# CRITERIA FOR DESIGNING LIGHTWEIGHT CONCRETE BRIDGES

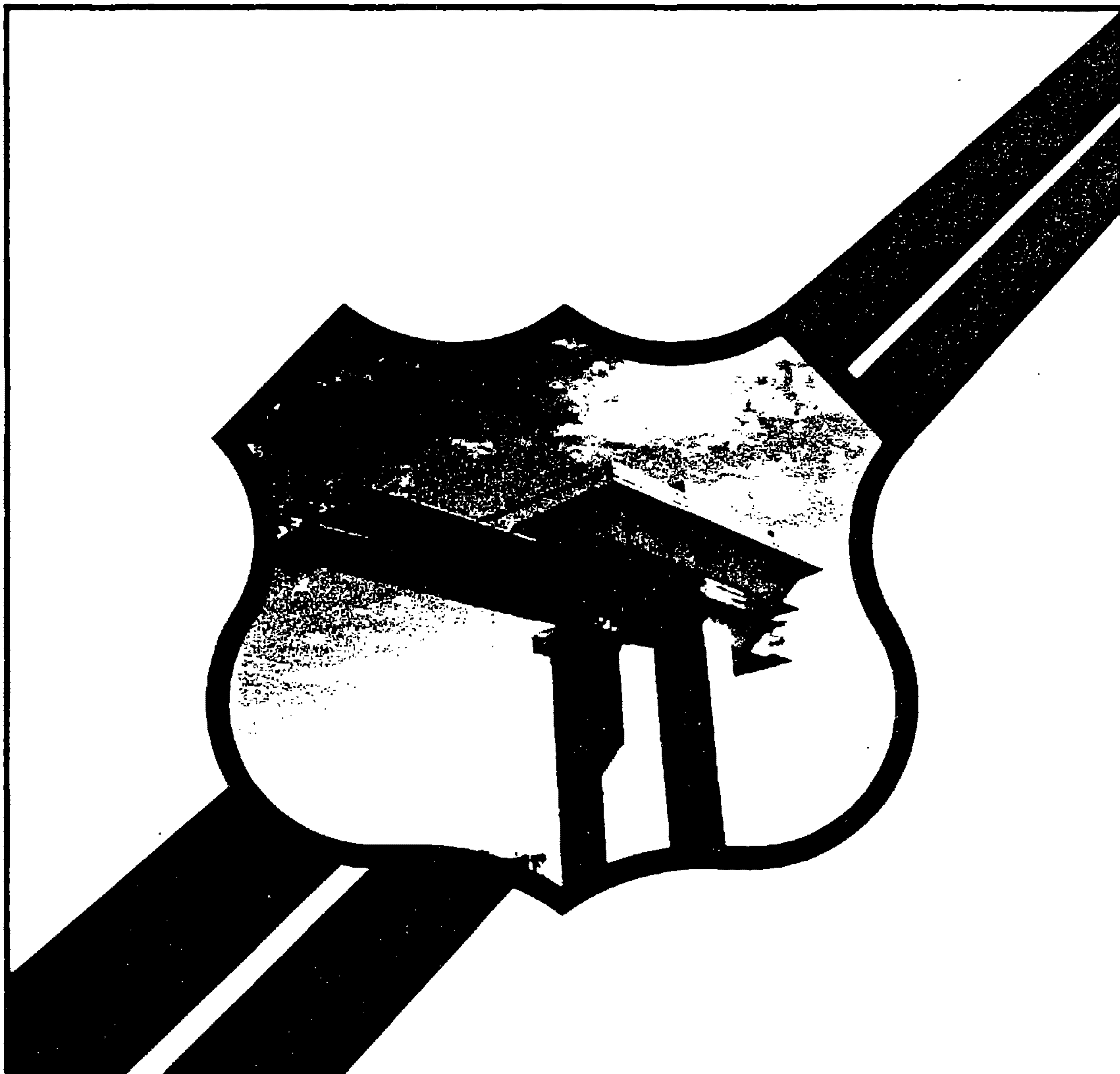
and Technology
Turner-Fairbank Highway
Research Center
6300 Georgetown Pike
McLean, Virginia 22101

Report No.
FHWA/RD-85/045

Final Report
August 1985

U.S. Department
of Transportation

**Federal Highway Administration**



## FOREWORD

This report documents the results of a study which evaluated existing information on the design, construction and serviceability of highway bridges and bridge decks built with lightweight concrete. It includes a review of information on lightweight aggregates, currently used structural design criteria as well as limitations to the use of lightweight concrete.

It is hoped that this report will provide guidance for the economic use of the material in the design, construction and rehabilitation of reinforced and prestressed concrete highway bridges.

Sufficient copies of the report are being distributed to provide a minimum of two copies to each regional office, one copy to each division office and two copies to each State highway agency. Direct distribution is being made to the division offices.

Richard E. Hay
Richard E. Hay, Director
Office of Engineering
and Highway Operations
Research and Development
Federal Highway Administration

## NOTICE

**Technical Report Documentation Page**

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| FHWA/RD-85/045 | | PB86 126315/AS |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| CRITERIA FOR DESIGNING LIGHTWEIGHT CONCRETE BRIDGES | August 1985 |
| | 6. Performing Organization Code |
| | 8. Performing Organization Report No. |
| 7. Author(s)<br>T.Y. Lin International | |
| 9. Performing Organization Name and Address<br>T.Y. Lin International<br>315 Bay Street<br>San Francisco, California 94133 | 10. Work Unit No. (TRAIS)<br>35K3-262<br>11. Contract or Grant No.<br>DTFH61-83-C-00063<br>13. Type of Report and Period Covered |
| 12. Sponsoring Agency Name and Address<br>Office of Research, Development, and Technology<br>Federal Highway Administration<br>6300 Georgetown Pike<br>McLean, Virginia 22101 | Final Report<br>Oct. 1983 - Dec. 1984<br>14. Sponsoring Agency Code |

15. Supplementary Notes

FHWA Contract Manager - Thomas Krylowski, HNR-10

16. Abstract


The state of the art pertaining to the use of lightweight concrete in the design, construction, and maintenance of bridges, is presented in this report. It includes a review of the history of the development of lightweight concrete, its properties and limitations, and its production. It evaluates the performance and experience of 12 selected study cases from visits and visual inspection, and reports on the current policies and practices in several states in the use of lightweight concrete. Analytical study is conducted to develop data on material economics for lightweight and normal-weight concretes in various applications.

The report concludes with a list of the findings as a result of this effort, and recommends future actions. It also includes references and bibliography, and provides guide specifications and field control procedures for the benefit of potential users of lightweight concrete.


| 17. Key Words | 18. Distribution Statement |
|---|---|
| lightweight concrete, normal-weight concrete, slate, shale, clay, rotary kiln, segmental box girders, plate girders, AASHTO I girders, cable-stayed | No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161. |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 157 | |

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEGMENT

Grateful appreciation must be recorded for the cooperation and contributions received from the many State bridge engineers, technical institutions, among which the Expanded Shale, Clay, and Slate Institute must be mentioned, contractors, and aggregate manufacturers whose participation in this effort is vital to its success. Special thanks are due to Professor Milos Polivka of the University of California, whose authoritative counseling and reviews have added greatly to the report.

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# INTRODUCTION

This report has been prepared for the Federal Highway Administration (FHWA), to study the state of the art of lightweight concrete in application to structures, particularly bridge structures. Its main purpose is to investigate the performance and potential of lightweight concrete for bridge use. Although not intended to be a manual of practice, it should provide the bridge designers with useful information on past experience when considering the possible use of lightweight concrete in their structures.

Lightweight concrete is concrete containing lightweight aggregates, coarse or fine or both, which make it lighter in weight than concrete made with normal-weight coarse aggregates and sand. Lightweight aggregates are generally classified as naturally occurring materials, industrial byproducts, and expanded shales, clays, and slates. Naturally occurring aggregates come mainly from volcanic deposits, such as pumice or scoria. Industrial byproducts include such materials as expanded blast-furnace slag or sintered fly ash. Expanded shale, clay, and slate aggregates are formed by expanding or bloating the materials with heat. The latter type of aggregates are commonly used in structural concrete, and are therefore of prime interest in bridge design and construction. A summary of the present state of the technology is given in ACI 213 report "Guide for Structural Lightweight Aggregate Concrete."(1)*

The main attraction of structural lightweight concrete is its lower unit weight, which is about 115 pcf (1,760 kg/m$^3$). It is therefore mostly used in structures where weight reduction is an important economic or design consideration.

*Numbers denote references listed at the end of the report.

The first extensive use of structural lightweight concrete was in the building of ships during World War I. Its use soon spread to buildings, and then to bridges. On a volume basis, lightweight aggregates are at present mostly used in the production of concrete masonry blocks for buildings. Other uses in the building industry include lightweight structural members, both cast-in-place and precast. The lighter concrete weight is especially advantageous for the transportation and erection of precast concrete members.

Lightweight concrete has become established in the building construction industry. Building designers and contractors are familiar with the material, and have routinely used it where it is economically or functionally justified.

The acceptance of lightweight concrete in the construction of bridges has been slower than in buildings. So far, it has mainly been used in roadway decks over steel girders. Only occasionally is it used in the primary structural members of a bridge.

The performance of the lightweight concrete in bridges has generally been satisfactory, but there have been problems. Most of the problems have to do with the specifications of the concrete, its placement in the field, and the familiarity with its behavior. There have also been conflicting opinions regarding the occasional poor performance of the material.

Although there is no consensus of opinion concerning the suitability of lightweight concrete for bridge structures, nor concerning experiences with its performance, it should be noted that the material does have sufficient record of successful applications to make it a suitable construction material for buildings and ships, as well as for bridges.

Sufficient information is available on all aspects of its performance for design and construction purposes. Much of this report is in fact based upon available publications, a selected list of which is given in the references. Other important reference publications are presented in the bibliography.

To be useful this report must provide information concerning the state of the art and experiences with the use of lightweight concrete in bridges. For this reason considerable effort has been made to collect relevant data from past users, the industry, and institutions. The data-collection program included the following:

- A search for pertinent literature.

- Inquiries through personal contact with key individuals in the industry and institutions, together with a survey of United States and Canadian rotary-kiln producers of expanded shale, clay, or slate aggregate.

- Survey of bridge engineers from 23 States.

- Invitation to four selected State bridge departments to report on their experiences in the use of lightweight concrete.

- Visits to lightweight-aggregate manufacturing plants.

- Visits to 30 bridge projects using lightweight concrete.

The data collected were studied, analyzed, and the results developed for presentation in this report.

# HISTORY

Modern lightweight aggregate had its start in the United States when Stephen J. Hayde came upon the idea of expanding shale and clay by heat treatment into a porous but hard lightweight material, suitable as aggregate in structural concrete. By 1917 he had developed the rotary-kiln method of heating and expanding shales and clays.

Structural lightweight concrete with expanded shale aggregate was first used in ships and barges during World War I. In June 1919, the Emergency Fleet Building Corporation built the USS "Selma", a 7,500-ton tanker, as the first of 14 vessels to be constructed with lightweight concrete. The concrete had a compressive strength of 5,000 psi (35 MPa) and a unit weight of 110 pcf (1,700 kg/m$^3$).

The first recorded major buildings using lightweight concrete were the Park Plaza Hotel in St. Louis and the Southwestern Bell Telephone Company in Kansas City, both built in 1928. The earliest reported use of lightweight concrete in U.S. bridges dates back to 1922. During the 1920's, about a dozen bridges were built using expanded-shale lightweight concrete.

During World War II, lightweight concrete was again used in shipbuilding. Of the 104 lightweight-concrete vessels constructed, 80 were sea-going barges. After the war, the Housing and Home Financing Agency and the National Bureau of Standards conducted the first investigations of the properties of various lightweight aggregates for possible application to land structures. In the spring of 1952, the Expanded Shale, Clay, and Slate Institute was formed by the rotary-kiln producers of lightweight aggregates for the purpose of developing technical data and promoting the young industry.

Starting in the 1950's, lightweight concrete was used in buildings and bridges throughout the United States. The number of lightweight-aggregate plants was increased, reaching a maximum in 1970. High energy costs in the mid-1970's forced some of them out of business. Today there are 23 plants still in operation in the United States.

Lightweight concrete made a significant impact on the building industry because of its weight. In one of the earlier uses, four stories were added to a department store in Cleveland without strengthening the foundation. Its use quickly spread to high-rise buildings, such as the 42-story Prudential Life Building in Chicago, and the 18-story Statler Hotel in Dallas, both built in 1955. The twin towers of Chicago's well-known 60-story Marina City, reaching a height of 588 ft (179 m), were built of lightweight concrete.

Lightweight concrete proved especially advantageous for precast concrete work, since it permits the use of lighter handling equipment. In garages and other long-span structures, lightweight concrete has been prestressed to achieve better clearances and greater economy. In tilt-up construction, lightweight concrete permits the use of larger wall panels. Similarly, lift slabs can be made larger, and shell structures, such as the Trans World Airline's (TWA) terminal at John F. Kennedy Airport in New York, can be reduced in thickness with lightweight concrete.

Lightweight concrete has also contributed to the efficiency of bridge construction. One example is the reconstruction of the Tacoma Narrows Bridge in the State of Washington. By using lightweight-concrete deck slabs, additional traffic lanes were added without strengthening the original foundation. In the

Evergreen Point floating bridge across Lake Washington, lightweight concrete was used to reduce the weight and the draft of the floating pontoons. Lightweight concrete became widely used for decks in steel bridges, particularly long-span bridges. One prominent example is the San Francisco-Oakland Bay Bridge in California. Lightweight concrete has often been used for girders and other structural members in bridges. More recently, it has been used in segmental concrete cantilever bridges to reduce the amounts of reinforcing and posttensioning steel and, equally important, the weight and size of the handling equipment.

LIGHTWEIGHT AGGREGATE AND ITS PRODUCTION

The term "lightweight aggregate" refers to aggregates having a specific gravity considerably lower than that of fine and coarse aggregate used in normal-weight concrete.

## CLASSIFICATION

Lightweight aggregates differ in geologic origin as well as in manufacturing methods. The chart in figure 1 shows the common range and basic classification according to unit weight and strength.

The low-density concretes, shown at the bottom of the chart, range in weight from about 20 to 50 pcf (320 to 800 kg/m$^3$) and from 100 to 1,000 psi (0.7 to 7.0 MPa) in strength. These concretes have good heat-insulating properties, and are used primarily as insulating concretes. In the center of the chart are the moderate-strength concretes, which are mostly made of natural aggregates, such as pumice and scoria. These concretes have unit weights of up to 85 pcf (1,360 kg/m$^3$) and strengths in the 1,000 to 2,500 psi (7.0 to 17 MPa) range. They are known as "fill concretes," because of their primary use as insulation and filler materials. At the top of the chart are the structural concretes that use expanded shale, clays, and slates produced by rotary kilns, and expanded slag and sintered shale, clay, or fly ash. These concretes have compressive strength above 2,500 psi (17 MPa) and air-dry unit weight of up to 115 pcf (1,840 kg/m$^3$).

## AVAILABILITY OF LIGHTWEIGHT AGGREGATE

Lightweight structural aggregate, unlike normal-weight aggregate, is produced in more sophisticated, capital-intensive plants. A list of lightweight-aggregate plants is included in appendix 1.

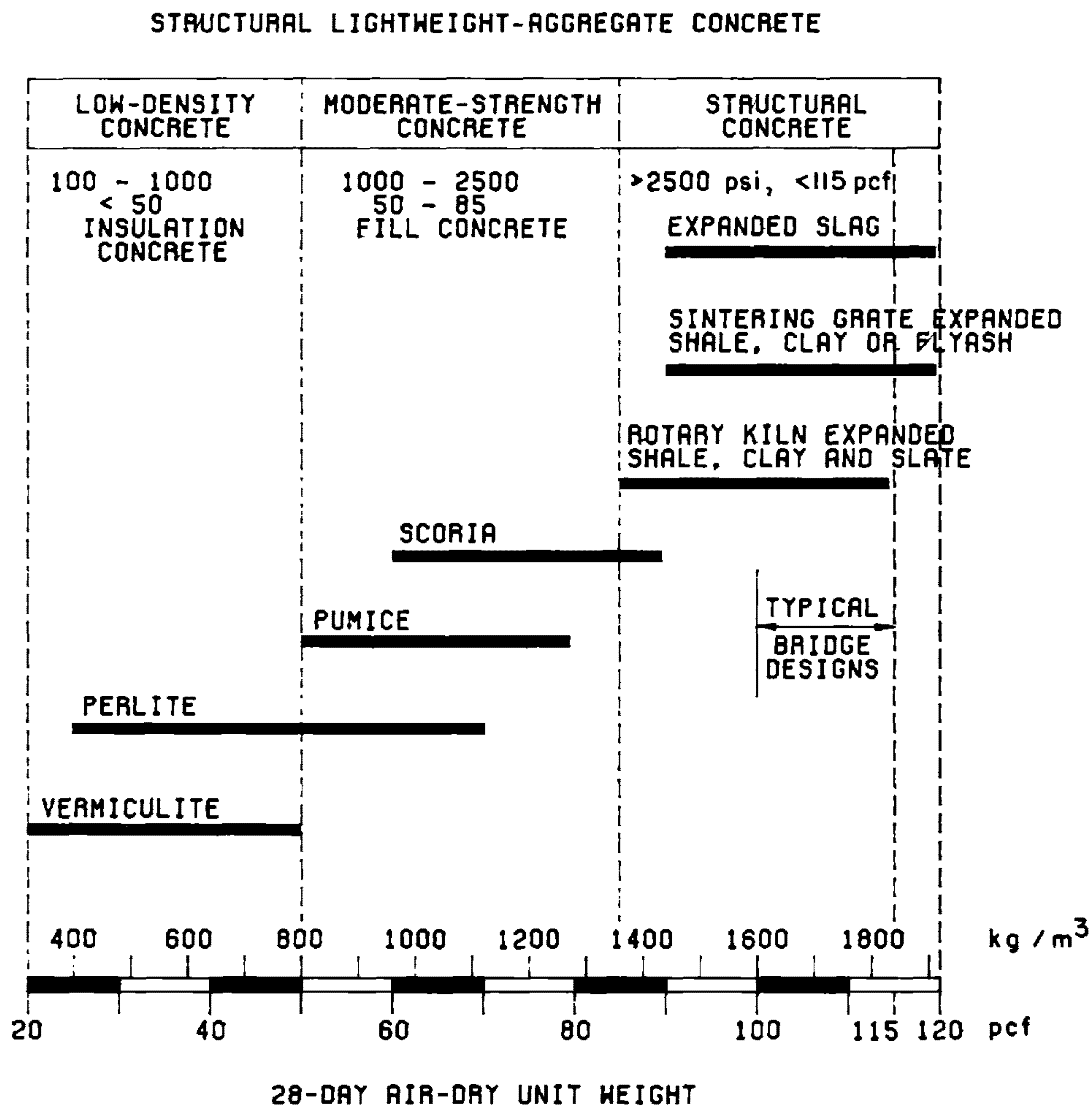



Figure 1. Approximate unit weight and uses classification of lightweight aggregate concretes.(1)

Lightweight-aggregate producers tend to be concentrated in the Midwest, Middle South, East, and California (figure 2). It is seen from this figure that slates and shales are found primarily on the East Coast; shales in the West and central region; and clays in the West, Central South, and South. Figure 3 shows lightweight-concrete usage in the United States, in terms of volume or surface area with respect to the unit weights of concrete used for buildings and bridges. It can be seen from these figures that while lightweight concrete is used throughout the United States, it is used more in areas close to the aggregate sources.

