear reinforcement which requires knowledge of the level of precompression in the concrete[8].

The two most significant mechanisms that contribute to prestress transfer bond are friction and mechanical resistance[9]. Radial compressive stress, commonly attributed to the Hoyer Effect, is required to develop frictional bond stresses. In the short region of the transfer length where the concrete remains elastic, the radial compressive stress depends directly on the elastic modulus of the concrete. In the inelastic region, the radial compressive stress depends on both the elastic modulus and the tensile capacity of concrete.

Both the elastic modulus and tensile capacity of LWHPC are less than normal weight concrete of the same compressive strength. Previous test specimens using LWHPC have had varied results as to the whether the AASHTO Specifications gave a conservative prediction of the transfer length[4,10,11].

The proposed research will utilize full-size AASHTO girders. The major variables to be investigated are the concrete compressive strength, lightweight aggregate type, prestressing force, strand size, and shear reinforcement. The transfer length will be measured using the concrete surface strain technique and the strand draw-in technique.

DEVELOPMENT LENGTH OF PRESTRESSING STRANDS

The development length of prestressing strands is defined as the embedment length required to develop the nominal design strength of the strand. Inadequate development length could result in strand slip before the strand reaches its nominal strength, which could result in not attaining the calculated nominal resistance.

Similar to the transfer length tests, previous tests on the development length of LWHPC specimens have had varied results as to whether the AASHTO Specifications gave a conservative prediction of the development length[4,10,11].

The proposed research will utilize several of the full-size AASHTO girders that are part of transfer length study. The major variables to be investigated are the concrete compressive strength, lightweight aggregate type, specimen size, prestressing force, strand size, and shear reinforcement. The development length will be determined by testing both ends of the girder specimens to flexural failure. This is an indirect method employed in numerous studies. If the test at one specimen end results in a ductile flexural failure, then the tested embedment length will be assumed to be greater than the development length. However, if strand slip occurs first, then the tested embedment length will be assumed to be less than the development length. In this manner, the tests on one girder specimen are used to "bracket" the development length; however, the development length will not be specifically determined.

SHEAR BEHAVIOR OF LWHPC

The current AASHTO Specification imposes a significant reduction factor for calculating the design capacity of lightweight concrete section under shear stresses. Several research projects have investigated the use of LWHPC under shear and have found that the nominal capacity calculated according to the AASHTO Specification is conservative without any modification[12]. A recent NCHRP project covering the shear behavior of normal weight high-strength concrete has recommended changes to the AASHTO Specification. These recommended changes need to be evaluated for LWHPC.

The highest shear demand in a typical bridge girder is near the support. This is also the region where the prestressing strands may not be fully developed. This research effort will focus on the shear behavior in the region near the support. The project will utilize full-size AASHTO girders. The major issues to be investigated are the affect of concrete compressive strength, type of lightweight aggregate, amount of transverse reinforcement, and the AASHTO specified end longitudinal reinforcement on the nominal shear capacity, reinforcement stress, and crack angles. The AASHTO Specification requirements for minimum reinforcement, the maximum compressive stress in the diagonal strut, and the adequacy of end longitudinal reinforcement will also be investigated.

PRESTRESS LOSSES

The stress in the prestressing strand is immediately reduced at transfer due to elastic losses in the concrete. Additional time-dependant losses such as creep and shrinkage will further reduce the long-term effective prestressing force. Prestress losses reduce the beneficial effect of prestressing at service load which can cause additional cracking and deformation in bridge girders.

There have been a limited number of recent studies on prestress losses in LWHPC. One study has shown that reduced elastic modulus of LWHPC can cause elastic losses that are considerably larger than for normal weight concrete[13]. Another study showed that the creep and shrinkage of LWHPC is similar to the normal weight high-performance concrete[14]. The same study showed that LWHPC girders had measured prestress losses that were less than the losses predicted by the AASHTO specification.

Long term losses will be investigated in the present research program by monitoring the long term deflection and internal concrete strain in the AASHTO girder specimens that are part of the shear behavior program. Creep and shrinkage tests will also be run following standard AASHTO/ASTM specifications.

DEVELOPMENT AND SPLICE LENGTH OF MILD STEEL REINFORCEMENT

Mild steel is used as the primary reinforcement in bridge decks and as shear reinforcement and end longitudinal reinforcement in bridge girders. The development and splice length of mild steel reinforcement used in LWHPC bridge decks and girders is therefore important. However, there is limited test data on the bond strength of mild steel reinforcement in lightweight concrete[15].

