RECENT PROJECTS USING LIGHTWEIGHT AND SPECIFIED DENSITY CONCRETE FOR PRECAST BRIDGE ELEMENTS

Reid W. Castrodale, PhD, PE, Carolina Stalite Company, Salisbury, NC
Kenneth S. Harmon, PE, Carolina Stalite Company, Salisbury, NC

ABSTRACT

As the weight of precast elements being designed and constructed for bridges continues to increase, the use of lightweight concrete has become an important design tool to assist designers, fabricators and contractors as they try to take these projects from concept to reality. Recently, the use of specified density concrete, which can be defined as concrete that incorporates lightweight aggregate to reduce its density, has also increased to address handling and transportation concerns for heavy precast concrete elements.

This paper begins by defining specified density concrete. Some of the design issues that need to be considered when using specified density concrete for bridge girders and other elements are then discussed. The focus of the paper is on several recently constructed projects in which lightweight or specified density concrete has been used. Design information about the projects, as well as approaches for specifying specified density concrete, are given. The paper concludes with a brief discussion of cost considerations.

KEYWORDS: Prestressed Concrete, Precast Concrete, Specified Density Concrete, Lightweight Concrete, Bridges, Girders, Piers, Pier Caps, Design, Material Properties, LRFD

INTRODUCTION

The recent push for longer span girders and accelerated construction through the use of precast bridge elements has resulted in the design, production, transportation and erection of some very heavy pieces of concrete. The increased use of large precast elements can certainly accelerate construction and make designs more efficient, but handling and erecting these elements may lead to special challenges that can result in increased costs, such as lost production in a prestress plant, special equipment for hauling, or rental of larger cranes at the project site. In some cases, obtaining permits for shipping heavy loads can lead to project delays.

As the weight of precast elements being designed and constructed for bridges continues to increase, the use of lightweight concrete (LWC) has become an important design tool to assist designers, fabricators and contractors as they try to take these projects from concept to reality. Recently, the use of specified density concrete (SDC), which has a density less than normalweight concrete (NWC), has also increased to address handling and transportation concerns for heavy precast elements.

This paper will discuss the need for reducing the concrete density for precast elements and will briefly address some of the issues that need to be considered when using specified density concrete for bridge girders and other elements. The focus of the paper will be on several recently constructed projects in which lightweight or specified density concrete has been used. Issues that need to be considered when specifying reduced density concrete will be discussed, followed by a brief discussion of cost considerations. A list of references is provided to direct the reader to sources for additional information.

SPECIFIED DENSITY CONCRETE

Specified density concrete is defined by ACI Committee 213 as "Structural concrete having a specified equilibrium density between 50 to 140 lb/ft^3 or greater than 155 lb/ft^3."[1] While the ACI Committee 213 definition includes both lightweight and heavyweight concrete, for the purposes of this paper specified density concrete will be defined as concrete with a density between lightweight and normalweight concrete. Using this definition, specified density concrete is usually achieved by blending lightweight and normalweight coarse aggregates to achieve the desired density.

Table 1 shows the typical densities for lightweight and normalweight concrete for the range of compressive strengths that are generally used in bridge construction. Both fresh and equilibrium densities are given for the lightweight concrete, with only one density is given for normalweight concrete. With specified density concrete, any density between the values shown for lightweight and normalweight concrete can be achieved by varying the quantity of lightweight coarse aggregate used in the mix. For the densities shown in the table, the percent reduction in density from normalweight to lightweight concrete is shown for each concrete strength. The reduction for equilibrium density ranges from 23% for the lowest concrete strength to almost 19% for the highest concrete strength, while the reduction based on fresh density ranges from nearly 20% to about 16%. It should be noted that the densities shown in the table have been computed for suggested mix designs. Results will differ when different materials and proportions are used in the concrete.