There are 23 structural aggregate plants in the United States, and all produce aggregates by the rotary-kiln method. Fifty-five percent of the structural aggregate producers expand shale, 27 percent clay, and 18 percent slate.

## SPECIFICATIONS

The requirements for lightweight aggregate for the production of structural lightweight concrete are given in AASHTO M 195(2) and in ASTM C330.(3) The aggregates are classified as follows:

### Fine Aggregate

Graded per ASTM C330.(3) Eighty-five to 100 percent passing No. 4 sieve; maximum dry loose weight 70 pcf (1,120 kg/m$^3$).

### Coarse Aggregate

Graded per ASTM C330.(3) Maximum size designations generally are 3/4, 1/2, and 3/8 in (19, 13, and 9 mm); maximum dry loose weight is 55 pcf (880 kg/m$^3$).

## PROPERTIES

Among the significant properties of lightweight aggregates are the following:


Figure 2. Distribution of lightweight aggregate producers in the United States.

| CONCRETE USAGE IN $yd^2$ AND $yd^3$ | | | |
|---|---|---|---|
| $yd^2$ ($0.84\ m^2 = 1.00\ yd^2$) | | $yd^3$ ($0.76\ m^3 \doteq 1.00\ yd^3$) | |
| 600 - 5,000 | | 0 - 500 | |
| 5,000 - 15,000 | | 500 - 2,000 | |
| 45,000 - 100,000 | | 2,000 - 6,000 | |
| 150,000 - 300,000 | | 6,000 - 8,000 | |
| 800,000 - 900,000 | | NO REPORTED USE | |

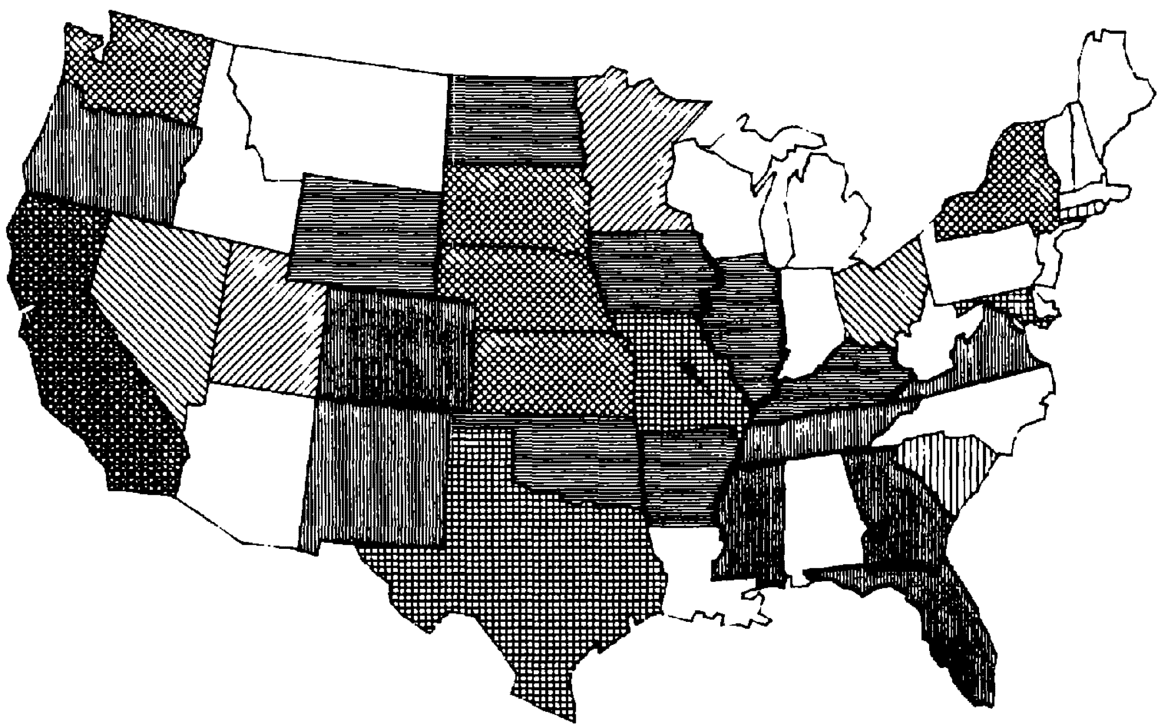


Figure 3. Lightweight concrete usage throughout the United States.

### Water Absorption

Water is absorbed by the pores or cells in the aggregate which are open to the atmosphere. Water absorption of expanded shale is much greater than that of normal-weight aggregate. The amount varies with particle size: the larger the particle size, the greater the porosity, and therefore the greater the absorption. Water absorbed after a 24-hour soaking period may be 15 to 25 percent of the dry weight for coarse aggregate, and 5 to 10 percent for fine aggregate. The absorption of a fully saturated expanded shale coarse aggregate may be 40 to 50 percent. Water absorption of normal-weight aggregate is commonly or usually less than 3 percent. The disparity is due to the cellular structure of the lightweight aggregate.

Water absorption affects the bulk density and some of the properties of lightweight concrete. High water absorption may cause severe slump loss during pumping or placement of the concrete if the aggregate is not adequately presaturated. Slump loss can also be reduced by vacuum or thermal saturation of the aggregate.

### Strength

The compressive strength of expanded shale aggregates varies with the source and the maximum size of the aggregate used: the larger the aggregate size, the lower the strength. Strength characteristics of a given source are best evaluated by tests.

### Bulk Specific Gravity

The saturated surface-dry specific gravity of an expanded shale aggregate is about 1/2 to 2/3 that of normal-weight aggregate. It varies with particle size, ranging from less than 1 for coarse aggregates to 2.2 for fine particles. In comparison, normal-weight aggregate has a specific gravity of about 2.7.

## PRODUCTION

The production of the expanded-shale type of lightweight aggregates consists of heating selected raw materials to high temperatures under controlled conditions. Two methods of manufacture are employed: the "Rotary-Kiln" method and the "Sintering" method. In each case, the raw material is heated until it becomes soft and pliable, but not to the point of melting. The raw material is highly siliceous, and forms gases at the temperature of incipient fusion. The softened mass of the raw material becomes sufficiently viscous to trap the gases, and to form masses of small unconnected air cells. This cellular structure is retained after the material cools.

In the rotary-kiln method, the raw material is introduced into the higher end of a slightly inclined rotary kiln, which is a long, steel cylinder lined with refractory material, and heated to a temperature of about 2,000 °F (1,100 °C). With the turning of the cylinder, the material is moved toward the lower end of the kiln. Control of material expansion is accomplished by varying rotation speed, temperatures, feed rate, and retention time. The material is cooled after leaving the kiln.

There are variations to the crushing and grading of the material. It could be presized by crushing and screening or by pelletizing, before it is introduced into the kiln. Rounded particles or pellets with a relatively smooth exterior surface are produced as a result. In another method, crushing and grading are carried out after the expanded material leaves the kiln. In this case, particles with more angular surfaces are produced. Sometimes both methods are used, with the coarse material crushed and presized before entering the kiln, and the fine material crushed and graded after it leaves the kiln.

In the sintering process, pulverized fuel is mixed with the raw material to enable it to burn. The expansion of the material takes place on a moving grate which is heated by burners below. Burning begins at the surface of the raw material, and continues through its depth. Gases are formed to produce clinkers with a cellular structure, similar to the rotary-kiln process. The clinker is cooled, crushed, and graded, producing a fairly angular aggregate. In some cases, the raw material is first pulverized and mixed with moisture and fuel before burning, producing a generally rounded or cylindrical-shaped aggregate.

Both rotary-kiln and sintering methods produce aggregates of hard, vitreous, cellular structure. The unit weight of lightweight aggregates ranges from 30 to 55 pcf (480 to 880 $kg/m^3$) for coarse aggregates, and 45 to 70 pcf (720 to 1,120 $kg/m^3$) for fine aggregates.

The rotary-kiln is the preferred method of production, and accounts for more than 90 percent of the aggregates used in structural lightweight concrete. Sintered aggregate is mostly used in making lightweight concrete blocks, and seldom as structural concrete. Therefore, this report addresses structural lightweight concrete using only the aggregates produced by the rotary kilns.

## PROPERTIES OF LIGHTWEIGHT CONCRETE

Structural lightweight concretes are concretes having a 28-day compressive strength of above 2,500 psi (17 MPa), and a 28-day air-dry unit weight not exceeding 115 pcf (1,840 kg/$m^3$). However, the unit weight may be as much as 120 pcf (1,920 kg/$m^3$) for the higher-strength mixes required in some structures. Since the proportioning and the placement of lightweight concrete have to do with its properties, it is pertinent to include these topics in this discussion.

### PROPORTIONING AND FIELD PLACEMENT

The principles governing the proportioning of lightweight concrete are about the same as for normal-weight concrete. Special attention must be given to the adjustments in the amount of mixing water because of the unusual water absorption characteristics of lightweight aggregates. Mix design for the required strengths must be established by trial mixes, not by arbitrary specifications of quantities. Standard practice for proportioning concrete is given by the ACI Committee 211 report, "Recommended Practice for Selecting Proportions for Structural Lightweight Concrete."[4]

Cement content requirement for lightweight concrete will vary with the sources of aggregate. Aggregate producers usually furnish information on cement-content requirement to achieve the desired concrete strength.

Lightweight-concrete mixes may contain a higher percentage of fines due to the angular shape and the rough surfaces of the aggregates. Coated lightweight aggregates require less fines, being similar to gravel-type aggregates. The use of natural sand instead of lightweight fines is more economical, but will increase the unit weight of the concrete.

In general, workable mixes of lightweight aggregates have a higher percentage of fines by weight compared to normal-weight aggregates (45 to 60 percent for lightweight compared to 35 to 45 percent for normal-weight).

Air entrainment is used to increase workability and freeze-thaw durability. Entrainment of less than 4 percent air is not effective, and does not improve durability. Recommended ranges are 6 to 8 percent for 3/4-in (19-mm) aggregate, and 7 to 9 percent for 3/8-in (9.5-mm) aggregate. The improved workability also permits a reduction in the water requirement while maintaining the same slump, thereby reducing bleeding and segregation. As with normal-weight concrete, chemical admixtures may be used in lightweight concrete, ASTM C494.[5]

Placing and finishing are essentially the same as for normal-weight concrete. Slump is important, and should not exceed 3 to 4 in (75 to 100 mm) in order to reduce segregation. At these low slumps, good workability should be easily achieved with air-entrained concrete. A 3- to 4-in (75- to 100-mm) slump for lightweight concrete is equivalent in workability to a 4- to 5-in (100- to 125-mm) slump for normal-weight concrete.

Pumping is feasible. However, the aggregates must be sufficiently saturated to minimize water absorption caused by the pumping pressure and thus avoid slump loss during pumping.

## BASIC PROPERTIES OF LIGHTWEIGHT CONCRETE

In general, the properties of lightweight concrete are not unlike those of normal-weight concrete. However, there are some significant differences. These will be discussed in the following sections.

Unit Weight

Average air-dry unit weight of lightweight concrete ranges from 100 to 110 pcf (1,600 to 1,760 kg/$m^3$) for concrete using all lightweight aggregates, and 105 to 120 pcf (1,680 to 1,920 kg/$m^3$) for concrete using normal-weight sand. Air-dry unit weight, determined by ASTM C567 on a concrete specimen cured for 7 days and dried for 21 days, is generally about 5 pcf (80 kg/$m^3$) lighter than the unit weight of freshly mixed concrete.[6] When lightweight aggregates are vacuum or thermally saturated, the weight loss would range from 8 to 10 pcf (130 to 160 kg/$m^3$). Weight loss continues for at least 60 days after casting. Equilibrium is reached 90 days or more after casting.

The unit weight of a lightweight-concrete mix is related to its strength; the higher the strength, the higher the unit weight. A graph showing this relationship is given in figure 4.

Compressive Strength

Compressive strength of up to 5,000 psi (35 MPa) can be easily achieved. For higher strengths of up to 7,000 psi (50 MPa), high-quality aggregate must be used. Concrete strength also depends upon the size of the aggregates; the smaller the aggregate the stronger and heavier the concrete will become. Common aggregate sizes range from a maximum of 3/4 in (19 mm) to 5/16 in (8 mm).

Compressive strength can be increased by substituting normal-weight sand for lightweight-fine aggregates. Figure 5 shows the relationship between 28-day compressive strength and cement content for structural lightweight concretes using 3/4-in (19-cm) coarse aggregate with lightweight fines or normal-weight sand.[4]

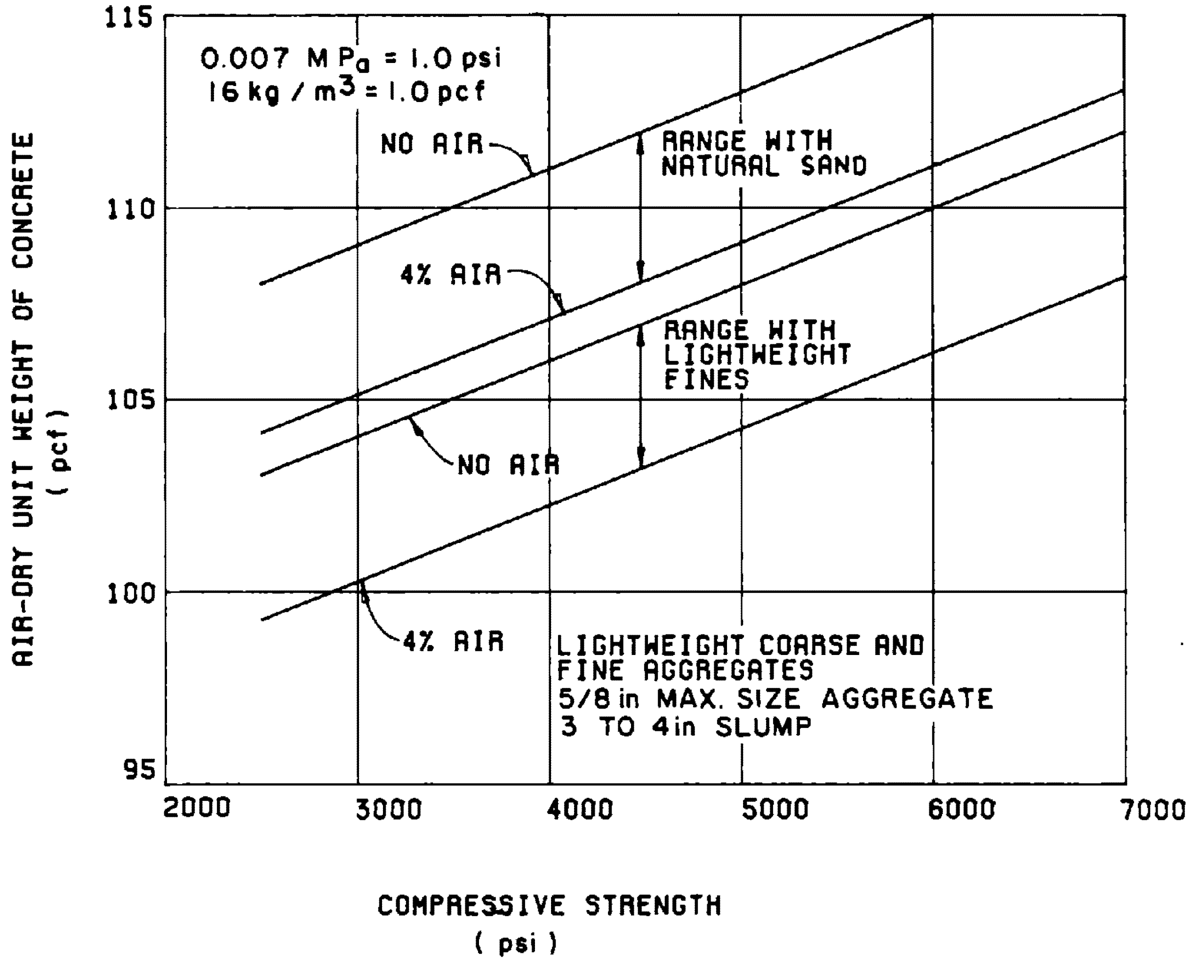



Figure 4. Air-dry unit weight of lightweight concrete vs. compressive strength.

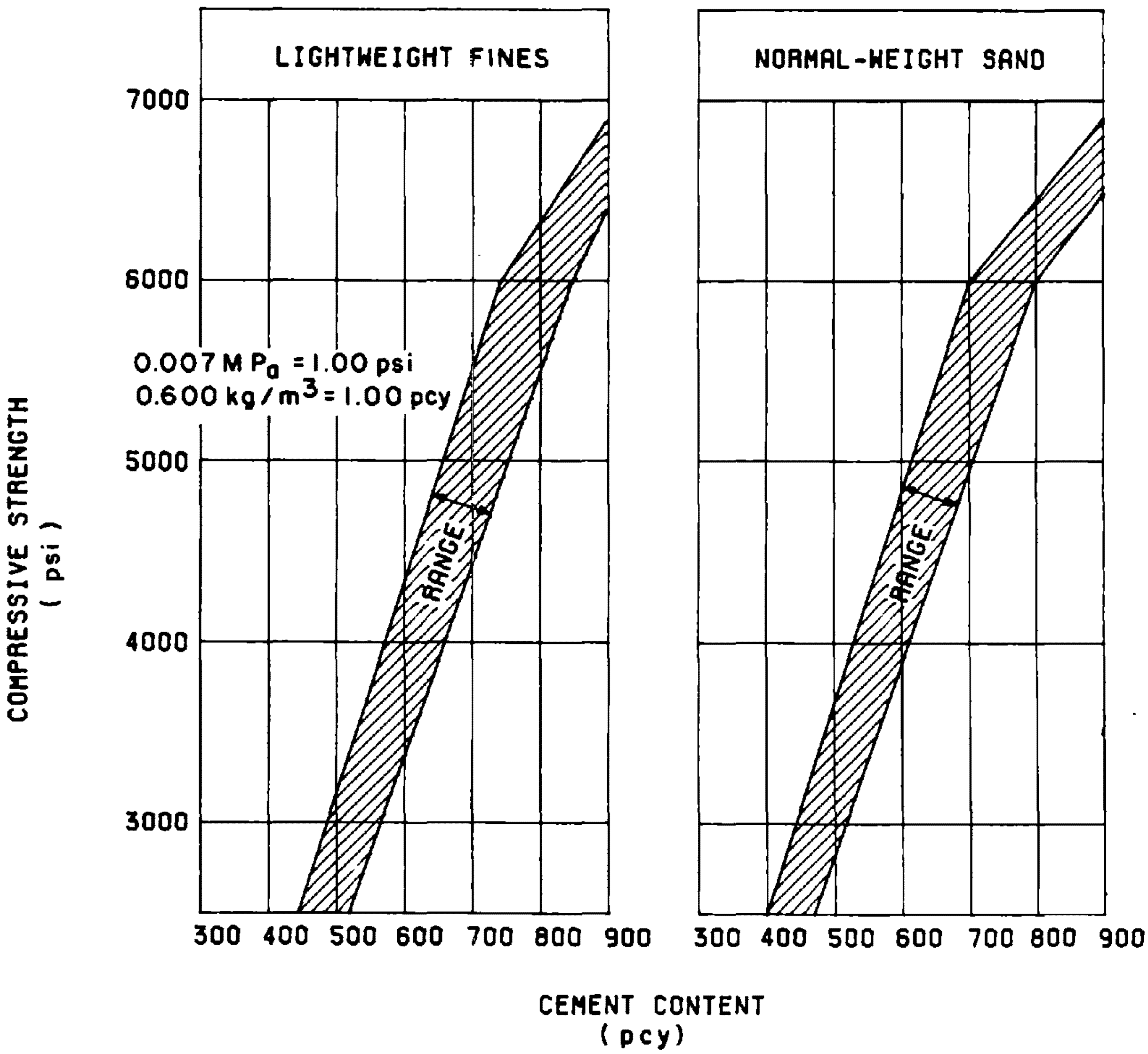



Figure 5. Sample relationship between 28-day compressive strength and cement content for structural lightweight concretes using 3/4-in (19-cm) coarse aggregates with lightweight fines or normal-weight sand.[4]

## Flexural and Tensile Strength

Tensile strength of concrete is determined by the splitting tensile strength of cylinders as specified in ASTM C496.(7) For moist-cured concrete, the tensile strength varies with compressive strength, and is nearly equal to the tensile strength of normal-weight concrete of equal compressive strength. For air-dry concrete, the splitting strength is roughly 70 to 100 percent of that for normal-weight concrete. Substitution of sand for lightweight fines increases tensile strength. The relationship between splitting tensile strength and compressive strength of lightweight concrete is similar to that of normal-weight concrete, as shown in figure 6. The flexural strength, or modulus of rupture, is also a measure of tensile strength, and can be determined by test using a simple beam with third-point loading, as described in ASTM C78.(8)

## Modulus of Elasticity

The modulus of elasticity of structural lightweight concrete can be computed by the formula in the ACI Code:(9)

$$E_c = 33\ w_c^{1.5}\sqrt{f'c}\ \text{(in psi)} \quad (0.043\ w_c^{1.5}\sqrt{f'c}\ \text{(in MPa)})$$

where $w_c$ is the concrete unit weight in pcf ($kg/m^3$), and $f'_c$ the cylinder strength at 28 days. The modulus of elasticity can also be determined by tests in the laboratory following ASTM C469 test procedure.(10) At high-strength levels, the computed values using the ACI code formula will frequently be higher than the values obtained by test. Figure 7 shows test values of $E_c$ for a concrete using one particular expanded-shale aggregate compared to those computed by the ACI formula. Figure 8 shows $E_c$ for concrete mixes of various unit weights and compressive strength computed by the ACI formula.