Part of the present research program will be to investigate development and splice length in beam end specimens and in lap splice specimens. The specimens will use normal and high strength LWHPC to be representative of deck and girder concrete, respectively.

CONCLUDING REMARKS

This paper describes an FHWA research program focused primarily on LWHPC in the gap of equilibrium densities ranging from conventional lightweight to normal weight concrete. The purpose of the research program is to (i) investigate the performance of LWHPC produced using aggregates representative of those available in North America, (ii) investigate the transfer length, development length, and shear strength of precast/prestressed LWHPC members, and (iii) study the development and splice length of mild steel reinforcement used in LWHPC. The result of the study will be to recommend changes to the AASHTO LRFD Bridge Design Specifications relevant to LWHPC.

REFERENCES

1. Russell, H., "Synthesis of Research and Provisions Regarding the Use of Lightweight Concrete in Highway Bridges," National Technical Information Service, Springfield, VA, 2007, 108 pp. (In press)
2. Thatcher, D. B., Heffinton, J. A., Kolozs, R. T., Sylva, G. S., Breen, J. E., and Burns, N. H., "Structural Lightweight Concrete Prestressed Girders and Panels," Report TX-02/1852-1, Center for Transportation Research, University of Texas at Austin, Austin, TX, January 2002, 208 pp.
3. Ozyildirim, C., and Gomez, J. P., "First Bridge Structure with Lightweight High-Performance Concrete Beams and Deck in Virginia," Final Report (VTRC 06-R12), Virginia Transportation Research Council, Charlottesville, VA, December 2005, 23

pp.
4. Meyer, K. F., and Kahn, L. F., "Lightweight Concrete Reduces Weight and Increases Span Length of Pretensioned Concrete Bridge Girders," *PCI Journal*, Vol. 47, No. 1, January/February 2002, pp. 68-75.
5. Murugesh, G., and Cormier, K., "When Lighter is Better," *Aspire*, Summer 2007, pp. 20-24.
6. ACI Committee 213, "Guide for Structural Lightweight Aggregate Concrete," ACI 213R-03, American concrete Institute Committee 213, Farmington Hills, MI., 2003.
7. Holm, T. A., Bremner, T. W., and Newman, J. B., "Lightweight Aggregate Concrete Subject to Severe Weathering," Concrete International. V. 6, No. 6, June 1984, pp. 49-54.
8. Barnes, R.W., Burns, N. H., and Kreger, M. E., "Development Length of 0.6-Inch Prestressing Strand in Standard I-Shaped Pretensioned Concrete Beams," Report TX-02/1388-1, Center for Transportation Research, University of Texas at Austin, Austin, TX, December 1999, 338 pp.
9. Barnes, R. W., Grove, J. W., and Burns, N. H., "Experimental Assessment of Factors Affecting Transfer Length," *ACI Structural Journal*, V. 100, No. 6, November-December 2003, pp. 740-748.
10. Meyer, K. F., and Kahn, L. F., "Transfer and Development Length of 0.6-inch Strand in High Strength Lightweight Concrete," *High-Performance Structural Lightweight Concrete*, SP-218, American Concrete Institute, Farmington Hills, MI, 2004, pp. 9-27.
11. Cousins, T. E., and Nassar, A., "Investigation of Transfer Length, Development Length, Flexural Strength, and Prestress Losses in Lightweight Prestressed Concrete Girders," Final Report (VTRC 03-CR20), Virginia Transportation Research Council, Charlottesville, VA, April 2003, 44 pp.
12. Ramirez, J., Olek, J., Rolle, E., and Malone, B., "Performance of Bridge Decks and Girders with Light-weight-Aggregate Concrete," Report IN/JTRP-89/17, Purdue University, West Lafayette, IN, May 1999, 191 pp.
13. Sylva, G. S., Burns, N. H., and Breen, J. E., "Composite Bridge Systems with High-Performance Lightweight Concrete," *High-Performance Structural Lightweight Concrete*, SP-218, American Concrete Institute, Farmington Hills, MI, 2004, pp. 91-100.
14. Lopez, M., Kahn, L. F., Kurtis, K. E., and Lai, J. S., "Creep, Shrinkage, and Prestress Losses of High-Performance Lightweight Concrete," Research Report for Project No. 2004, Office of Materials and Research, Georgia Department of Transportation, Atlanta, GA, July 2003, 176 pp.
15. ACI Committee 408, "Bond and Development of Straight Reinforcing Bars in Tension, ACI 408R-03, American concrete Institute Committee 408, Farmington Hills, MI., 2003.