Table 1 Fresh and Equilibrium Densities for Range of Concrete Compressive Strengths

	LWC		***NWC***	***% Reduction in Density***	
Compressive Strength (ksi)	***Fresh Density*** (pcf)	***Equilibrium Density*** (pcf)	***Density*** (pcf)	***NWC to Fresh***	***NWC to Equilibrium***
4.5 - Deck	116.5	111.6	145	19.7%	23.0%
6	118.4	114.5	146	18.9%	21.2%
8	122.2	116.8	148	17.4%	20.9%
10	125.9	121.1	150	16.1%	18.7%

Notes:

LWC densities are fresh and equilibrium densities from "Suggested Mix Designs" at www.stalite.com.

NWC densities are computed using the equations for normalweight concrete in Table 3.5.1-1 of the AASHTO LRFD Specifications[2].

Using this table, the fraction of lightweight aggregate required to achieve a given density can be estimated by linear interpolation between the two densities for a given compressive strength. For example, for 6 ksi concrete, if the required density is 128 pcf, just over 50% of the coarse aggregate would need to be lightweight to achieve that density. This is a rough estimate that can be used to estimate the cost of specified density concrete and the reduction multipliers that are applied to specified density concrete for some quantities in design.

DESIGNING WITH SPECIFIED DENSITY CONCRETE

The properties of lightweight and specified density concrete differ in some ways from normalweight concrete. The most significant differences are related to the tensile strength and modulus of elasticity of lightweight concrete. The design codes, such as the *AASHTO LRFD Specifications*[2] and the ACI Building Code (ACI 318)[3], address the differences. The ACI Building Code is currently considering significant revisions to clarify and make more consistent the design provisions related to lightweight concrete.

In the past, the design specifications have not addressed specified density concrete, where the density is between the density of sand-lightweight and normalweight concrete. This has left designers with little guidance for designing members with this type of concrete. Therefore, designers have generally used reduction factors for sand-lightweight concrete when designing with specified density concrete. However, the revisions to the ACI Building Code currently being considered provide a framework for using linear interpolation to compute factors to be used for design of specified density concrete. These or similar changes may be presented to AASHTO to be considered for adoption into the *LRFD Specifications*.

The most significant issues that must be considered in the design of specified density concrete girders and other elements include:

- Compressive strength
- Density
- Modulus of elasticity
- Tensile strength
- Shear
- Development of reinforcement
- Flexural capacity
- Prestress losses

A research program to evaluate the properties of specified density concrete for the Hibernia offshore concrete platform[4] concluded “that the substitution of up to 50% by volume of the normalweight coarse aggregate with a high strength, low absorption structural lightweight aggregate had little effect on the mechanical properties of the concrete with the exception of the modulus of elasticity which was reduced 10-15% … due to the lower modulus of the lightweight aggregate.[5]” Because of this finding, the design of the platform could proceed as if normalweight concrete was being used, except for the use of the reduced modulus of elasticity. The specified density concrete was found to have adequate resistance to the environmental effects of the north Atlantic, including freezing and thawing, chloride ion permeability, and ice abrasion resistance.

The ways in which the different characteristics of lightweight concrete are addressed in the design of prestressed concrete bridge girders are discussed in an earlier paper by the authors[6].

PROJECTS USING SPECIFIED DENSITY CONCRETE

Several of the projects that have recently used specified density concrete for precast concrete bridge elements are discussed below. A final example of how specified density concrete could have been used in substructure elements for a project will also be given. As each project is presented, the reasons that specified density concrete was used will be stated.

In the following projects, the major reason for the use of lightweight or specified density concrete is to reduce the mass of precast elements. This is typically the main justification for the use of reduced density concrete. However, there are other significant benefits for using lightweight aggregate in concrete, including enhanced durability and internal curing. These are discussed by the authors in an earlier paper[7].