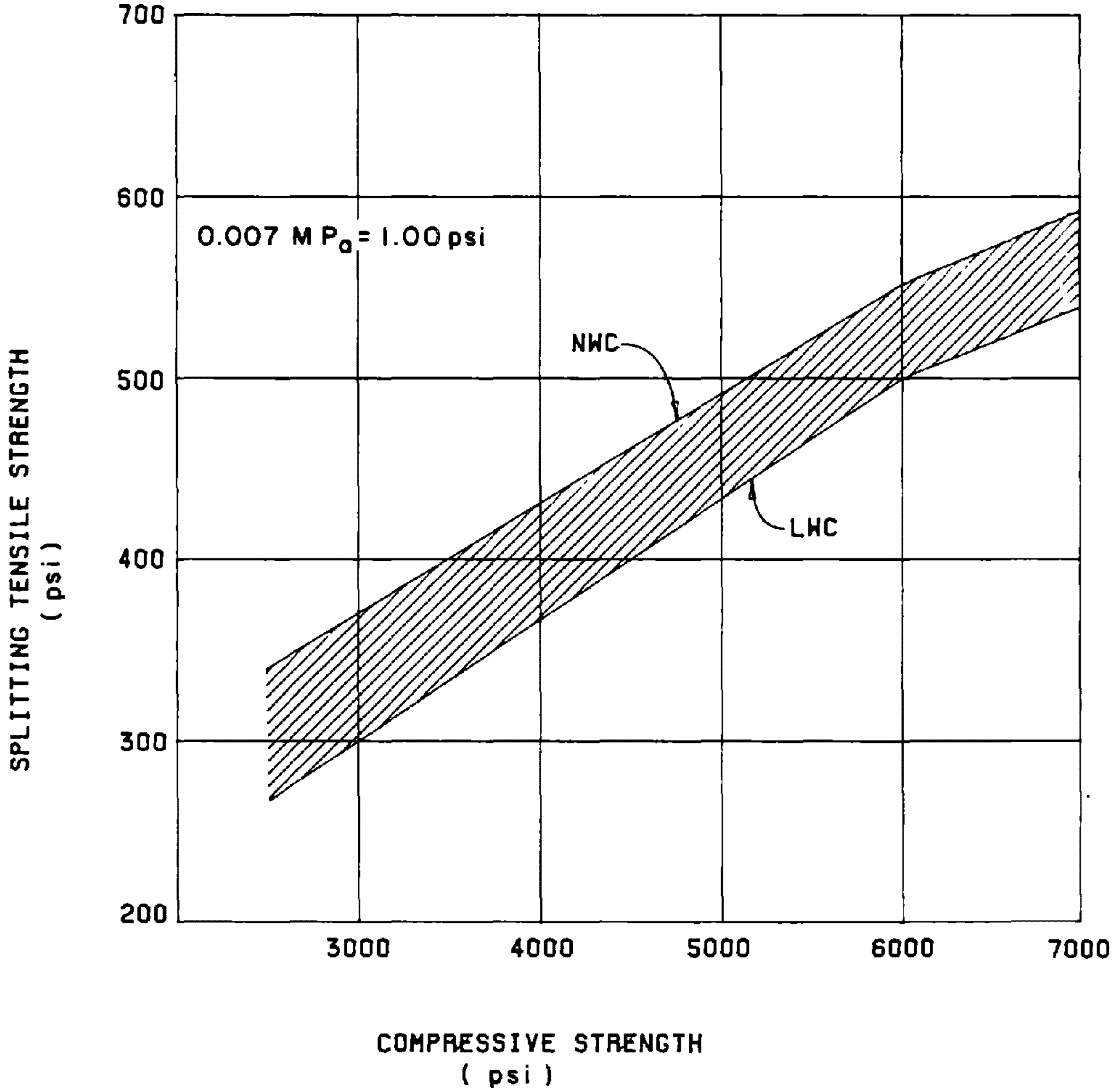



Figure 6. Splitting tensile strength vs. compressive strength for normal and lightweight concretes.

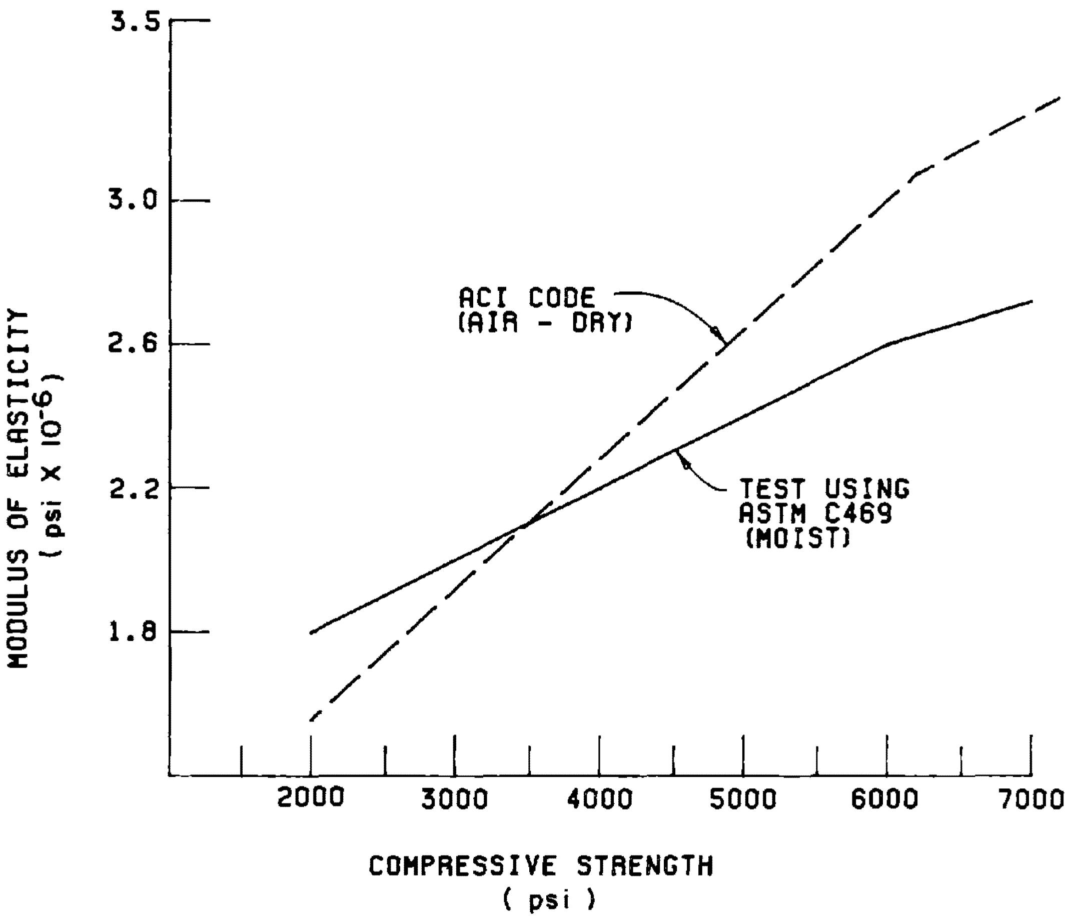



Figure 7. Modulus of elasticity as a function of compressive strength for a particular lightweight concrete.

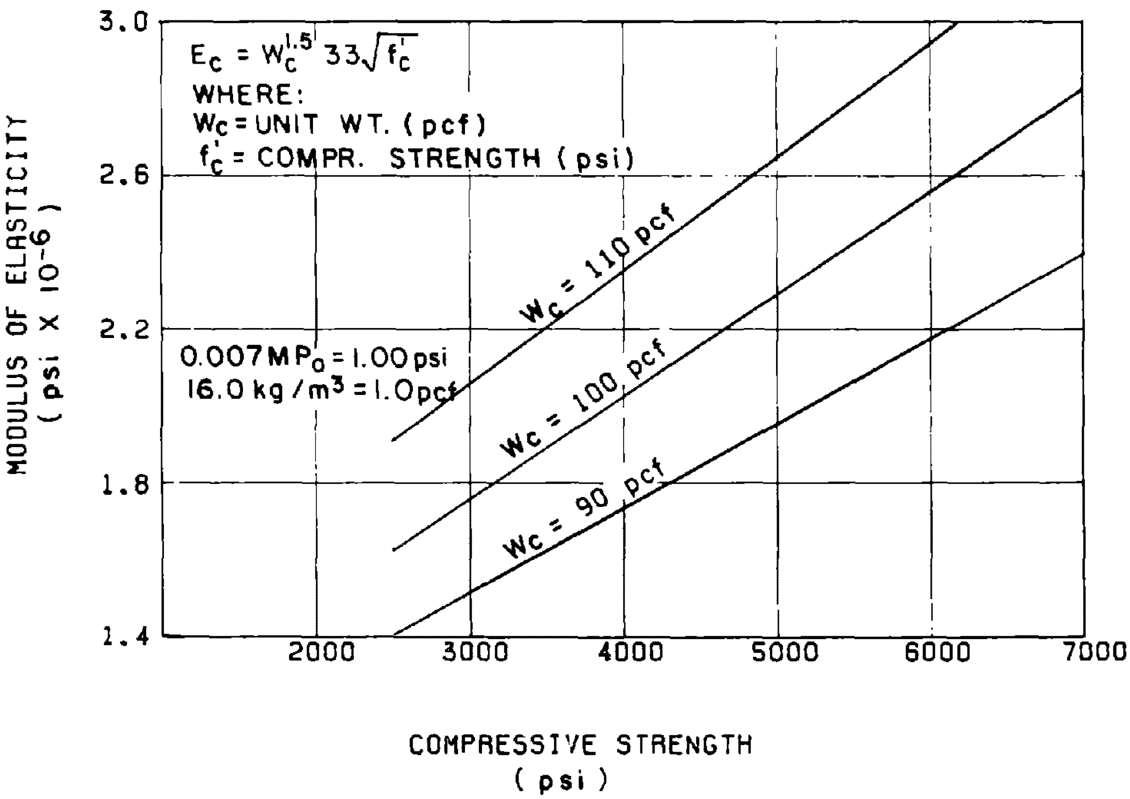



Figure 8. Modulus of elasticity of lightweight concrete as a function of strength and unit weight computed by ACI code equation.

Normal-weight concrete has a modulus of elasticity of 3 to 6 million psi (20,000 to 40,000 MPa), depending on the compressive strength. For lightweight concrete, $E_c$ is 25 to 50 percent lower. Most lightweight concretes have $E_c$ values from about 1.5 to 3 million psi (10,000 to 20,000 MPa).

Poisson's Ratio

Poisson's ratio can be determined by test as described in ASTM C469.[10] The values for lightweight concrete are similar to those for normal-weight concrete, both ranging from 0.15 to 0.25.

Bond Strength

Lightweight concrete develops satisfactory bond strength with reinforcing steel. Pull-out tests according to ASTM C234 show bond strength to be in the range of 600 to 800 psi (4 to 5 MPa).[11] Because of the lower tensile strength of lightweight concrete, the development length of reinforcement anchorage in critical zones is increased according to ACI 318.83 or AASHTO codes.

Shrinkage and Creep

Shrinkage and creep characteristics of structural lightweight concrete are similar to those of normal-weight concrete of equal strength. (Refer to early tests by C.H. Best and M. Polivka.[12]) Some lightweight concretes have lower shrinkage than normal-weight concrete, especially during the early ages. This information is obtainable from aggregate producers. Creep values are generally, but not always, higher than those of normal-weight concrete of equal strength. Creep decreases with the increase in concrete strength. Structural lightweight concrete exhibits larger total deformation under load than that of normal-weight concrete, because of its lower modulus of elasticity which produces greater elastic strain. The tests also show that steam-curing decreases the deformation due to shrinkage and creep.[12]

The range of values for creep and drying shrinkage are given in figure 9. Creep values are given in terms of specific creep, which is creep per psi of sustained stress applied at age 28 days as determined by the test method according to ASTM C512.(13)

When applied to actual structures, creep and shrinkage are found to be much smaller than the values obtained from small test specimens used in the laboratory. In a typical structure, shrinkage and creep values would be reduced 15 to 20 percent due to the size of member, 10 to 20 percent due to the humidity of the environment, and about 10 to 15 percent due to reinforcement.(14, 15) Thus, shrinkage and creep values are only about 50 percent of laboratory values obtained on small unreinforced specimens. Assuming that a 5,000-psi (35-MPa) lightweight-concrete structural member will be stressed to 1,000 psi (7 MPa) at age 28 days, and that the specific creep of the concrete is 0.70, then the creep strain observed on a laboratory specimen would be $1{,}000 \times 0.70 = 700 \times 10^{-6}$. But only about half as much, or $350 \times 10^{-6}$, would occur in the field. It is observed that about 80 percent of the ultimate creep takes place after the concrete is under stress for a year. The values of specific creep for a given lightweight-aggregate concrete may be determined by laboratory tests using ASTM C512 method.(13)

Thermal Properties

Generally, lightweight-aggregate concrete has a lower coefficient of thermal expansion than normal-weight concrete, and will develop lower thermal stresses for a given temperature gradient. Values of the coefficient of thermal expansion range from 4 to $6 \times 10^{-6}$ per $^{\circ}$F (7 to $11 \times 10^{-6}$ per $^{\circ}$C).

The thermal conductivity coefficient is a measure of the rate at which heat passes perpendicularly through a unit area of homogeneous material of unit thickness for a temperature gradient of one

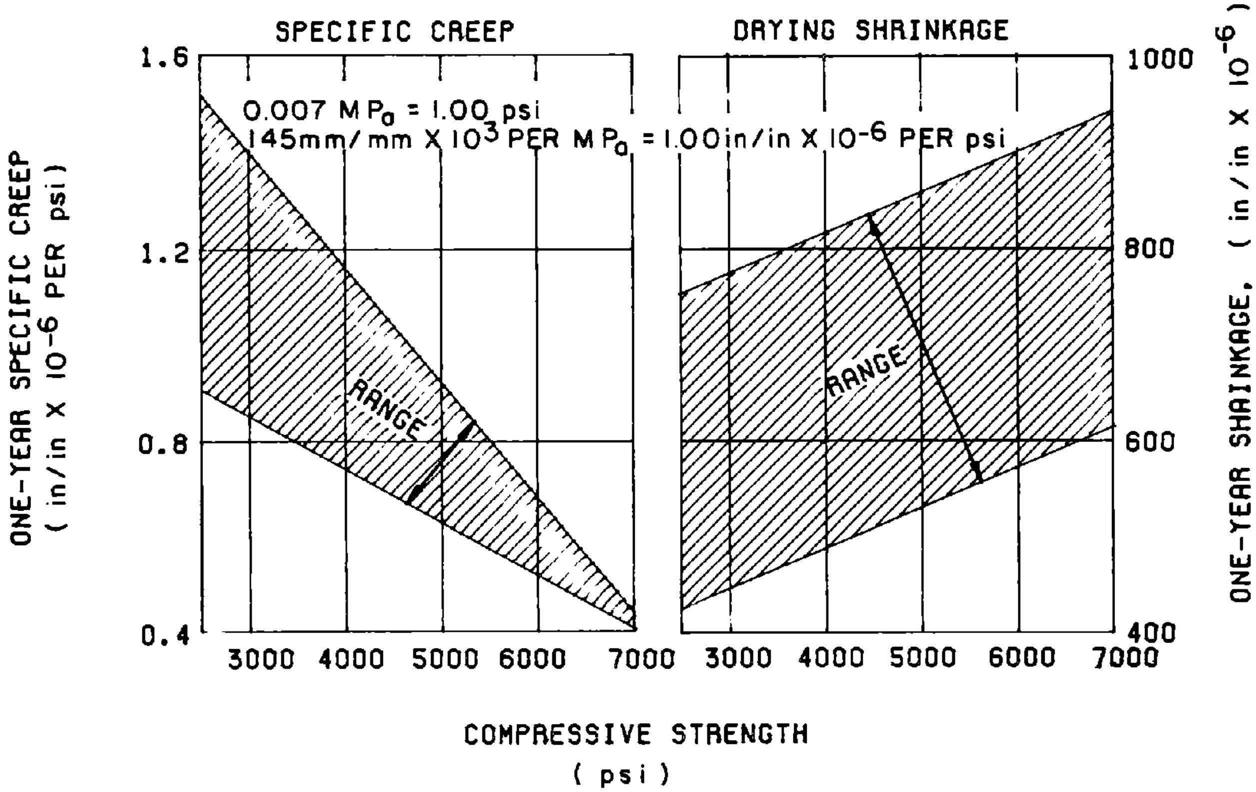



Figure 9. One-year creep and drying shrinkage of lightweight concrete as a function of compressive strength.(1)

degree. The thermal conductivity of lightweight-aggregate concrete, which is less than half that of normal-weight concrete, ranges from 3 to 5 Btu/h/ft$^2$/$^\circ$F per in (0.4 to 0.7 watts/m$^2$/$^\circ$C per m) of thickness.

The lower thermal conductivity of lightweight concrete is generally advantageous. It increases the time for the exposed members to reach steady state temperature, resulting in smaller variations of the effective interior temperature under transient temperature conditions.