SHELBY CREEK BRIDGE – PIKE COUNTY, KY

The successful construction of this bridge is generally taken as the beginning of the use of spliced concrete girders for long-span bridges. Details of the project are given in an article in the *PCI Journal*[8], where it is also recognized as a PCI award winner. A steel bridge was originally designed for the site. The spliced girder bridge was proposed as an alternate design. The bridge spans a deep valley, so the piers are over 200 ft tall with spans of 218 ft. With the combination of the high lift for the crane with the heavy segments, as well as the 140 mile haul from the fabrication plant to the project site, the designer called for specified density concrete for the girders. Concrete with a density of 125 to 130 pcf was used with a specified compressive strength of 7,000 psi. The concrete typically achieved a compressive strength of 6,000 to 7,000 psi in 14 hours, much greater than the specified compressive strength at release of 4,500 psi. The compressive strength at 28 days approached 8,000 psi. Segment weights varied between 135 and 145 kips, which were about 20 kips (12%) lighter than if normal weight concrete had been used. The bridge was opened to traffic in December 1991.

MARK CLARK EXPRESSWAY OVER US ROUTE 17– CHARLESTON, VA

The bridge carrying the Mark Clark Expressway over US 17 and SC 7 is located at the southwest terminus of the expressway. It was designed using normalweight concrete girders. The 74 in. deep bulb tee girders were nearly 151 ft long, and were the longest designed for SCDOT at the time. The specified compressive strength of the girder concrete was 8,000 psi, with a strength at release of 6,350 psi. The girders used 0.6-in. diameter strands. The bridge was completed in 1991.

The fabricator, which was manufacturing the girders in Georgia, was unable to secure a permit for shipping the normalweight girders because of the weight. Therefore, lightweight aggregate was blended into the mix to reduce the density of the concrete from about 148 pcf to 135 pcf. The reduction (about 9%) was enough to reduce the weight of the vehicle and girder below the required limit. A density of 135 pcf was used because it was the lower limit in the definition of "normal-weight concrete" in the *AASHTO LRFD Specifications* and provided the necessary weight reduction.

AUTOMATED PEOPLE MOVER (APM) PROJECT – ATLANTA, GA

This design build project required the fabrication of very large pretensioned box girders with flange widths from 12 to 16 ft wide. The 5 ft deep girders, which span up to 143 ft, support a light-rail system to connect a new remote auto rental facility to Atlanta's Hartsfield-Jackson International Airport. Erection of the girders has recently been completed.

The fabricator wanted to limit the weight of each girder to less than 255,000 lbs, which was the combined lifting capacity of two of their straddle cranes. The design engineer had agreed to try to keep as many girders as possible under this limit. However, when reviewing the design drawings, the fabricator discovered that, when using the actual density of concrete used at the plant and the actual weight of the required reinforcement, the largest girders would weigh 291,000 lbs. This load would force the fabricator to use all four of the straddle cranes at the facility to lift a single girder, which would have a significant negative impact on other operations in the plant. Specified density concrete was identified as a solution to address this issue.

Table 2 Test Data for Trial Batches for Specified Density Concrete

	Fresh Density = 127 pcf		***Fresh Density = 136 pcf***	
Test Age (days)	***f'_c*** (psi)	***E_c*** ($\times 10^6$ psi)	***f'_c*** (psi)	***E_c*** ($\times 10^6$ psi)
0.75	7588	NA	7967	NA
2	8251	3.35	8416	3.53
7	9727	3.71	9548	3.81
14	10390	3.77	11154	3.92
28	10927	3.79	11571	3.90

The fabricator determined that using two reduced density concrete mixes in addition to the normalweight mix would allow all girders to be produced with weights below the 255,000 lb limit. Concrete mixes were then developed to give the minimum specified compressive strength of 8,500 psi and the required densities. Trial batches were prepared and tested to confirm the compressive strength and to obtain the modulus of elasticity for use in design.