Fire Resistance

Lightweight-aggregate concrete has excellent fire-resisting characteristics, due to its low thermal conductivity, lower modulus of elasticity, and the inherent fire stability of a porous lightweight aggregate. Fire tests have indicated that lightweight concrete has about 30 percent greater fire resistance than normal-weight concrete.[1]

Freeze-Thaw Resistance

As for normal-weight concrete, the resistance of lightweight concrete against freeze-thaw damage is attributable to entrained air, and low water/cement ratio. Lightweight concrete has good freeze-thaw durability because the internal pores of its aggregates are relatively large and mostly not interconnected.

Results of tests reported by P. Klieger and J.A. Hanson show that freeze-thaw durability of lightweight concrete is achieved by using entrained air and a low water-cement ratio.[16] After 300 cycles of freezing and thawing in water of air-entrained 4,500-psi (30-MPa) lightweight concretes, 5 of the 9 aggregates tested showed greater durability, 3 somewhat lower, and 1 significantly lower durability than that of the control mix of normal-weight aggregate

(Elgin sand and gravel). The influence of moisture content on the freeze-thaw durability of these concretes was minimal. In general, the use of soaked (18 to 28 hours) aggregates reduced the durability of the concrete, although 9 of the 19 concretes tested showed slightly greater durability when compared to that of air-dried aggregates. Even though the durability does not vary much among the concretes made with different lightweight aggregates, it is nevertheless desirable to evaluate the suitability of a lightweight aggregate for freeze-thaw conditions by laboratory tests, or by examples of long-term, successful performance of structures under similar conditions.

A test program to determine the freeze-thaw durability of lightweight concretes made with aggregates from 8 different producers of expanded shale type aggregates was conducted at the University of Toledo by Professor E.L. Saxer, and the results reported by the Expanded Shale, Clay, and Slate Institute.(17) It confirms the satisfactory performance of air-entrained structural lightweight concrete after at least 300 cycles of freezing and thawing in water. The amount of moisture present in the aggregates at the time of mixing (either after 24-hour absorption, or after two-thirds of the 24-hour absorption period) had no significant influence on the durability of the concretes.

T.A. Holm, T.W. Bremner, and J.B. Newman report in a paper the investigation of several bridge decks and of a concrete ship made of lightweight concrete exposed to severe weathering for many years.(18) The results indicate that only minimal deterioration of the concrete had been found.

In the ACI 213 report the Committee reports that the freeze-thaw resistance of high-strength structural lightweight concrete was equal to or better than that of normal-weight concrete.(1)

Skid Resistance

Lightweight-shale aggregates have high skid resistance, because of their rough texture. Furthermore, this aggregate does not lose its skid resistance over long periods of use, as do some normal-weight aggregates (limestone and gravel). This is because lightweight aggregates continually renew their wornout surfaces with new, rough surfaces exposed through wear and tear.

## STATE OF THE ART

### CONSTRUCTION OF LIGHTWEIGHT-CONCRETE BRIDGES

It is estimated that more than 400 bridges have used lightweight concrete in the United States. In the course of this study, existing literature describing 257 bridges was surveyed, producing the histogram in figure 10 that spans a period of 56 years, from 1927 to 1983.

Bridges using lightweight concrete in some form were constructed between 1920 and 1946. Construction peaked during the mid-fifties, and leveled off from about 1966. The main reason for using lightweight concrete had been to reduce the weight of concrete decks, which in turn reduces the material requirement in the supporting steel girders and substructure and permits an increase in structural span length. There are other reasons: for example, the reduction of weight to reduce seismic forces. Recent usage has been in the rehabilitation of bridges, especially steel-plate girder bridges, by replacing the old concrete in the decks with lightweight concrete.

The main reasons for deck replacement are: deck deterioration, upgrading of load-carrying capacity, and increasing roadway width without correspondingly adding dead load to the supporting girders and substructure. As an example, the Woodrow Wilson Bridge in Virginia was redecked with lightweight concrete in 1983 to replace the deteriorated deck and to increase the roadway width. The Golden Gate Bridge in San Francisco was recently redecked to replace the deteriorated concrete deck and reduce dead load. In the latter application, lightweight concrete serves as non-structural filler for a steel grid deck.

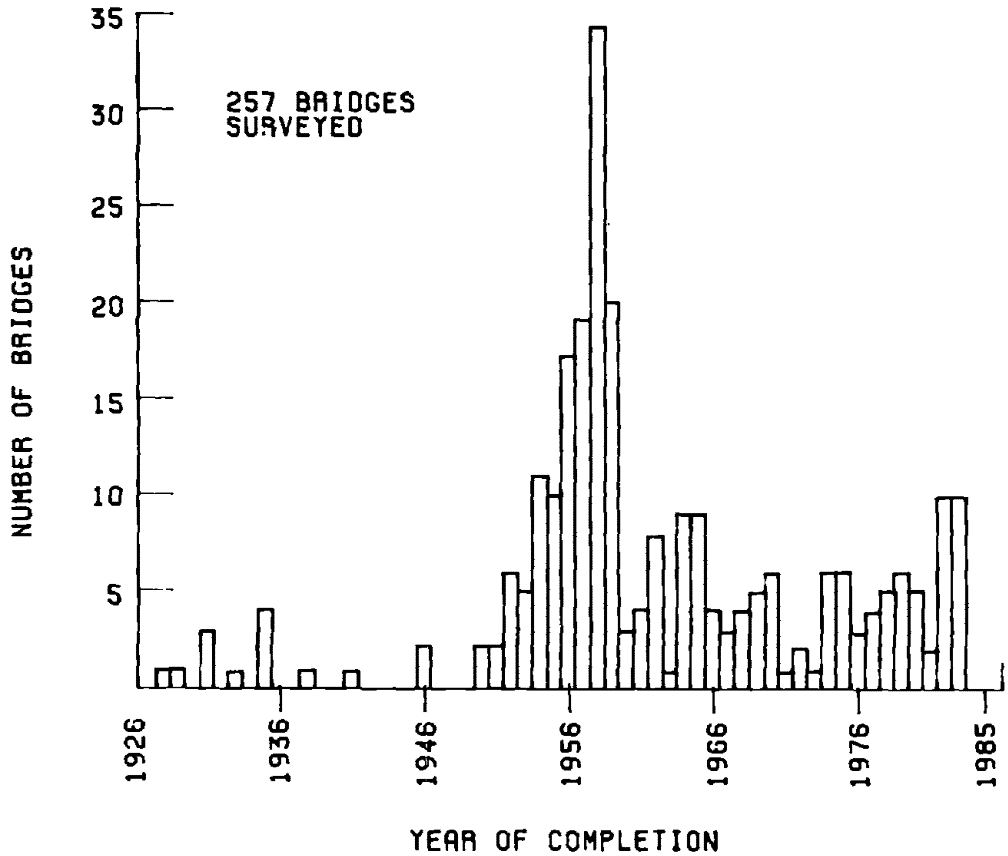



Figure 10. Construction history of bridges incorporating lightweight concrete.

Figure 11 shows the distribution of over 250 bridges within the United States reported to be constructed with structural lightweight concrete. Lightweight concrete bridge decks and/or superstructures have been constructed in about half of the States. The location of these bridge structures corresponds generally to the distribution of lightweight aggregate producers shown in figure 2.

Figure 12 shows the distribution of lightweight-concrete bridges for steel and concrete types of superstructures. Each superstructure type is further broken down according to the structural system or girder type. Approximately 55 percent of the bridges surveyed have lightweight-concrete decks on steel superstructures. The remaining bridges used lightweight concrete for the entire superstructure. By far the greatest usage has been lightweight-concrete decks on steel plate girders and long-span truss bridges. Lightweight-concrete decks have also been used on steel tied arches, box girders, suspension, and rolled section bridges. Concrete bridges using lightweight concrete as the primary superstructure material include slab, AASHTO I-girder, conventionally reinforced box girders, and segmental-concrete box-girder bridges.

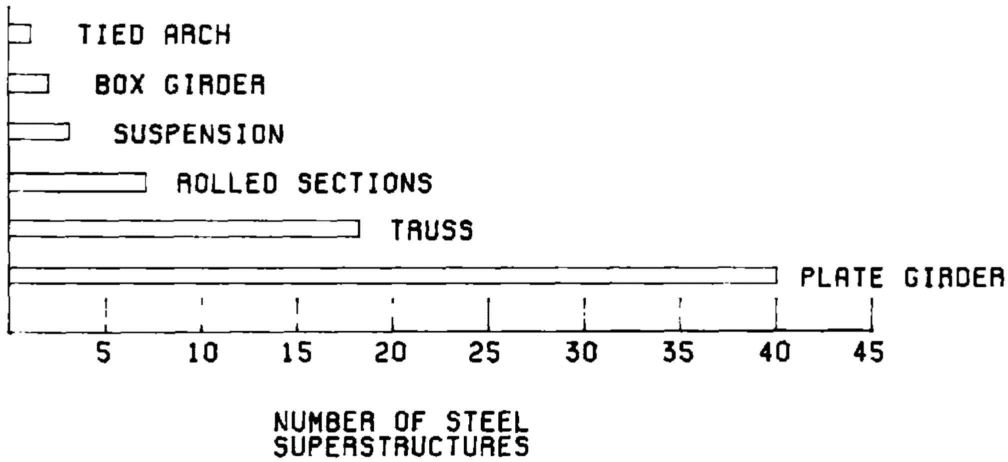
The survey of bridges revealed that:

- The average deck thickness of some 100 bridges was 7.3 in (185 mm), and that decks of 8 in (200 mm) or more in thickness had better maintenance records.

- The average span length of the bridges surveyed was 120 ft (37 m), and the average of the longest span in each bridge was 261 ft (80 m).

- The average design unit weight specified was 111 pcf (1780 $kg/m^3$), and the average design ultimate compressive strength was 3,900 psi (27 MPa).

Figure 11. Distribution of lightweight-concrete bridge structures in the United States.



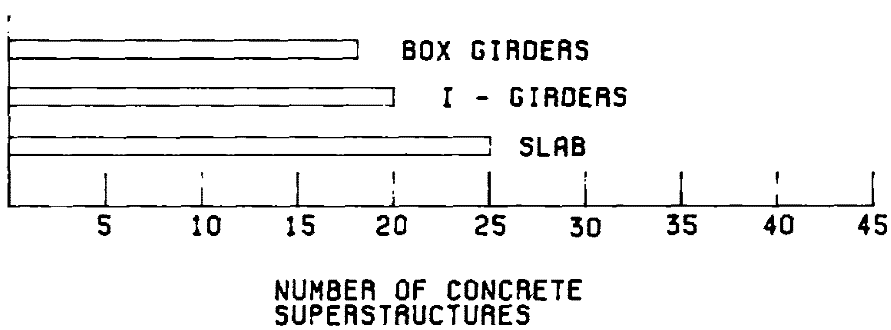




Figure 12. Steel and concrete superstructure types incorporating lightweight concrete.

- Protective wearing surfaces and asphaltic concrete with membranes were used on 44 percent of the bridge decks surveyed. The remaining decks were exposed.

In the United States, lightweight concrete has only been used in a few segmental cantilever box-girder bridges, notably the Parrots Ferry Bridge located in California. This structure used lightweight concrete to reduce the dead load of the 640-ft (195-m) main span, thereby reducing seismic loads. The dead load of segmental cantilever box girders having span lengths over 300 ft (90 m), typically accounts for 70 to 85 percent of dead plus live loads. Dead-load reduction is therefore of major importance to achieve an economical system.

## USE OF LIGHTWEIGHT CONCRETE IN EUROPE AND CANADA

In Western Europe, lightweight concrete has been used to a limited extent for major bridges and other structures. In the Soviet Union and Eastern European countries, lightweight concrete has been used more often in bridge construction. A compilation of lightweight concrete bridges in Europe is found in a Technical Report by the Concrete Society, published in 1981.[19]

### United Kingdom

In the United Kingdom, the use of lightweight concrete in bridges is extremely limited. For a long time the Department of Transport did not permit its use in major bridge structures, although the present code does not explicitly prohibit lightweight concrete. Lightweight-concrete structures reported so far consist of reinforced concrete, prestressed precast concrete and composite-steel concrete road bridges with spans up to 103 ft (31.5 m). One major structure using lightweight concrete is the Friartown Bridge in Scotland. This is a steel box-girder bridge with a composite lightweight-concrete deck, with spans ranging from 207 to 570 ft (63 to 174 m).

West Germany

West Germany has used lightweight concrete since 1967. Significant lightweight-concrete bridge structures reported include a 279-ft (85-m) box-girder cantilever-type bridge in Osnabrueck, an industrial bridge in Wiesbaden incorporating precast T-sections spanning 260 ft (80 m), and a box-girder bridge over Fuehlinger See near Cologne, where a portion of the 275-ft (84-m) segmental prestressed-concrete span is lightweight concrete. Similarly, a new bridge crossing the Rhine in Cologne, built in 1979 as a segmental box-girder bridge with a main span of 607 ft (185 m), uses lightweight concrete in the center 203 ft (62 m) of the main span.

An interesting development in Germany is the "lightweight normal concrete." This is normal-weight concrete that has about 20 percent of its aggregate replaced by lightweight aggregate, resulting in a weight savings of 10 to 15 percent.

France

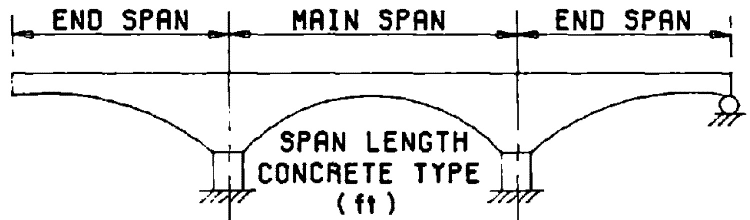
France has used lightweight concrete for a number of major bridges. Two of these are the Ottmarsheim Bridge, a post-tensioned twin-box girder structure where lightweight concrete was used in the center 328 ft (100 m) of the 564-ft (172-m) main span, and a bridge at Tricastin that also used lightweight concrete for the central portion of the main span.

Belgium

In Belgium lightweight concrete has been used for bridges since 1972. These include structures with spans up to 112 ft (34 m).

Netherlands

Holland has used lightweight concrete since 1968, particularly in segmental box girders. Figure 13 shows 12 segmental box girders constructed in the Netherlands between 1968 and 1982, which have




NWC = NORMAL-WEIGHT CONCRETE

LWC = LIGHT-WEIGHT CONCRETE

0.30 m = 1.0 ft

| | End span | Support | Main span | Support | End span |
|---|---|---|---|---|---|
| 1 | 123.37 NWC | NWC | 368.13 LWC | NWC | 123.37 NWC |
| 2 | 258.38 LWC | LWC | 505.27 LWC | LWC | 258.38 LWC |
| 3 | 258.38 LWC | LWC | 493.79 LWC | LWC | 258.38 LWC |
| 4 | 246.08 LWC | LWC | 470.82 LWC | LWC | 246.08 LWC |
| 5 | 218.19 LWC | LWC | 447.86 LWC | LWC | 218.19 LWC |
| 6 | 163.20 NWC | NWC | 479.68 LWC | NWC | 163.20 NWC |
| 7 | 210.97 NWC | NWC | 507.90 LWC | NWC | 210.97 NWC |
| 8 | 229.67 LWC | NWC | 426.53 LWC | NWC | 229.67 LWC |
| 9 | 229.67 LWC | NWC | 367.47 LWC | NWC | 229.67 LWC |
| 10 | 156.18 NWC | NWC | 368.13 LWC | NWC | 156.18 NWC |
| 11 | 287.09 LWC | NWC | 516.76 LWC | NWC | 287.09 LWC |
| 12 | 246.08 LWC | NWC | 492.15 LWC | NWC | 246.08 LWC |

Figure 13. Segmental box-girder bridges constructed in the Netherlands using lightweight concrete.

incorporated lightweight and/or a combination of lightweight and normal-weight concrete. Lightweight concrete was used for all the main spans ranging in length from 367 to 514 ft (112 to 157 m). A combination of lightweight and normal-weight concrete was used in a number of bridge designs to anchor the end spans against uplift where the main span was more than twice the length of the adjacent spans. Response from The Ministry of Transportation, The Netherlands, indicated that the performance of the bridges has been good. The bridge decks were covered with an asphaltic surface to provide a smooth riding surface and to act as a protective barrier against salt contaminants. Clay, expanded by the rotary-kiln method, was used to produce the coarse aggregate. Natural sand was used for the fine aggregate. Due to the limited tensile capacity of the lightweight concrete, special attention was given to the design of reinforcing steel in the prestressing anchorage zones.

USSR and Poland

The USSR and Poland have used lightweight concrete since 1961. Over 100 bridges with spans up to 108 ft (33 m) have been built. The aggregate used consists of rotary-kiln produced expanded shale and clay, and sintered expanded shale.

Canada

In a 1960 bridge survey reporting the use of lightweight-concrete bridges in Canada, 11 bridges had been built up to that time; 7 in British Columbia, 3 in Ontario, and 1 in Alberta. Canadian engineers reported that no bridges have been built recently with lightweight concrete. This is apparently due to the shortage of lightweight aggregate as a result of environmental concerns and high fuel costs.

## SPECIFICATIONS

The standard specification used in the United States for structural-concrete lightweight aggregates is either the American Association of State Highway and Transportation Officials (AASHTO) designation M195-62(1974), or the American Society of Testing and Materials (ASTM) designation C330-82a, with modification depending upon the individual State specification.[2,3]

### Materials

ASTM and AASHTO allow two types of lightweight-concrete aggregates; namely:

- Aggregates produced by expanding or sintering raw materials of blast-furnace slag, clay, dratonite, fly ash, shale or slate.

- Naturally porous aggregates, such as pumice, scoria, or tuff.

Some State specifications limit permissible aggregates to shales, slates, or clay expanded by either the rotary-kiln or the sintering methods. Missouri Standard Specifications for Highway Construction - 1981, for instance, allow aggregates prepared by expanding, calcining, or sintering clay, shales, and slates. On the other hand, California Standard Specifications - 1984, allow only lightweight aggregates produced by the rotary-kiln method. In addition, California requires that the raw material must be either shale or clay, and the resulting aggregate must have a sealed surface after expanding. The aggregate may not be crushed after expanding, except for a small amount in order to attain the required coarse aggregate grading. The road and bridge specifications in most states conform to AASHTO M 195, but only a few States have standard specifications for lightweight aggregates.[2]

The Uniform Building Code Standards and the American Concrete Institute Building Code Requirements for Reinforced Concrete conform generally to ASTM C330.[20,9,3]

## Design

AASHTO and ACI codes give design specifications for both lightweight and normal-weight concretes, but make special provision for the modulus of rupture, shear and development length capacities of lightweight concrete. Both codes specify identical values. The allowable modulus of rupture, if not otherwise shown by test data, is given as 6.3 $f'_c$ psi (0.52 $f'_c$ MPa) for sand-lightweight concrete, and 5.5 $f'_c$ psi (0.46 $f'_c$ MPa) for all-lightweight concrete (with lightweight fines). Linear interpolation between 5.5 $f'_c$ psi and 6.3 $f'_c$ psi (0.46 $f'_c$ MPa and 0.52 $f'_c$ MPa) may be applied when both lightweight fines and natural sand are used.

The provisions for shear stresses carried by the lightweight concrete, $v_c$, is based upon the splitting tensile strength $f_{ct}$. When $f_{ct}$ is specified, the shear stress carried by the concrete must be modified by substituting $f_{ct}/6.7$ for $f'_c$, but the value $f_{ct}/6.7$ must be less than $f'_c$ (0.083 $f'_c$). If the splitting tensile strength is not specified, then the shear stress carried by the concrete must be multiplied by 0.75 for an all-lightweight concrete, and 0.85 for sand-lightweight concrete. Linear interpolation may be applied when both lightweight and natural fines are used.

The basic development length in tension of deformed bars, deformed wire, welded deformed wire fabric, and welded smooth wire fabric is modified for lightweight concrete in the ACI and AASHTO codes reflecting the difference between lightweight and normal-weight concrete. The modification factor is 6.7 $f'_c/f_{ct}$ (0.56 $f'_c/f_{ct}$), but not less than 1.0.

When $f_{ct}$ is not specified, the development length should be increased by 1.33 for all-lightweight concrete, and 1.18 for sand-lightweight concrete.

ACI and AASHTO relates the elastic modulus to the concrete density and compressive strength by the formula:

$$E_c = 33\ w_c^{1.5}\sqrt{f'_c}\ \text{(in psi)} \quad (0.043\ w_c^{1.5}\sqrt{f'_c}\ \text{(in MPa)})$$

where $w_c$ is the concrete unit weight in pcf (kg/m$^3$), and $f'_c$ the cylinder strength at 28 days. While this empirical formula is generally valid in the strength range between 3,000 to 4,500 psi (20 to 30 MPa), it consistently over estimates the values obtained from tests of high-strength lightweight concretes. To over-estimate the elastic modulus can be critical for long-span, prestressed concrete bridges where deflection control, creep, moment redistribution, and elastic and thermal movements must be considered during construction and service life. To obtain more realistic values for the elastic modulus, certified test results should be obtained from local aggregate producers during the design stages, and adjusted if necessary during the construction stages.

## REVIEW OF LIGHTWEIGHT-CONCRETE BRIDGES AND EXPERIENCE

To relate the state of the art pertaining to lightweight concrete used in bridges in the United States, 12 study cases from some 30 possibilities were selected for inspection and reporting. The bridges represented different bridge types operating in a variety of conditions, such as geographic location and climatic conditions. The study included the policies of several States toward lightweight-concrete bridges. The objective was not only to observe the condition of bridges, but also to learn of the acceptability of lightweight concrete to the design and construction staff and their experience concerning its use. The 12 study cases selected are listed in figure 14.

Some of the bridges selected were built before 1970, and records of their design and construction were not available. Information collected was therefore mainly qualitative in nature, serving only to bring to light this country's past experience in the use of lightweight concrete in bridges.

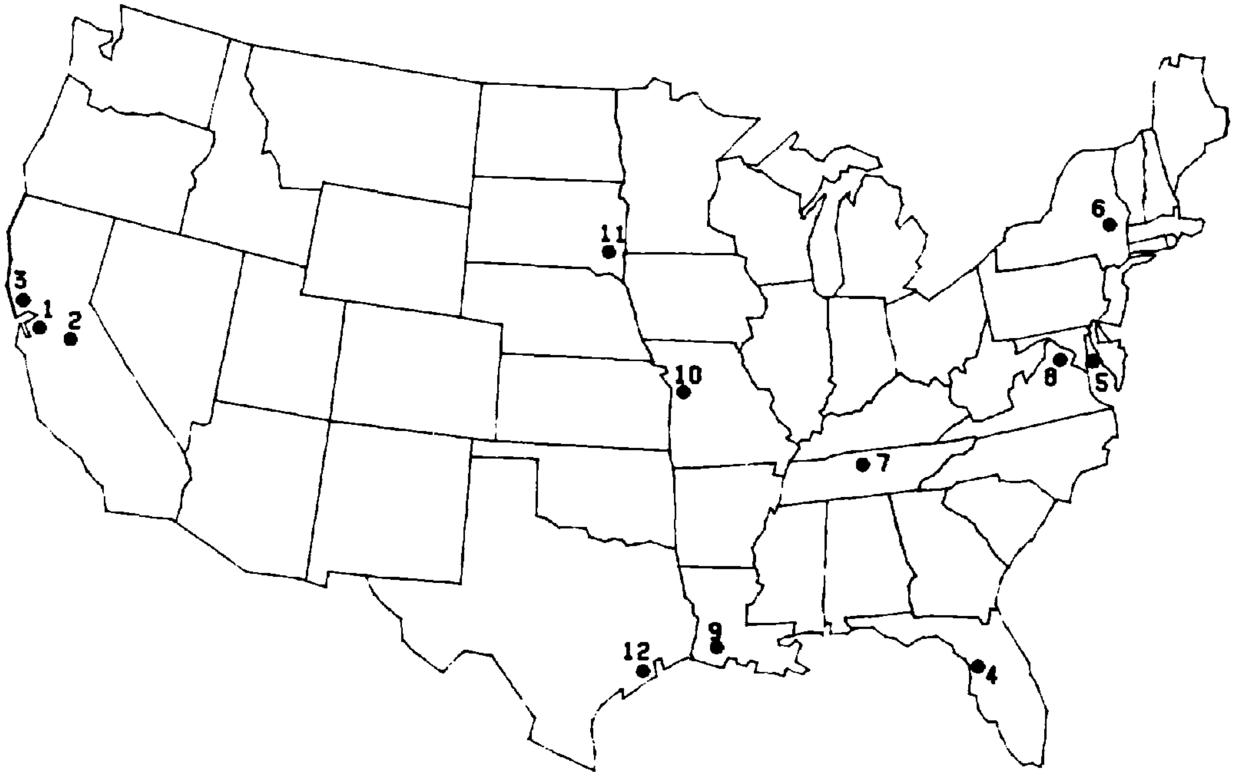



Figure 14. Distribution of study cases.

1. San Francisco - Oakland Bay Bridge, California
2. Parrots Ferry Bridge, California
3. Napa River Bridge, California
4. Suwannee River Bridge, Florida
5. William Preston Lane, Jr. Memorial Bridge, Maryland
6. Coxsakie Bridge, New York
7. I-24 Over SR 76 Montgomery County, Tennessee
8. Woodrow Wilson Memorial Bridge, Virginia
9. Louisiana
10. Missouri
11. South Dakota
12. Texas

SAN FRANCISCO - OAKLAND BAY BRIDGE, CALIFORNIA

Location: Interstate Route 80,
between San Francisco and Oakland

Owner: State of California

Completion of Construction: 1936

ADT: 190,000 (1977)

Environment: The structure is exposed to a sea environment, located in the east-west direction over the San Francisco Bay.

The bridge consists of two double-deck structures, called East-Bay and West-Bay Bridge in this report, which are separated by a 540-ft (165-m) tunnel through Yerba Buena Island (figure 15). The West-Bay bridge has 2 suspension systems, which are joined in the middle by an anchor pier. Each suspension system has a center span of 2,310 ft (700 m) between towers, and side spans of 1,160 ft (354 m) each. The total length between San Francisco and Yerba Buena Island is approximately 9,000 ft (2740 m). The East-Bay structure consists of a steel truss, with a 1,400-ft (427-m) center-span cantilever, 2 anchor spans, and several appoach spans, totaling some 10,200 ft (3,110 m).

The upper roadway deck was constructed of water-cured lightweight concrete using expanded-shale aggregate and natural sand. In the early 1960's, the lower-deck level, designed originally for truck and train traffic, was reconstructed for vehicular traffic. Lightweight shale aggregate and natural sand were used in the reconstruction.

In 1977, an epoxy asphalt overlay was placed on the upper deck, and chlorinated rubber paint applied to its soffit. Similar treatment was given to the lower level in 1981. The overlay was placed on the upper deck to replace a deteriorated overlay placed in 1963. The original overlay was placed to cover embedded tile lane markers when

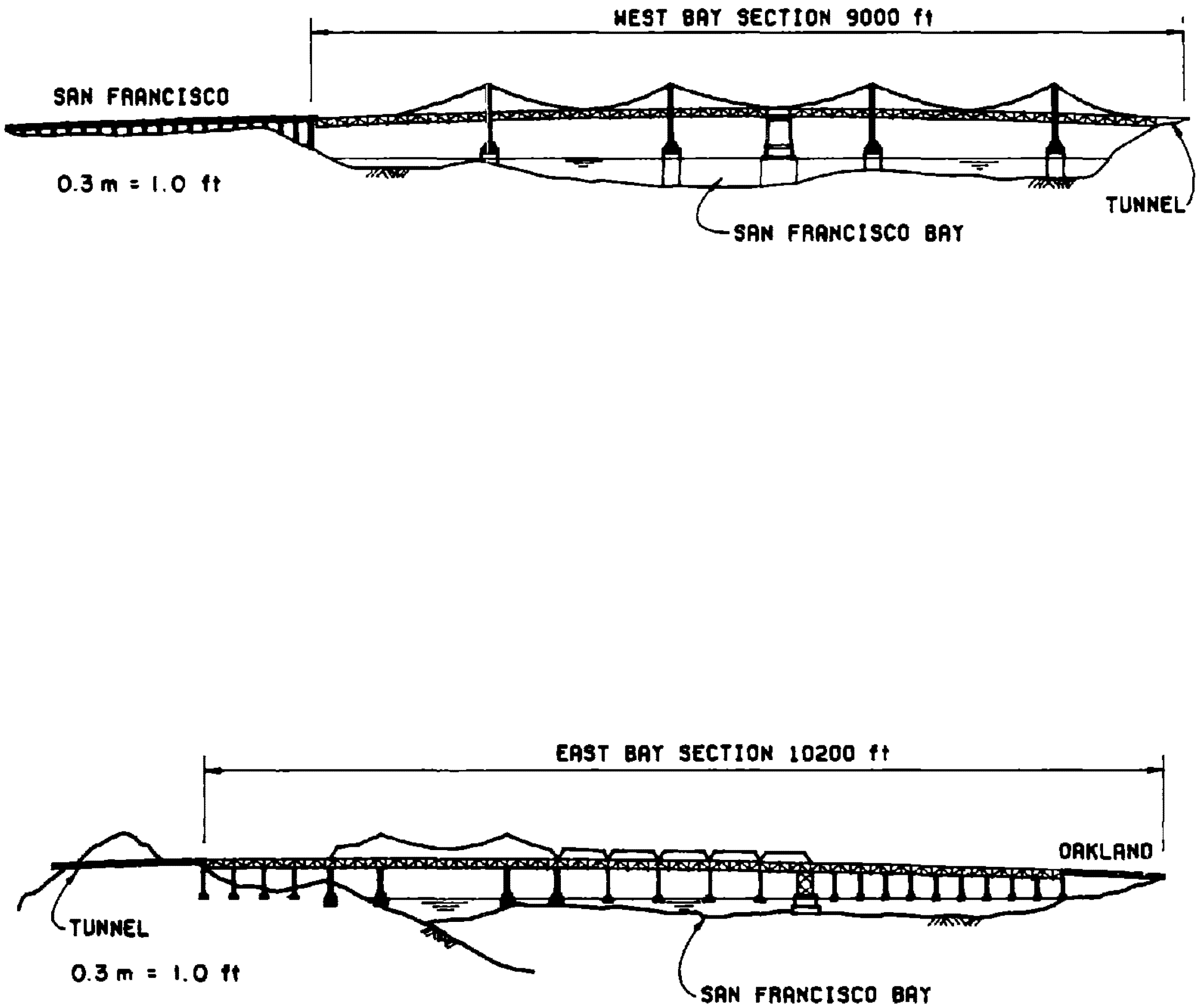



Figure 15. San Francisco - Oakland Bay Bridge.

the deck was converted from 6 lanes to 5 lanes. The paint was applied to seal the soffit concrete from chloride intrusion.

The performance of the lightweight upper deck in its 48 years of operation has been satisfactory. No deterioration of the concrete was found during visual inspection. In 1979, deck core samples were taken to determine the chloride content through the deck. Half-cell readings were also taken to provide reference for chloride contamination in the future.

Results of these tests show the first inch (25.4 mm) of deck slab was highly contaminated with chloride. However, contamination dropped below 1.0 pcy (0.59 $kg/m^3$) with increased depth. Chloride contamination at the level of the reinforcing steel was generally below the threshold level for steel corrosion to take place, i.e., 1.0 pcy (0.59 $kg/m^3$) and 0.250 millivolts. The underside of the deck, which is more exposed to a corrosive environment, showed higher chloride contamination than the topside.

During 1984, concrete core samples were taken from the East-Bay approach spans which were constructed of normal-weight concrete. The results indicate that chloride contamination above 1.0 pcy (0.59 $kg/m^3$) had penetrated 4 in (10 cm) into the concrete. In some sections, contamination was in excess of 10 pcy (5.9 $kg/m^3$). Some spalling was taking place. Repairs included the removal and replacement of concrete surfaces.

The lightweight-concrete deck of this bridge must be one of the oldest still in existence. Its success can be attributed to good design, construction practices, and maintenance. California State engineers who have worked with lightweight concrete, believe that lightweight concrete can be as successful as normal-weight concrete, providing it is properly constructed.

PARROTS FERRY BRIDGE, CALIFORNIA

Location: Stanislaus River near Vallecito, California

Owner: U.S. Corps of Engineers

Completion of Construction: 1979

ADT: 3500

Environment: Moderate climatic condition

The Parrots Ferry Bridge over the Stanislaus River is part of the New Melones Dam project recently completed by the Sacramento District of the U.S. Corps of Engineers. It is one of the largest and most complex bridge projects using lightweight concrete.

This high-level bridge is 350 ft (107 m) above the riverbed. It is a post-tensioned box-girder bridge using cast-in-place segmental-cantilever construction. The dimensions of the structure are shown in figure 16.

Lightweight concrete is used in the superstructure to reduce the weight and cost of the long cantilevers, as well as their seismic loads. Bonded posttensioning was applied longitudinally in the box girders, vertically in the webs, and transversely in the deck.

Design and construction were performed according to the Corps of Engineers (COE) guide specifications CE 1401.01, modified to accommodate the lightweight-concrete portion of the bridge. Mix designs were recommended by the lightweight-aggregate producer. Samples of lightweight aggregates and trial mixes were sent to the COE laboratory in Troutdale, Oregon for the determination of modulus of elasticity, creep, and shrinkage of the concrete and its suitability for the project. The mix was designed to meet ASTM C330 requirement for an average maximum air-dry unit weight of 115 pcf (1840 kg/m$^3$), and a 28-day compressive strength of 5000 psi (35

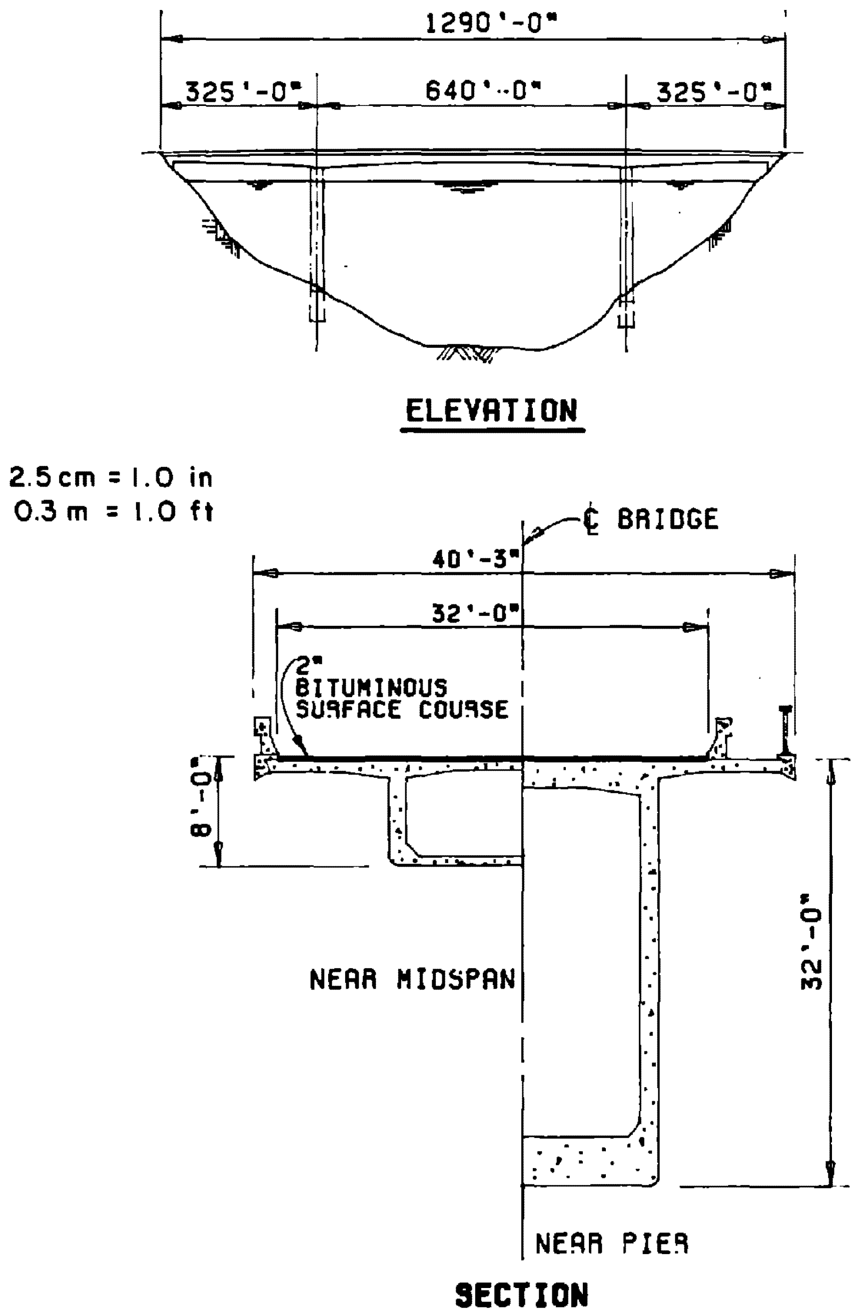



Figure 16. Elevation and section, Parrots Ferry Bridge.

MPa).[3] Air-dry unit-weight tests and freeze-thaw durability tests of the aggregates were performed by the California State Department of Transportation laboratory in Sacramento according to California Test Method No. 528.

After the contract was awarded, the Contractor proposed the substitution of normal-weight concrete for the lightweight concrete as designed. The proposal was rejected. But in view of the concern over some aspects of the design, a consultant was engaged to review the lightweight concrete design. The review found the design satisfactory, but suggested some modifications. These were accepted and used. The locally available lightweight aggregates were also found to be satisfactory for the project.

A 10-ft (3-m) segment of the shallow box girder was built to test the procedures of concreting and prestressing. Concrete was delivered by pumping as it would be for the actual structure. After curing and hardening, the segment was posttensioned. The test was a success.

There were, however, problems with quality control. For example, the unit weight, strength, and slump varied more than expected. Part of the unit-weight problem was due to the fact that while ASTM C330 specifies acceptance by dry unit weight, ACI 221 permits proportioning by the saturated specific gravity method (SSD).[3, 21] Thus, with specifically moisture-processed aggregate, a mix meeting ASTM specifications might still produce nonconforming unit weights, if its high degree of saturation is not taken into consideration. The problems were corrected after the causes were identified.

Concrete in the box girders was cured by spraying the surface with Hunts Process membrane curing compound. Insulation blankets were used to cover the top slab during winter placements. During cold weather, a salamander heater was placed inside the box girder during the placement of the concrete and through the first night to keep the concrete warm.

Rapid strength gain of the concrete was important to meet the post-tensioning schedule. During warm weather, strengths of 2500 psi (17 MPa), which is sufficient for partial posttensioning, were reached as early as 18 hours after placing and 3500 psi (24 MPa) after 24 hours. In cold weather as much as 38 and 60 hours respectively were required to reach the same strengths.