Test results for the two specified density trial batches are given in Table 2. The fresh densities shown are measured values, where the target densities for the two mixes were 127 pcf and 139 pcf. The water/cementitious materials ratios for the mixes were 0.31 and 0.28 respectively. The computed equilibrium densities for the two mixes were 123 and 136 pcf, respectively, which demonstrate that for mixes with low water/cementitious materials ratios and higher strengths, the difference between the fresh and equilibrium densities is not large (3 or 4 pcf – see later discussion on specifying reduced density concrete). During the design process it was discovered that the local normalweight aggregate produced concrete with a modulus of elasticity that was about 80% of the value predicted using the equation in the AASHTO design specifications. Therefore, the reduction in stiffness for the specified density concrete compared to locally available normalweight concrete was not as great as initially expected.

SR 66 OVER GREEN RIVER ROAD – EVANSVILLE, IN

This single point urban interchange (SPUI) expressway overpass was recognized with a PCI Award in 2005[9]. Reduced density concrete was specified for the pretensioned girder segments for the long span spliced girder bridge, a practice which is typical of many other prestressed concrete bridge girder projects designed and built in Indiana and Ohio. For this project, which utilized girders that were spliced at integral straddle bents to span distances up to 130 ft, the designers specified a concrete density of 135 pcf to reduce the weight of the girder segments for handling, transportation and erection. The minimum concrete compressive strength was specified as 6,850 psi.

THE MATTAPONI AND PAMUNKEY RIVER BRIDGES – WEST POINT, VA

Two bridges were recently completed carrying VA Route 33 across the rivers that run on each side of West Point, Virginia. Both bridges utilized reduced density concrete for the girders and deck for portions of the bridge with spans over 120 ft. In each bridge there were two four-span spliced girder units with maximum spans of 240 ft. Each spliced girder unit, which was either 875 or 880 ft long and included haunched pier segments, was post-tensioned for its full length prior to placing the deck. The bridges were opened to traffic in 2006 and 2007.

The specified minimum concrete compressive strength for all girders was 8,000 psi with a density of 125 pcf. The specified minimum concrete compressive strength for the cast-in-place composite deck was 5,000 psi with a density of 120 pcf. The designers also specified limiting values for the modulus of elasticity, creep, shrinkage and permeability for both the girder and deck concrete. Researchers at the Virginia Transportation Research Council (VTRC) tested the materials used in the bridges and are monitoring their performance[10]. Reduced density concrete was used in this project to improve the efficiency of the design by increasing span lengths and by reducing foundation loads.

GDOT RESEARCH ON LIGHTWEIGHT CONCRETE BRIDGE GIRDERS

The Georgia DOT was interested in using longer prestressed concrete bridge girders, but were faced with “super load” permits because of the girder weights. As a result, the DOT sponsored research to demonstrate that by using lightweight concrete, girders up to 150ft long could be manufactured and shipped without requiring “super load” permits. Researchers at the Georgia Institute of Technology developed mix designs, characterized material properties of the lightweight concrete, studied the effect of using lightweight concrete girders for bridges, and tested the performance of full-scale girders. They found that the current bridge design specifications could be used for the lightweight concrete[11-14].

In September 2006, GDOT let a bridge project in Coweta County that included lightweight concrete girders with a minimum concrete compressive strength of 10,000 psi and a density of 120 pcf. The project was intended to demonstrate the potential for using high-strength lightweight concrete for prestressed concrete bridge girders, although the designers indicated that lightweight concrete girders were needed to make the design work. The 54-in. deep PCI bulb-tee girders span a maximum of 110 ft. For the shorter flanking spans, lightweight concrete was also used, but with a lower compressive strength requirement.

While this research focused on maximizing the effect of using lightweight concrete by developing and testing concrete with a design compressive strength of 10,000 psi with a density of 120 pcf, the findings are also applicable to specified density concrete.

EDISON BRIDGE – FORT MYERS, FL

These twin bridges, which were each over a mile long, utilized precast columns and pier caps. Using these precast elements allowed the contractor to build each bridge in a year, which was two months faster than convention construction, thus reducing the significant costs associated with over-water construction. The use of plant-produced precast components also provided improved quality of concrete, which results in enhanced durability.