Field testing of the concrete and its ingredients followed usual procedures. In addition, testing of special aspects of the construction were conducted. One of the most interesting of these tests concerned the weight loss of concrete with respect to time. The results show a weight loss of 4.5 pcf (70 $kg/m^3$) in 28 days and 8 pcf (130 $kg/m^3$) in 90 days. Thereafter, weight loss continued at a decreasing rate for another few months.

This is a good example of the use of lightweight concrete for a segmental-cantilever bridge. Its success was due to careful design and detailing, and to the meticulous application of specifications and field procedures. It should be noted that construction control had been implemented in the early stages, in time for the necessary adjustments to remedy obvious discrepancies.

NAPA RIVER BRIDGE, CALIFORNIA

Location: Highway 29 crossing the Napa River,
north of Napa, California

Owner: State of California

Completion of Construction: 1977

ADT: 21,500

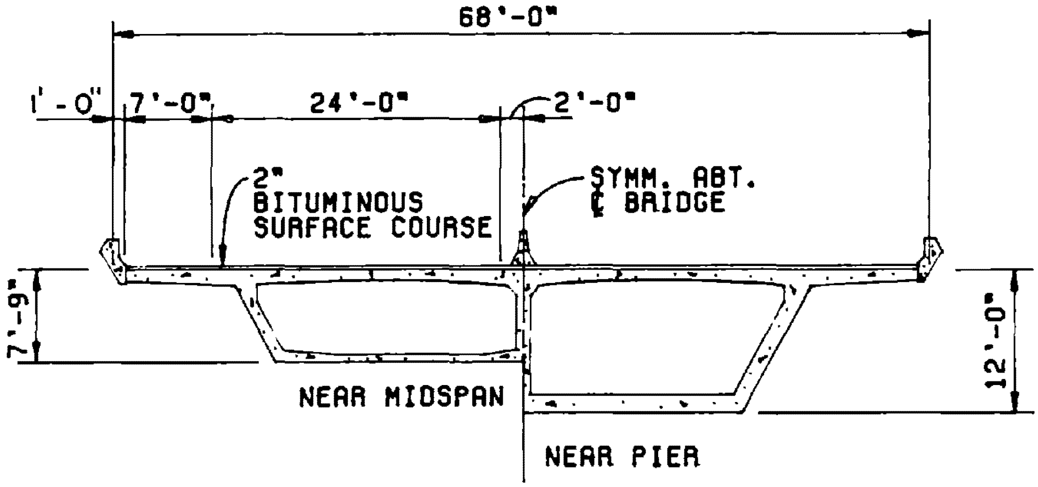
Environment: The structure is located in a mild climate, with no salting or other contaminations of the deck.

The Napa River Bridge is a four-lane prestressed concrete structure (figure 17). It was originally bid as a segmental cantilever box-girder type, but the contractor elected to cast it in place on falsework.

The bridge was designed and the construction supervised by the California Department of Transportation (CALTRANS). Lightweight concrete made with Basalite aggregate, expanded shale, and having a 28-day cylinder strength of 4,500 psi (30 MPa), was specified. The deck was topped with a 2-in (50-mm) asphalt overlay.

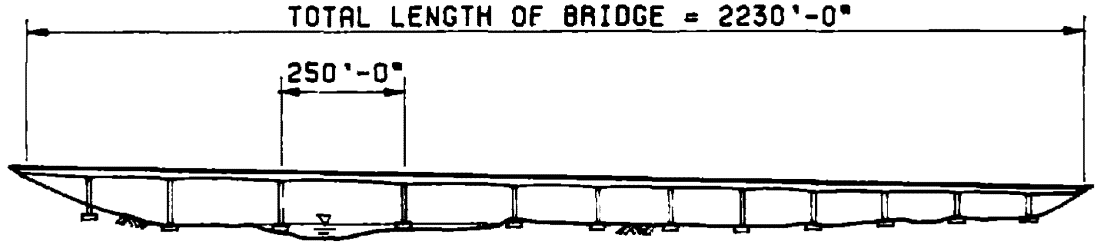
The performance of the bridge was reported to be very satisfactory. Periodic inspections had not revealed any significant cracking or spalling in the superstructure.

The experience of the Napa River Bridge conforms with the general, satisfactory experience of the use of lightweight concrete in California. This favorable experience is due to a large extent to the care and attention given by CALTRANS to all aspects of the design, construction, and maintenance of bridges.




TYPICAL SECTION

2.5 cm = 1.0 in
0.3 m = 1.0 ft




ELEVATION

Figure 17. Typical section and elevation, Napa River Bridge.

SUWANNEE RIVER BRIDGE, FLORIDA

Location: US 19, Fannin Springs, Florida

Owner: Florida Department of Transportation

Completion of Construction: 1963

ADT: 3800

Environment: The structure is in a humid, semi-tropical climate and not subjected to application of deicing chemicals.

This bridge parallels an old through-steel truss across the Suwannee River on U.S. 19 at Fannin Springs, Florida, and carries northbound traffic (figure 18). It was built in 1963 using lightweight-concrete AASHTO girders and a cast-in-place lightweight-concrete deck.

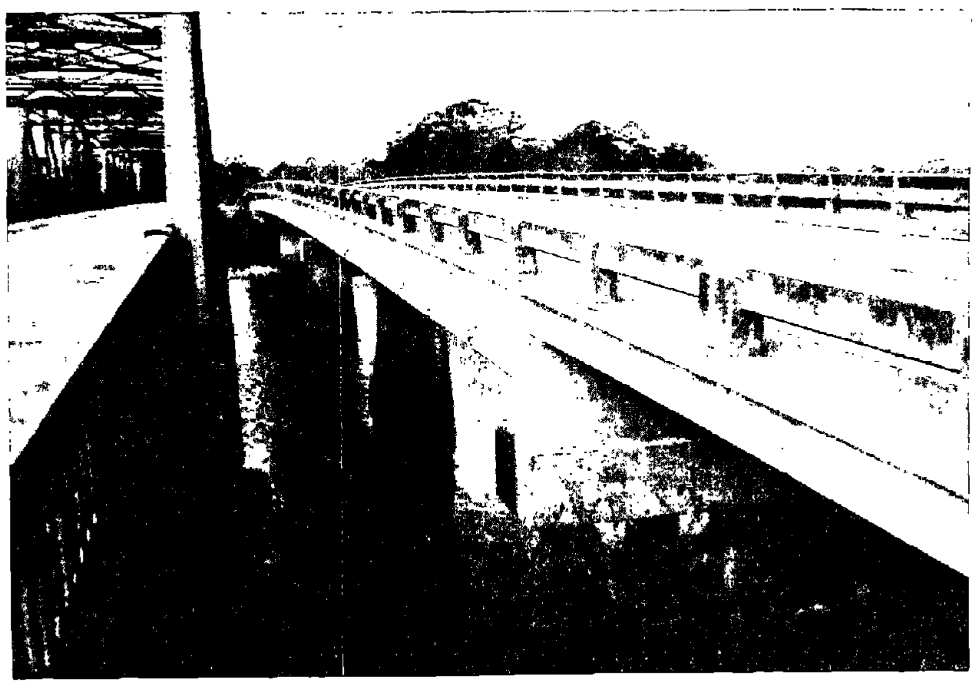


Figure 18. Suwannee River Bridge.

The lightweight aggregate used was 3/4-in (19-mm) Florida Solite with natural sand. The specification required a maximum weight of 120 pcf (1,920 kg/$m^3$) and a strength of 4,000 psi (28 MPa) for the girders. Eight sacks of cement were used and 90-day strengths were in excess of 6,500 psi (45 MPa).

The deck concrete used the same aggregate and 6.75 sacks of cement. Twenty-eight-day test results were in excess of 5,000 psi (35 MPa). An asphalt wearing surface was placed on the deck.

The 1984 inspection described the bridge to be in excellent condition. The humid climate, low traffic, and the absence of adverse environmental conditions, were all conducive to a long life of service. The dark spots on the lower flange shown on the photograph are drip locations from the bridge drains.

Although the lightweight-concrete bridge structures built in Florida have been successful, apparently the construction control required for lightweight concrete, and the competition of natural aggregate suppliers have discouraged its use.

WILLIAM PRESTON LANE, JR. MEMORIAL BRIDGE, MARYLAND

Location: U.S. 50 Across Chesapeake Bay, Annapolis, Maryland

Owner: Toll Facility Administration, Maryland Transportation Authority

Completion of Construction: 1952, 1973

ADT: 34,000

Environment: The structure is located over a large body of water with moderate to severe weather.

This crossing consists of two parallel high-level suspension bridges across the Chesapeake Bay, on U.S. 50, east of Annapolis, Maryland. The first of these bridges was opened to traffic in 1952 and the second in 1973. The main span is 1,600 ft (488 m) with a vertical clearance of 186 ft (57 m). The overall length of the bridge is 21,286 ft (6500 m). The first bridge carries two eastbound lanes, and the second carries three westbound lanes.

The deck of the first bridge was constructed of shale-lightweight concrete for the suspension spans and normal-weight concrete for the beam approach spans. An inspection of the first bridge in 1975 after 23 years of service indicated that the deck of the normal-weight beam spans had deteriorated, apparently due to the deicing salt concentration in the flat approach areas. The normal-weight concrete deck of these spans was replaced with expanded shale concrete. Now, after only 9 years of service, these spans are already showing the threshold level of chlorides for rebar corrosion, which is higher than that of the original expanded slate concrete of the main span. A recent inspection report notes that the expanded shale concrete did not show signs of deterioration, and that this lightweight concrete could have a high tolerance for salt.

Although the asphalt wearing surface on the suspended spans was replaced in 1975, the expanded slate concrete deck stood up well, in fact so well that the owner decided to replace the deteriorated normal-weight deck with lightweight concrete. An evaluation of the condition of the replaced normal-weight concrete deck or its mix characteristics is not available at this time.

COXSAKIE BRIDGE, NEW YORK

Location: Greene County, New York, Thruway Milepost 124.53

Owner: New York Thruway Authority

Completion of Construction: 1972

ADT: 1,000

Environment: This structure is exposed to severe winter weather and much deicing.

The lightweight-concrete bridge decks and pier caps on the Coxsakie Interchange bridge over the New York Thruway, were constructed in 1970. The bridge was designed for the Thruway Authority by private consultants. Construction supervision was provided by the New York State Department of Transportation.

The bridge consists of steel girders spanning 100 ft (30 m) with an 8 1/2-in (200-mm) monolithic lightweight-concrete deck slab spanning 8 ft (3 m). The top steel in the slab has a cover of 2 1/4 in (65 mm), and the bottom steel has 1 in (25 mm). The concrete slab was connected by studs to the plate girders. No wearing surface was provided.

Specifications for the lightweight concrete called for a mix of lightweight coarse aggregates and natural sand. The 28-day compressive strength was to be 3500 psi (24 MPa) air content 6 to 9 percent and air-dry density less than 115 pcf (1,840 kg/m$^3$). The concrete was to be placed with a slump of 3 in (75 mm).

The lightweight aggregate used on the project was a rotary kiln-produced expanded slate with a gradation of 3/4 in by No. 4 (19 by 4 mm) and was required to meet all the requirements of ASTM C330.[3] The lightweight aggregate was proportioned on the basis of 1.55 $\pm$ 0.05 specific gravity (SSD) at a typical moisture content of 10 percent by weight.

The climate at this location, approximately 20 miles south of Albany, New York, is severe from the standpoint of temperature extremes, with about 60 annual freeze-thaw cycles. The New York Thruway Authority is well-known for its commitment to an all-weather roads policy, and this bridge is subjected to multiple salt applications with each of the more than 20 ice and snow storms experienced every winter. To this date the bridge has probably been exposed to more than 700 salt applications.

The condition of the exposed lightweight concrete deck, as viewed in the summer of 1984, was excellent, with only minor evidence of cracking and no spalling. Cores taken from the exposed deck showed clearly a uniform mix with a high degree of integrity of the contact zone between the expanded aggregate and the enveloping mortar fraction.

In 1980 the bridge was subjected to half-cell potential readings by the New York Thruway Authority maintenance engineers, and readings indicated potential corrosion conditions. However, stereoscopic microscope examination of reinforcing steel did not confirm significant corrosion where such was indicated by half-cell readings. Further tests by the Portland Cement Association involved profiles of acid-soluble and water-soluble ion contents of two cores and found potential corrosion in one core. Additional field tests in which acoustical sounds are made by means of a rotating cam impacting on the slab, indicated no delamination or visible spalling.

The bridge is a good example of a successful lightweight-concrete structure subjected to severe climatic and salting conditions. It confirms the findings of the New York Thruway Authority's internal durability testing program, in which all types of major rock types, including lightweight aggregates, endured more than 200 cycles of freezing and thawing and over 100 applications of deicing chemicals. Lightweight concrete showed equal if not superior performance.

I-24 OVER SR 76 MONTGOMERY COUNTY, TENNESSEE

Location: 25 miles north of Nashville, Tennessee

Owner: Tennessee Department of Transportation

Completion of Construction: 1976

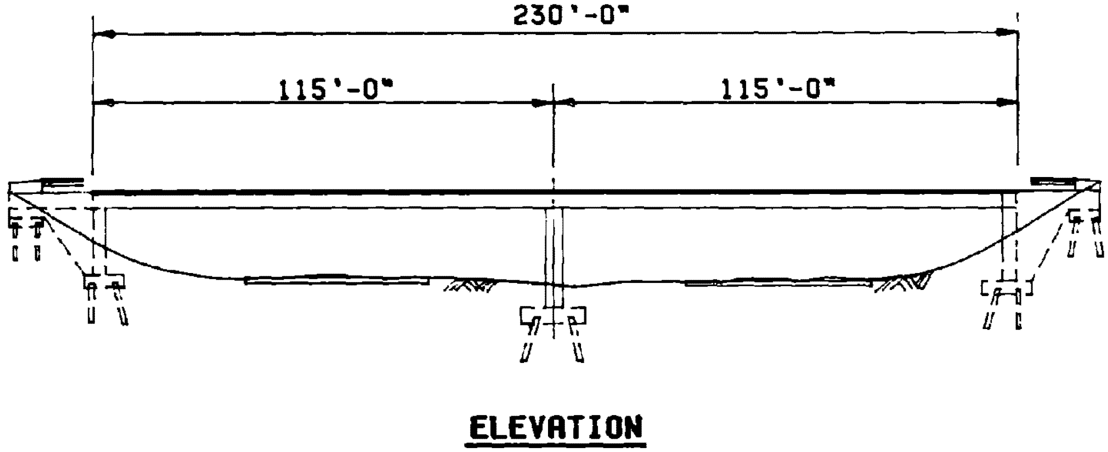
ADT: 14,000

Environment: This structure is exposed to severe climatic conditions and salting of the deck.

This actually consists of a pair of parallel 2-span, 115-ft (35-m) box-girder bridges with lightweight-concrete superstructure (figure 19). The westbound bridge has a 3-in (76-mm) asphalt overlay and the eastbound bridge has a Texcote finish.

The lightweight concrete used Tennlite aggregate, an expanded shale. The fine aggregates were natural sand. Lightweight concrete was mixed and cast according to the special provisions in the specifications, which require the aggregate to be a rotary-kiln product, with a maximum wear of 40 percent as per AASHTO T 96.(22) Maximum moisture content of the aggregate was 25 percent. Cement content was 658 pcy (390 $kg/m^3$), minimum compressive strength 4000 psi (28 MPa) at 28 days; unit weight 120 pcf (1,920 $kg/m^3$), maximum slump 3 in $\pm$ 1 in (76 mm $\pm$ 25 mm), air content 7 $\pm$ 2 percent. The provisions also required a uniform moisture content to be maintained within the moisture limits, and cautioned that the mix was susceptible to aggregate segregation because of the difference in specific gravity in the coarse and fine aggregates.

The present condition of the superstructure appears to be excellent. There seems to be little or no performance difference between the structures, the one with asphalt topping and the other with Texcote.




2.5 cm = 1.0 in
0.3 m = 1.0 ft

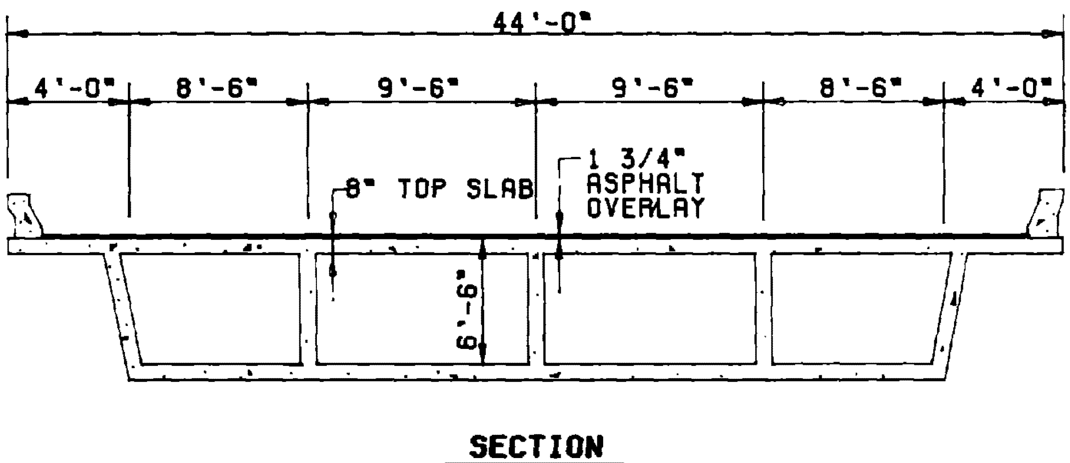



Figure 19. Elevation and section, I-24 over SR 76 Montgomery County.

Until recently, the standard practice of protecting bridge decks was to place an asphalt seal over a membrane on top of the concrete deck. This procedure was replaced by using an epoxy-coated reinforcing steel and a textured Texcote finish on the deck to protect the concrete surface.

WOODROW WILSON MEMORIAL BRIDGE, VIRGINIA

Location: Alexandria, Virginia

Owner: Federal Highway Administration, U.S. Government

Completion of Construction: Original 1962, redecking 1983

ADT: 110,000

Environment: This structure is exposed to moderate to severe weather with much deicing.

The Woodrow Wilson Memorial Bridge is a good example of the use of lightweight concrete for the redecking of a steel structure.

The bridge is a major structure, carrying I-95 across the Potomac at Washington, DC. It is operated and maintained jointly by the State of Maryland, the Commonwealth of Virginia and the District of Columbia. It was constructed with normal-weight concrete in 1962, and in 1979, the reinforced-concrete deck had deteriorated to the point where redecking was necessary.

The structure is 5,900 ft (1,800 m) long, with a 212-ft (65-m) double-leaf bascule main span over the river channel, with 8 steel deck girder approach spans on the Virginia end, and 10 similar spans on the Maryland end. The spans vary from 63 to 184 ft (19 to 56 m), and floor beams span between the girders and carry rolled beam stringers, which are continuous over the floor beams (figure 20). The reinforced concrete deck, 89 ft (27 m) wide, carries 3 lanes on each side. It is noncomposite with the steel beams. A 2-in (51-mm) wearing surface of asphaltic concrete covers the deck.

The redecking of the bridge presented severe constraints in design and construction. The deck was widened to 93 ft 2 1/2 in (28 m), designed for AASHTO loading of HS 20-44 and traffic had to be

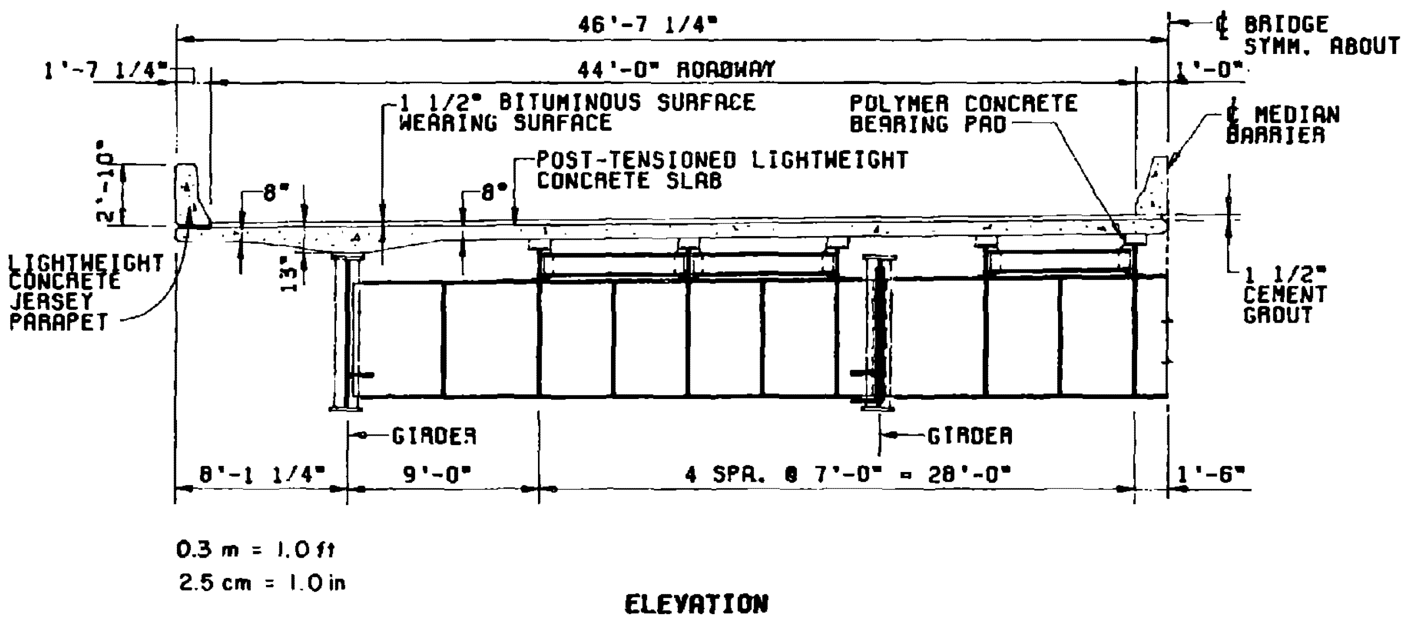



Figure 20. Elevation, Woodrow Wilson Memorial Bridge.

maintained fully during the day and partially during the night. The solution chosen as the result of numerous studies was a system of precast, transversally post-tensioned lightweight-concrete panels, supported on the existing steel without strengthening. The deck panels were posttensioned in place longitudinally. Polymer concrete was used at the joints (figure 21).

The panels were prefabricated in a precasting plant approximately 75 miles (121 km) from the site. The typical panel was 46 ft 7 1/4 in (14 m) long and 10 to 12 ft (3 to 4 m) wide, with a thickness of 8 in (200 mm). A total of 1,026 panels were cast for the roadway. Casting was done with steel forms, at the rate of 6 to 7 elements per day. After casting, the panels were steam-cured for 16 hours and kept moist under insulating tarps at a minimum temperature of 50 $^{\circ}$F (10 $^{\circ}$C) for 6 days. After curing, post-tensioning was applied transverse to the direction of traffic. Two coats of epoxy-sand overlay were applied, with 24 hours of curing between coats, for the protection of the panels under traffic until final wearing surface could be placed. The panels were required to be 30 days old before erection. Longitudinal post-tensioning connected the panels and their joints in place.

The lightweight concrete was governed by specifications prepared by the design consultant and enforced by the staff of the State of Maryland Department of Transportation. They required a minimum of 700 pcy (318 kg/m$^3$) of Type II cement in the mix, lightweight coarse aggregate and normal-weight crushed limestone sand, and 6 to 9 percent air entrainment. Design air-dry unit weight was to be 115 pcf (1,840 kg/m$^3$), slump 0 to 3 in (0 to 76 mm). Twenty-eight-day design compressive strength was 5,000 psi (35 MPa).

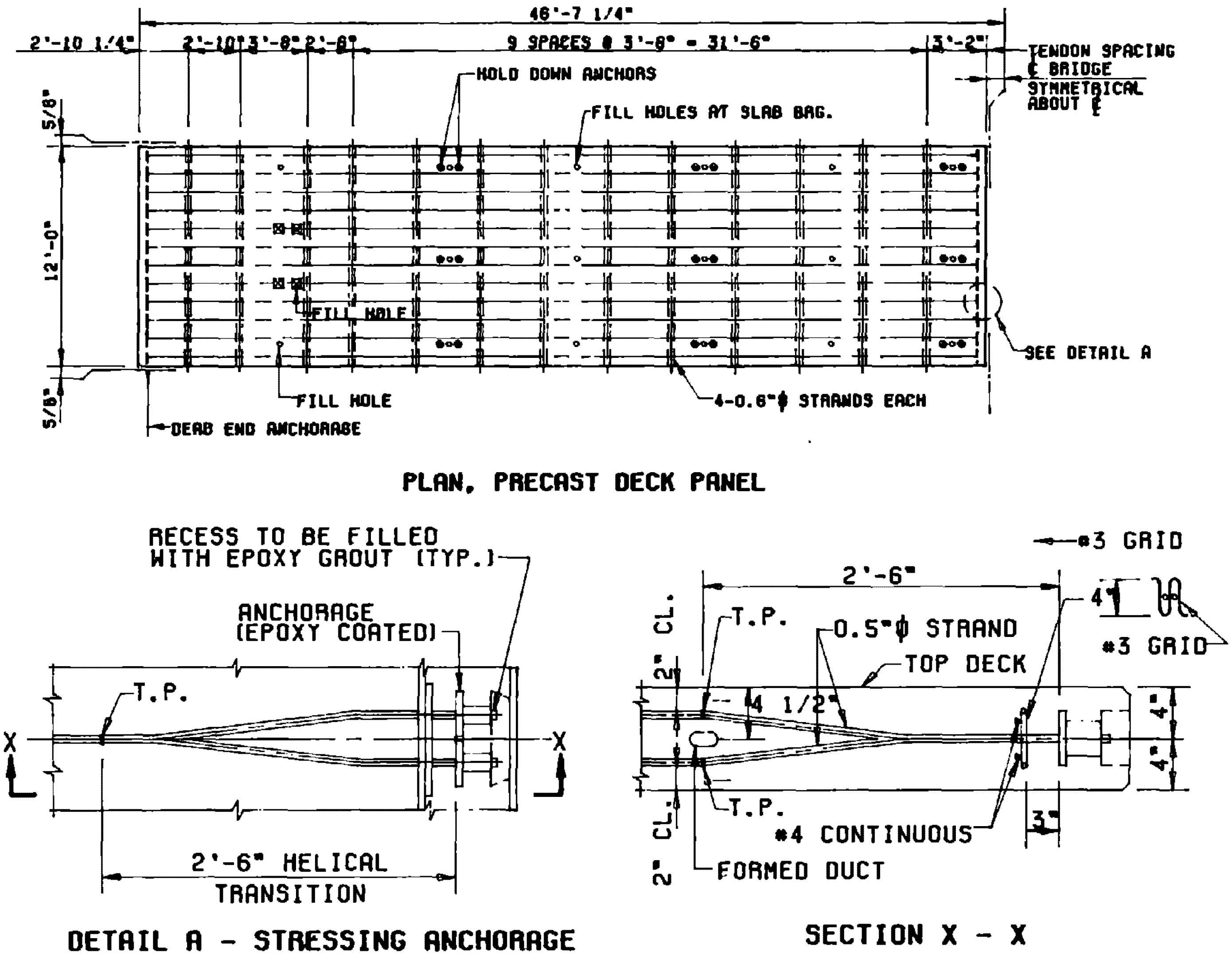



Figure 21. Typical lightweight-concrete deck panel, Woodrow Wilson Memorial Bridge.

One of the most significant aspects of this successful construction was the control exercised in the plant. Selection of the mix was by trial batches in the laboratory, followed by full-scale batching operation in the plant.

The lightweight-concrete mix is shown below.

<u>Materials</u>

| | | |
|---|---|---|
| Cement | : | Type II, Capitol Cement Corporation (ASTM C150) 700 pcy (415 kg/m$^3$) minimum |
| Coarse Aggregate | : | Expanded-slate, lightweight, Carolina Stalite Co. (ASTM C330) |
| Fine Aggregate | : | Crushed limestone sand, Stuart M. Perry, Inc. (ASTM C33) |
| Admixtures | : | Air-entraining, "Daravair" (ASTM C260); Retarding-water reducing, "Daratard" (ASTM C494 Type D), W.R. Grace, Inc. |

<u>Specification</u>

| | | |
|---|---|---|
| 28-Day Strength | : | 5,000 psi (35 MPa) |
| Slump | : | 0-3 in (0-76 mm) |
| Air Content | : | 6-9% |
| Unit Weight | : | Air-dry (ASTM C567) 113-117 pcf (1,810-1,874 kg/m$^3$) |

The following data were obtained during the period of October 1, 1982 to August 1, 1983. Each sample represents the average of two test cylinders. The cylinders for strength tests were steam-cured with the panels for 16 to 18 hours, and stored in a moist room until tested. The cylinders for the air-dry unit weight tests were stored in accordance with ASTM C567 procedures.[6]

7-Day Strength

| | | |
|---|---|---|
| No. of Samples | = | 555 |
| Average Strength | = | 5,656 psi (39.0 MPa) |
| Standard of Variation | = | 427.8 psi (2.95 MPa) |
| Coefficient of Variation | = | 7.56% |
| Average Range | = | 137.1 psi (0.94 MPa) |
| Within-Test Variation | = | 2.15% |

28-Day Strength

| | | |
|---|---|---|
| No. of Samples | = | 571 |
| Average Strength | = | 6,572 psi (45.3 MPa) |
| Standard Deviation | = | 470.5 psi (3.24 MPa) |
| Coefficient of Variation | = | 7.16% |
| Average Range | = | 196.7 psi (1.36 MPa) |
| Within-Test Variation | = | 2.65% |

56-Day Strength

| | | |
|---|---|---|
| No. of Samples | = | 181 |
| Average Strength | = | 7,160 psi (49.36 MPa) |
| Standard Deviation | = | 561.5 psi (3.87 MPa) |
| Coefficient of Variation | = | 7.84% |
| Average Range | = | 233.3 psi (1.61 MPa) |
| Within-Test Variation | = | 2.89% |

Unit Weight (ASTM C138)

| | | |
|---|---|---|
| No. of Samples | = | 377 |
| Average | = | 115.9 pcf (1,857 kg/$m^3$) |
| Standard Deviation | = | 1.35 pcf (21.6 kg/$m^3$) |

Air-Dry Unit Weight (ASTM C567)

| | | |
|---|---|---|
| No. of Samples | = | 438 |
| Average | = | 115.7 pcf (1,853 kg/$m^3$) |
| Standard Deviation | = | 1.65 pcf (26.4 kg/$m^3$) |

The aggregate chosen was an expanded slate. Trucks with coarse and fine aggregates came into the plant about every other day, and each truck load was sampled for the specific gravity. Coarse aggregate which did not meet the specific gravity specification of 1.5 $\pm$ 0.03 was rejected. Physical testing of cement to conform to ASTM C150[20] was carried out at the rate of once for every 60 tons (54,431 kg) of cement or at least once a week.

The lightweight aggregate had relatively low absorption, in the order of 6 percent, which is typical of expanded slate. It was kept wet by sprinkling of the storage pile, as well as the conveyor belt. Batching was by normal procedure, with central mixing in the mixing plant and agitating in trucks. Mix control was computerized, whereby input data such as moisture, etc. were automatically taken into consideration in the program and the mix adjusted automatically. Several engineers attributed some of the success of the mix control to the fact that slate lightweight aggregate permitted better control of water.

The wet concrete was carefully checked in every truck load. The control involved slump, air content, temperature, and unit weight. All specifications could be adhered to, except for slump, which was permitted to rise to 4 in (102 mm) at times, for a 3-in (76-mm) average.

Cylindrical specimens for compressive strength and air-dry unit weight were made and tested for approximately every 28 $yd^3$ (21 $m^3$).

Although the replaced deck is too new for its performance to be judged, the replacement job seems to be a total success. Lightweight concrete and post-tensioning permitted the weight reduction that was necessary to avoid the strengthening of the existing steel structure. Carefully controlled design and construction made the use of lightweight concrete a routine matter, with only little more care than needed for other concrete construction.

The Maryland Department of Transportation, which was responsible for the inspection of the project, expressed satisfaction with the performance of the lightweight concrete and the construction in general. The material engineers also were favorably inclined toward the use of lightweight concrete, not only in the Woodrow Wilson Memorial Bridge but in other repair projects as well. The Department's laboratory and inspection staff have adequate procedures for the inspection of both normal-weight concrete and lightweight concrete, and they will use either when the situation is appropriate.

Cost records show that the total cost of the deck panels in-place, including post-tensioning steel, was \$5.8 million for 13,400 $yd^3$ (10,250 $m^3$), that is \$435/$yd^3$ (\$569/$m^3$) or \$20.75/$ft^2$ (\$223/$m^2$). The reinforcing steel was a separate contract item.

LOUISIANA

The Louisiana Department of Transportation (LDOT) has had a great deal of trouble with lightweight concrete. In the late 1950's and early 1960's, a number of bridges including some major ones were built with lightweight concrete decks. In many cases, the concrete deck soon started to crack and deteriorate. Large sections of concrete broke and fell from roadway decks. Many of these lightweight decks had to be replaced. A dramatic case in point was the failure of the Metarie Bridge in New Orleans, where a large piece of lightweight concrete simply fell from the deck, causing much public concern.

Although there had been abundant technical and press reports about these failures, written evidence has not been conclusive. Part of the problem seemed to be related to the quality of the aggregate, the construction procedures, and the quantity of mild-steel reinforcement in the decks. It would be useful to find out, if possible, the reasons for the poor showing of lightweight concrete as it was used in the State.

Some of the aggregates then in use had apparently come from the Shreveport area. Indications were that this aggregate was produced by the sintering method which could have produced improperly expanded aggregates. Furthermore, the mix had included lightweight fines, which are known to produce concrete of lower strengths. One source reported that the performance of lightweight-concrete bridges had improved after natural sand was introduced into the mix. There was also evidence that the construction procedures might not have been properly followed. This evidence appeared to have been reinforced by the fact that some normal-weight-concrete bridge decks also displayed the same problems. All these could lead one to conclude that the poor performance of lightweight concrete had been due to unfortunate circumstances existing at the time of its use in Louisiana, and not to the lightweight concrete itself. Lightweight concrete is not currently used for bridge construction in Louisiana.

There are still a number of lightweight-concrete bridges in use in Louisiana. Two of these were inspected and reported herein. Although detailed information on their design and construction was not available, a few conclusions were nevertheless possible from the visual inspection.

US 190 Over the Amite River

The Amite River crossing consists of 2 bridges, one each for westbound and eastbound traffic. The eastbound bridge consists of a girder-type structure with a lightweight-concrete deck, the westbound a thru-truss with a normal-weight-concrete deck.

Both bridges seem to be in excellent condition with only minor cracking and very little spalling observed. Although the truss bridge is somewhat older, the lightweight deck of the girder bridge has provided over 20 years of satisfactory service.

US 61 Over Thomson Creek

This bridge has a steel girder structure with a lightweight-concrete deck. It was built in 1961 and given an asphalt topping around 1970.

The deck is in good condition. There are some cracks in the asphalt, but few seem to penetrate the concrete slab. There is very little spalling. Generally it seems to be performing well after 20 years of service.

## MISSOURI

The Missouri Highway and Transportation Department (MHTD) has had good experiences with lightweight concrete. Recently, the State used lightweight concrete in 10 to 12 bridges, most of which are long-span, steel-truss structures. Among these is the Caruthersville Bridge on Interstate 155 over the Mississippi River. The bridge was built in 1976, and reportedly is still in very good condition.

In 1964, MHTD prepared a report on deck deterioration as the result of its bad experiences with some concrete bridges. The report included interesting information concerning the formation of potholes, cracking, surface mortar deterioration, fracture planes, and the condition of some lightweight-concrete structures. This had contributed much to an awareness of the importance of good construction practices in the State.

The MHTD has its own specifications for lightweight concrete, and a manual of field practice. It also has a surveillance program carried out with the aid of computer.

The State mostly uses expanded-shale aggregate, coming from the area north of Kansas City, and natural sand in lightweight concrete construction. The concrete is air-entrained.

Missouri bridges are subject to heavy salting. New bridge decks are sometimes topped with an asphalt overlay. Visual inspection is conducted yearly, and necessary patching and other remedial measures are implemented as necessary.

The MHTD has had no particularly bad experiences with lightweight concrete in recent years. Better design and construction practices are obviously followed to achieve the success of the many concrete structures in the State. The preparation of a thorough report on construction problems in 1964 only reflects the integrity and determination on the part of MHTD to confront and resolve its problems, and portends its further success.

The results of an inspection of 2 bridges in Missouri are given below:

Jefferson City Bridge
Location: Highway 54 over the Missouri River
Owner: Highway and Transportation Department
Completion of Construction: 1953
ADT: 27,400
Environment: Heavy roadway salting, severe climate.

The main spans of the Jefferson City Bridge consist of continuous steel arches with span lengths of 416, 640, and 416 ft (126, 195, and 126 m). The approaches consist of steel I girders and plate girders of shorter spans. The deck in the main spans is made of lightweight concrete 6 1/2 in (165 mm) thick. The lightweight concrete used in the original deck is referred to as Haydite concrete. Information on the aggregate used is not available.

The bridge deck has performed well for almost 30 years. It was resurfaced with an asphalt overlay in 1964, sealcoated in 1973 and 1981, and resurfaced again in 1982. The results of survey of the bridge deck condition in March, 1982, show that the chloride content is heavy to a depth of 1 1/8 in (29 mm), but diminishes considerably at a depth of 2 in (51 mm). Chloride content is minimal at 2 7/8 in (73 mm).

Considering the fact that the bridge lasted almost 30 years without major rehabilitation, the behavior of the lightweight deck must be considered satisfactory. The Department makes an interesting observation of the fact that the deck in the approaches, which was normal-weight concrete, was in worse shape at the time of resurfacing. The Department felt that while the lightweight deck in the long spans had needed only an overlay, the deck in the approaches might have to be replaced.

Broadway Bridge Over the Missouri River

Location: Kansas City, Missouri
Owner: City of Kansas City
Completion of Construction: 1957
ADT: Approximately 15,000
Environment: Severe climatic conditions, heavy salting.

The Broadway Bridge has for its main span a steel-tied arch with spans of 540, 453, and 451 ft (165, 138, and 137 m). Approaches are plate girders with smaller spans. All spans have a 6 1/2 in-(165-mm) lightweight-concrete deck. The concrete deck has apparently performed well for more than 20 years. In 1979, it was replaced with another lightweight-concrete deck.

The new concrete deck used expanded-shale coarse aggregates and river sand. The compressive strength was 4,500 psi (30 MPa) at 28 days. Concrete slump was 3 in (76 mm). The unit weight was 115 pcf (1,840 $kg/m^3$), with 6-percent air entrainment. The specifications of the Midwest Concrete Industry Board were used for mix design. ASTM Standards were used for quality control.