Normalweight concrete was used for the precast substructure elements. The photograph shows one of the piers with tall columns. At this pier, the contractor was not able to lift a full length precast column with the equipment being used at the site, so a cast-in-place column pedestal was required at the base of the precast column. This interrupted the normal routine for footing construction and column erection, requiring a separate concrete placement. From the photo, it appears that the weight of the column would need to be reduced by about 12% in order to eliminate the pedestal. Assuming that the density of the normalweight concrete was 145 pcf, this would mean that the density of the concrete in the column would have to be reduced to 128 pcf to eliminate the need for the cast-in-place pedestal.

The maximum column weight for the project was 89 kips. The maximum pier cap weight was 155 kips. If lightweight concrete with a density of 125 pcf had been used instead of normalweight concrete with a density of 150 pcf (assuming that both densities include a 5 pcf allowance for reinforcement), these maximum weights would be reduced to 74 and 129 kips, respectively.

SPECIFYING REDUCED DENSITY CONCRETE

Contract documents must clearly indicate the intent of the designer regarding the density of specified density concrete. Since the density of the concrete can be measured at different times and in several ways, this can be a source of confusion if the contract documents do not clearly state the density requirements.

Equilibrium density has been adopted by ACI and others as the measure for determining compliance with specified in-service density requirements for lightweight concrete used in buildings. Equilibrium density is the density of the concrete after loss of mass has occurred with time, which is caused by moisture loss from the concrete. According to ASTM C 567[15], equilibrium density may be determined by measurement or computed using either the measured oven-dry density or the oven-dry density calculated from the mixture proportions. Unless specified otherwise, ASTM C 567 requires that equilibrium density be approximated by calculation (see definition and commentary for “concrete, structural lightweight” in ACI 318[3]). For more information on equilibrium density, see Holm and Ries[16] and ACI 213[1].

While the equilibrium density may be specified in the contract documents, it cannot be used for acceptance of concrete at the time of placement. Instead, it is typically used to qualify a mix design, and the corresponding fresh density of the concrete is used as the acceptance criteria when the concrete is placed. Therefore, if the equilibrium density is specified, a relationship must be established by the concrete supplier between the fresh and equilibrium densities, so compliance with the specified equilibrium density can be assured if the fresh density is within specifications. Where handling loads or early age loadings are critical, the fresh density should be used to compute the loads because there will not be enough time for the loss of moisture and weight to occur.

For low absorption lightweight aggregate, the difference between fresh and equilibrium density is usually small, as shown in Table 3, which is based on the data appearing in Table 1. Therefore, neglecting the additional reduction in density with time will usually have only a minor impact on the design. For higher strength specified density concrete, the increased cement content results in small differences between the fresh and equilibrium densities because more of the water is bound by the cement and the permeability is lower, so it is more difficult for moisture to leave the concrete. Furthermore, concrete in bridges is typically exposed to rainfall and higher humidity which may prevent the concrete from reaching the full density reduction reflected by the equilibrium density. Therefore, it is suggested that for most bridge applications the fresh density of the concrete should be specified in the contract documents rather than the equilibrium density.

Table 3 Computed Reduction in Densities for Range of Concrete Compressive Strengths

Compressive Strength (ksi)	***Fresh Density*** (pcf)	***Equilibrium Density*** (pcf)	***Reduction in Density: Fresh to Equilibrium*** (pcf)	(%)
4.5 - Deck	116.5	111.6	4.9	4.2%
6	118.4	114.5	3.9	3.3%
8	122.2	116.8	5.4	4.4%
10	125.9	121.1	4.8	3.8%

Notes:

LWC densities are fresh and equilibrium densities from "Suggested Mix Designs" at www.stalite.com.

The specified density should be stated as a maximum value or a value with a reasonable tolerance. In establishing the tolerance for density, the tolerance on air content should be considered since this has a direct impact on the fresh density. The tolerance on density should be greater than the variation in density that can occur due to the permitted range in air and water contents in order to allow some variation in other mix design parameters.

Since the fresh and equilibrium densities only represent the weight of the concrete, the contract documents must clearly state the density of concrete used for computing dead loads, which must include an allowance for the weight of reinforcement. In most cases, the allowance for reinforcement is taken as 5 pcf, so the density for dead load computations will be greater than the specified density of the concrete by this amount. However, for heavily reinforced members, the designer should compute the actual weight of reinforcement because the usual assumption of 5 pcf may not be adequate.

Other material properties may also be specified as required for the design, such as modulus of elasticity, splitting tensile strength, creep and shrinkage. However, the designer should consult a lightweight aggregate supplier to ensure that any quantities specified beyond density and compressive strength can be achieved economically using reasonable mixtures with available materials. If specifying additional material properties is not essential for the design, which is the case in most situations, the designer should avoid placing additional constraints on the design, production and testing of the concrete mix, since it will add cost.

COST

Lightweight concrete costs more than normalweight concrete because of the additional cost for processing and shipping the lightweight aggregate. There are 18 plants currently producing structural lightweight aggregates in the US, so transportation costs can be a significant component of the cost of the lightweight aggregate. However, the benefits of using lightweight concrete can easily offset the additional cost in many cases.

It is difficult to make a general statement regarding the cost premium for lightweight concrete compared to normalweight concrete because of the differences in the costs of lightweight and normalweight aggregates and factors related to shipping and handling of lightweight aggregate. The premium cost for lightweight concrete typically ranges from $20 to $65 per cubic yard, with higher costs when the aggregate must be shipped a long distance.

While the material cost of specified density or lightweight concrete is greater than normalweight concrete, the advantages of using reduced density concrete for a bridge design can offset the additional cost. To obtain a clear understanding of the difference in cost between a normalweight and specified density concrete design, it is important to consider the impact of the use of reduced density concrete on all parts of the bridge, including bearings, substructure units and foundations. The potential cost savings for handling, transportation and erection should also be considered.

The number of successful projects that have incorporated reduced density concrete demonstrates that its use can reduce overall project costs. An example is the Rugsund Bridge in Norway where use of lightweight concrete, for which the aggregate was imported from the US, resulted in a 15% lower bid price for the lightweight concrete design alternate than for the original normalweight concrete bridge alternate[17]. A design comparison using normal- and lightweight concrete performed by Bender[18] for a precast segmental box girder bridge demonstrated a nearly 15% overall cost reduction when using lightweight concrete. See Castrodale and Harmon[7] for more discussion and comparisons regarding the cost of lightweight concrete bridges.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following contributors of information for this paper: Mike McCool of Beam, Longest and Neff, LLC; Merritt King of Tripplet-King & Associates, Inc.; Joe Golden of Tindall Corp.; Richard Potts of Standard Concrete Products; Massoud Shabazaz of Heath & Lineback Engineers, Inc.; Steve Zendegui of Jacobs Civil; and John Dick of PCI..

CONCLUDING REMARKS

This paper demonstrates that reduced density concrete has been successfully used to address design and construction issues, allowing more efficient and economical bridges to be built. To get additional information on the use of reduced density concrete, readers are encouraged to review the listed references, access more information at the Expanded Shale, Clay and Slate Institute website, escsi.org, or contact the authors.

REFERENCES

1 ACI Committee 213, “Guide for Structural Lightweight-Aggregate Concrete (ACI 213R-03)”, ACI, Farmington Hills, MI, 2003, 38 pp. Also *ACI Manual of Concrete Practice.*

2 *AASHTO LRFD Bridge Design Specifications*, 4th Edition, American Association of State Highway and Transportation Officials, Washington, DC, 2007.

3 ACI Committee 318, “Building Code Requirements for Structural Concrete (ACI 318-03) and Commentary (ACI 318R-03),” ACI, Farmington Hills, MI, 2003. Also *ACI Manual of Concrete Practice.*

4 Hoff, G.C., and Elimov, R., “Concrete Production for the Hibernia Platform,” *Proceedings, Annual Meeting of the Canadian Society of Civil Engineers*, Ottawa, Ontario, 1995.

5 Walum, R., Weng, J.K., Hoff, G.C., and Nunez, R.A., “The Use of High-Strength Modified Normal Density Concrete in Offshore Structures,” *Concrete under severe conditions, environment and loading: Proceedings of the International Conference on Concrete under Severe Conditions*, CONSEC '95, Sapporo, Japan, August 2-4, 1995.

6 Castrodale, R.W., and Harmon, K.S., “Design of Prestressed Concrete Bridge Members Using Lightweight Concrete,” Paper 43, *Proceedings*, 2006 National Bridge Conference, Grapevine, TX, PCI, October 22-25, 2006.

7 Castrodale, R.W., and Harmon, K.S., “Increasing Design Efficiency Using Lightweight Concrete for Prestressed Girder Bridges,” Paper 55, *Proceedings*, 2005 National Bridge Conference, Palm Springs, CA, PCI, October 16-19, 2005.

8 Caroland, W. B., Depp, D., Janssen, H. H., and Spaans, L., "Spliced Segmental Prestressed Concrete I-Beams for Shelby Creek Bridge," *PCI Journal*, V. 37, No. 5, September-October 1992, pp. 22-33.

9 "SR 66 Over Green River Road," *Ascent Magazine*, PCI, Fall 2005, p. 44.

10 Ozyildirim, C., and Davis, R.T., "Lightweight HPC Bulb-T Beams in the Mattaponi River Bridge," Paper 37, *Proceedings*, 2005 National Bridge Conference, Palm Springs, CA, PCI, October 16-19, 2005.

11 Meyer, K. F. and Kahn, L. F., "Analytical Investigation of Lightweight Concrete for High Strength/High Performance Precast Prestressed Bridge Girders," Task 1 Report, Georgia Department of Transportation, Project No. 2004, Georgia Institute of Technology, January 2000, 27 pp.

12 Buchberg, B., and Kahn, L. F., "Investigation of Mix Design and Properties of High-Strength/High-Performance Lightweight Concrete," Task 2 and 3 Report, Georgia Department of Transportation, Project No. 2004, Georgia Institute of Technology, January 2002, 233 pp.

13 Lopez, M., Kahn, L.F., Kurtis, K.E., and Lai, J.S., "Lightweight Concrete for High-Strength/High-Performance Precast Prestressed Bridge Girders," Task 3 Report, Georgia Department of Transportation, Project No. 2004, Georgia Institute of Technology, Revised December 2003, 320 pp.

14 Kahn, L. F., Kurtis, K. E., Lai, J. S., Meyer, K. F., Lopez, M, and Buchberg, B., "Lightweight Concrete for High Strength/High Performance Precast Prestressed Bridge Girders," Final Report, Georgia Department of Transportation, Project No. 2004, Georgia Institute of Technology, Revised November 2004, 155 pp.

15 ASTM C 567, "Test Method for Density of Structural Lightweight Concrete," *Annual Book of ASTM Standards*, Vol. 04.02, ASTM, West Conshohocken, PA, 2004.

16 Holm, T. A. and Ries, J. P., "Lightweight Concrete and Aggregates," Chaper 46 in *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, Special Technical Publication 169D, ASTM, West Conshohocken, PA, 2006. *Available as reprint from ESCSI.*

17 Harmon, K. S, "Norway Bridges Using High Performance Lightweight Aggregate Concrete," *High-Performance Structural Lightweight Concrete*, SP-218, J. P. Ries and T. A. Holm, eds., ACI, Farmington Hills, Mich., 2004, pp. 189-197.

18 Bender, B. F., "Economics and Use of Lightweight Concrete in Prestressed Structures," *PCI Journal*, V. 25, No. 6, November-December 1980, pp. 62-67.