The concrete delivered by pumping caused slump-loss problems, which were solved by the vacuum saturation of the aggregate prior to mixing. The finished slab was topped with a 2-in (50-mm) normal-weight-concrete wearing surface. It is reported to be in good condition at this time.

## SOUTH DAKOTA

The South Dakota Department of Transportation (SDDOT) has had excellent experience with the many lightweight-concrete bridge decks and reinforced lightweight-concrete box-girder superstructures. Lightweight concrete is used primarily to reduce superstructure weight.

A visit was made to the Sioux Falls area to inspect a number of lightweight concrete bridges along I-29. These bridges carry relatively light traffic, but include a large percentage of trucks. Heavy salting is used on all roads during winter. The climate is severe in winter and very hot in summer. The natural environment, however, is not corrosive.

The bridges inspected were built in the late 1950's based on SDDOT's specifications. The design mix, furnished by the Materials Testing Division of the SDDOT, was based on an ultimate compressive strength of 4,000 psi (28 MPa) at 28 days, using 3- to 5-percent air entrainment, and expanded shale aggregates. Minor spalling has occurred, but service has been extended with the application of a protective course of latex modified concrete or low-slump dense concrete. The current policy of SDDOT is to use epoxy-coated reinforcing steel for all new bridge decks.

A bridge on I-29 over railroad tracks is an excellent example of the use of lightweight concrete in conjunction with normal-weight concrete (figures 22 and 23). The bridge is constructed of normal-weight-concrete piers with umbrella-type caps and deck. The umbrella serves as a cantilever to support a lightweight deck portion in the uniform deck section.

Figure 22. I-29 over railroad tracks.

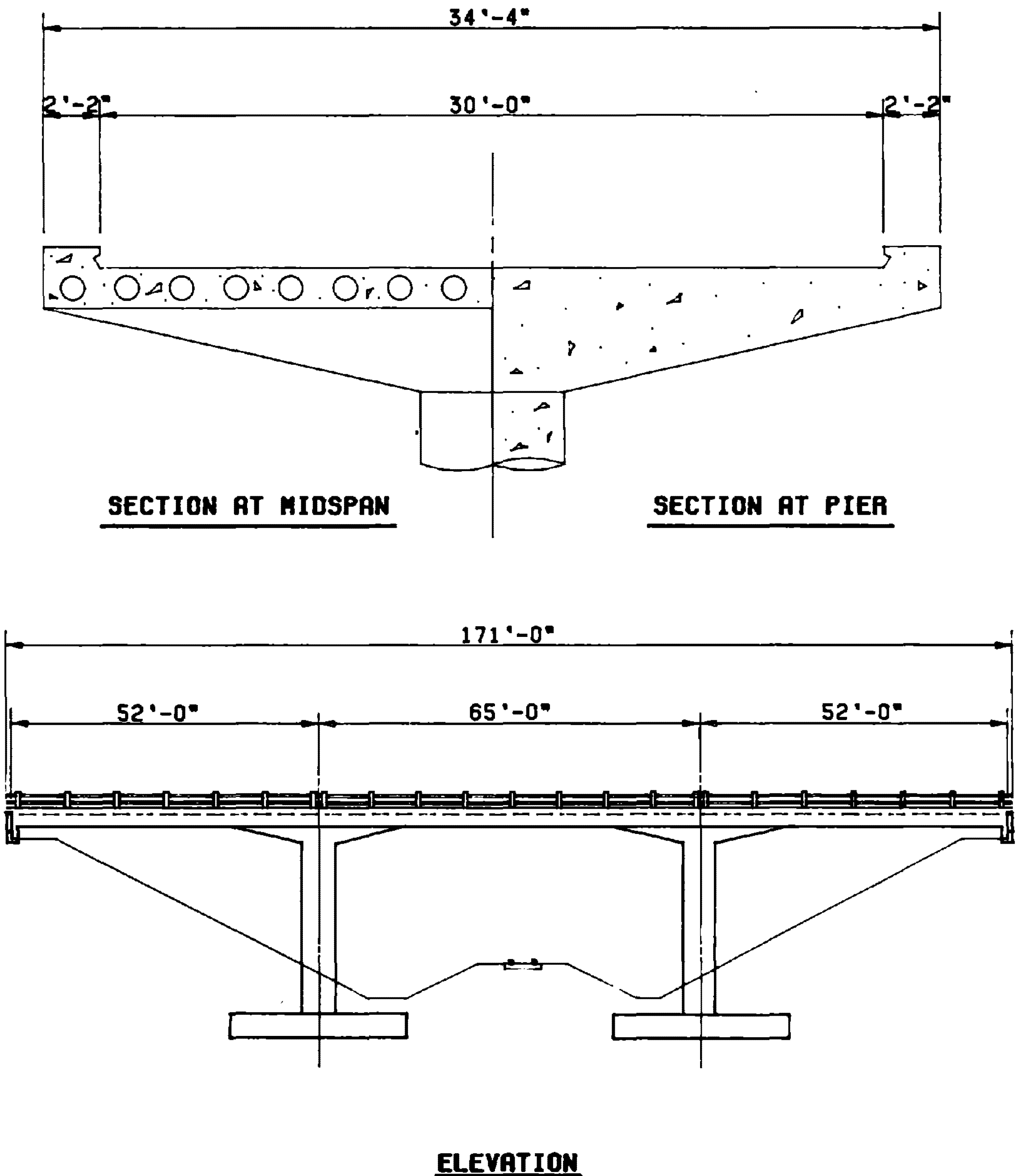



Figure 23. Elevation and sections, I-29.

A 1979 inspection report on the condition of this bridge indicated some spalled areas with the lightweight deck portions performing better than the normal-weight-concrete areas. This bridge, built in the late 1950's, was surfaced with a latex overlay in 1981.

The State has an excellent inspection and maintenance program.

TEXAS

The State of Texas has used lightweight concrete in its bridges since 1948. In a survey conducted for this report, 25 bridges were found to have been constructed of lightweight concrete. Of these approximately 20 were reported to be in good condition, but 5 bridges had been resurfaced, or had overlays added after 15 to 20 years of service. The lightweight concrete decks in five bridges did not perform well, and had to be replaced.

Early lightweight-concrete specifications were similar to those for normal-weight Class "A" concrete. Lightweight concrete used in bridge decks in the 1950's and 1960's probably had a minimum cement content, specified as 517 pcy (308 kg/m$^3$) of Type I cement. Specifications allowed Types I, II, or III cement. The minimum 28-day strength specified was 3,000 psi (21 MPa). There was no limitation on water cement ratio nor were water reducing admixtures required. A cement dispersing agent and an entrainment were required. Problems were encountered with the use of these specifications: for example, the occurrence of pattern cracking in bridge decks.

Another factor which may have contributed to early pattern cracking was the thin deck design (approximately 6 1/2 in (1650 mm) thick) which was being used extensively. The decks have since been increased in thickness and made of higher strength concrete.

The specifications were upgraded for both lightweight and normal-weight concretes in 1972 to produce concrete that are more dense and durable. Cement content was increased from 564 to 658 pcy (335 to 390 kg/m$^3$), with a minimum 28-day compressive strength of 3,600 psi (25 MPa). A retarding admixture or a water reducing agent, and air entrainment were required.

In 1982, the specifications for lightweight concrete were removed from the Texas standard specifications. This change was brought about by the desire to apply the necessary construction controls to produce required results on a job-to-job basis. No lightweight concrete has been used recently.

Following are reports on two lightweight-concrete bridges inspected:

Capitol Avenue over Buffalo Bayou
Location: Houston, Texas
Owner: State of Texas,
Department of Highways and Public Transportation
Completion: 1962
ADT: 70,000 each structure
Environment: Climatic conditions are mild in an urban setting. There is no deicing.

This two-structure project consists of I beams and plate girders, spanned by a 6 1/2-in (165-mm) lightweight-concrete deck slab. The lightweight-concrete slab was used to reduce the size of steel supporting beams and foundations. The lightweight aggregate used was an expanded clay. Other particulars are not known.

There were problems in the field with maintaining workability, moisture control, and quality of concrete. After completion of construction transverse shrinkage cracks occurred every 3 to 5 ft (0.9 to 1.5 m) along the deck. Cracking was aggravated by continued heavy traffic, resulting in map cracking and ultimately in punch-out failures. In 1981 the deck was replaced with hardrock concrete.

The poor performance of lightweight concrete in these early bridges does not necessarily point to material failure, but also to poor construction and quality control. These bridges were built at a time when the proper handling of lightweight aggregates and the casting of lightweight concrete were not too well known. In fairness, it should be noted that hardrock concrete had its problems as well in those early days.

<u>Chestnut - Haskell Overpass</u>

Location: Dallas, Texas

Owner: State of Texas,
Department of Highways and Public Transportation

Date of Completion: 1964

ADT: 130,000

Environment: The bridges are located in an urban setting with a moderate climate and minor freeze-thaw cycles.

These parallel bridges, with a length of 3,945 ft (1,200 m), consist of more than 60 steel-girder spans with lengths ranging from 40 to 100 ft (12 to 30 m). A 7 1/4-in (184-mm) slab spans between the girders. There is no wearing surface.

The deck is cast of lightweight concrete with an expanded shale aggregate. Fine aggregates are natural sand. The concrete was specified to reach 3000 psi (20 MPa) at 28 days, 2- to 3-in (50- to 75-mm) slump, and 6- to 9-percent air entrainment. Proportions of the mix were 5 1/2 sacks of cement per $yd^3$ (307 $kg/m^3$), 12.6 $ft^3$ sand per $yd^3$ (0.47 $m^3/m^3$), 19 $ft^3$ of coarse aggregate per $yd^3$ (0.71 $m^3/m^3$), and 31.4 gallons of water per $yd^3$ (155 liter/$m^3$). A retarder was used in addition to air entrainment.

The performance of the structure in servicing very heavy traffic is quite good. In 1982 the sufficiency rating for this structure was 75.3 out of a possible 100.

## MATERIAL ECONOMICS OF LIGHTWEIGHT CONCRETE

The use of lightweight concrete has the advantage of dead-load reduction, which results in material savings of supporting structural elements, and consequently in overall cost savings. Thus, for those structural systems with large ratio of dead load to total structural reactions, as in the case of long-span segmental box girder bridges, an economical saving in overall material cost may be achieved by using lightweight concrete in the superstructure.

The volume of superstructure concrete, either lightweight or normal-weight, will be about equal. Thus, the economic benefit in using lightweight concrete will depend on its unit cost and the reduced cost of other major structural materials such as prestressing and structural steels, piles, and required handling equipment.

Preliminary designs were made to obtain qualitative indications of the economic and structural tradeoffs between lightweight concrete and normal-weight concrete. The bridge types studied included: prismatic (constant-depth) single-cell box girders; steel plate girders incorporating composite-concrete decks; AASHTO I-girders pretensioned with composite concrete decks; nonprismatic (variable-depth) segmental-cantilever box girders and concrete cable-stayed bridges (figure 24). In all studies a two-span continuous bridge with a deck width of 40 ft (12 m) was assumed, using three lanes of AASHTO HS-20 loading. In this report the evaluation was based upon unit material quantities required except for illustrative samples.

### SINGLE-CELL BOX GIRDERS

Preliminary designs were made to determine the required quantities of concrete, prestressing steel, and live plus dead-load reactions.

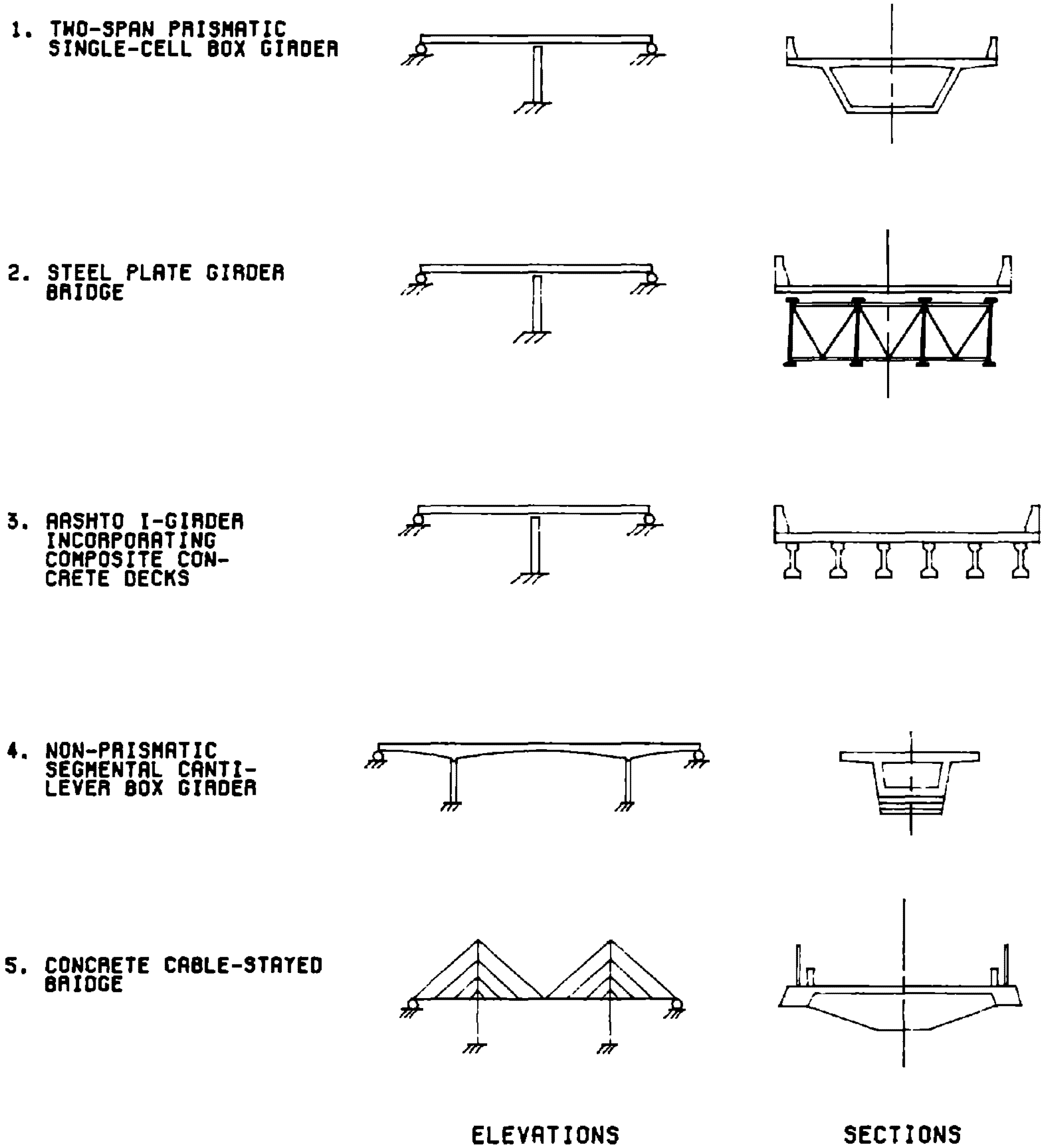



Figure 24. Structural systems studied.

The structural systems consisted of 2 equal continuous spans, 5,000 psi (35 MPa) concrete strength, 270 ksi (1,900 MPa) prestressing steel, and HS-20 loading. Seven span lengths of 50, 75, 100, 125, 150, 200, and 250 ft (15, 23, 30, 38, 46, 61, and 76 m) were considered and designed using lightweight and normal-weight concretes having unit weights of 115 and 150 pcf (1,840 and 2400 kg/m$^3$), respectively. Since the cross-sectional shape for each design was identical, the volume of concrete required for each would be equal. Figure 25 shows the volume of concrete required per linear foot of bridge for both lightweight and normal-weight concretes.

The weight of longitudinal prestressing steel and the dead plus live-load reaction are shown in figures 26 and 27, respectively. Referring to either figure, it can be noted that as the span length increases, the difference between lightweight and normal-weight concrete increases. This indicates that lightweight concrete can be most efficiently used for the longer span box girder bridges. Figure 28 was prepared using the quantities taken from figures 26 and 27, and compares the increase in difference between lightweight and normal-weight concrete as the span length increases. The reduction ratio is the percentage decrease of material required or reduction of load resulting from the substitution of lightweight for normal-weight concrete. It can be seen that the reduction for prestressing steel ranges from about 11.5 to 19 percent for longer spans and 15 to 21 percent for dead plus live-load reactions. Referring to figure 28, at span length of 100 ft (30 m), 16 percent less prestressing steel would be required and a 17-percent reduction in the dead plus live-load reaction could be achieved. The reduction in the dead plus live-load reactions would mean smaller supporting elements such as pier-columns and foundations.

For illustration, the following cost comparison was made. Assuming unit material cost of $1.50/lb ($3.30/kg) for prestressing steel,

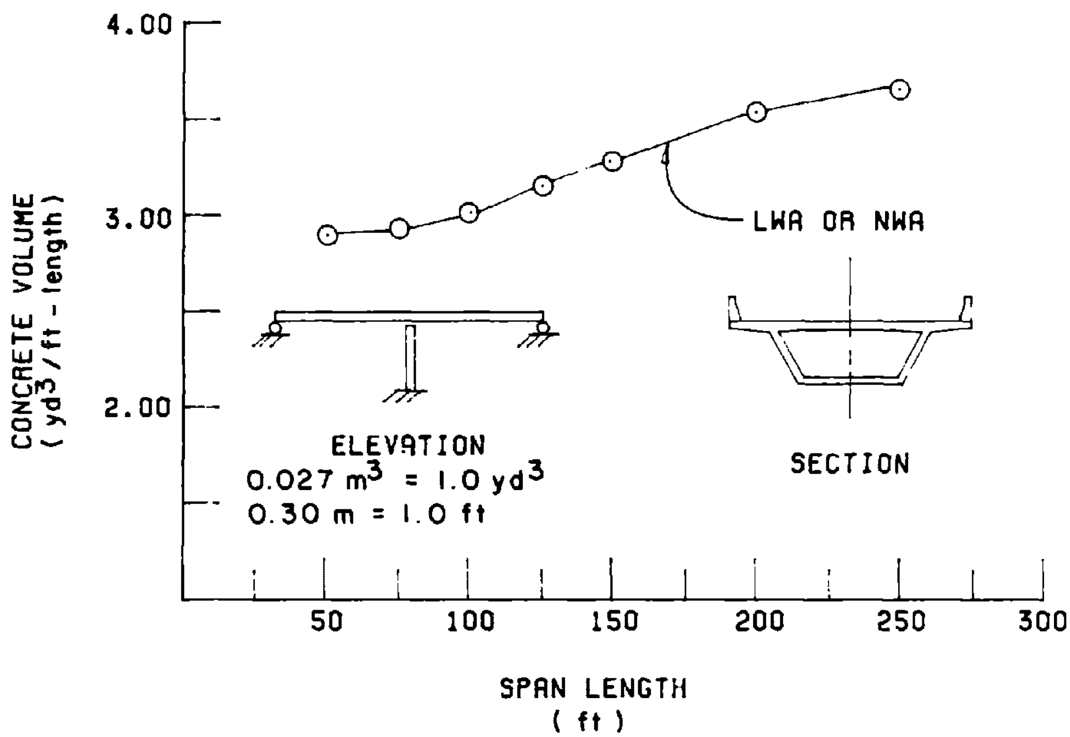



Figure 25. Volume of concrete for single-cell box girders.

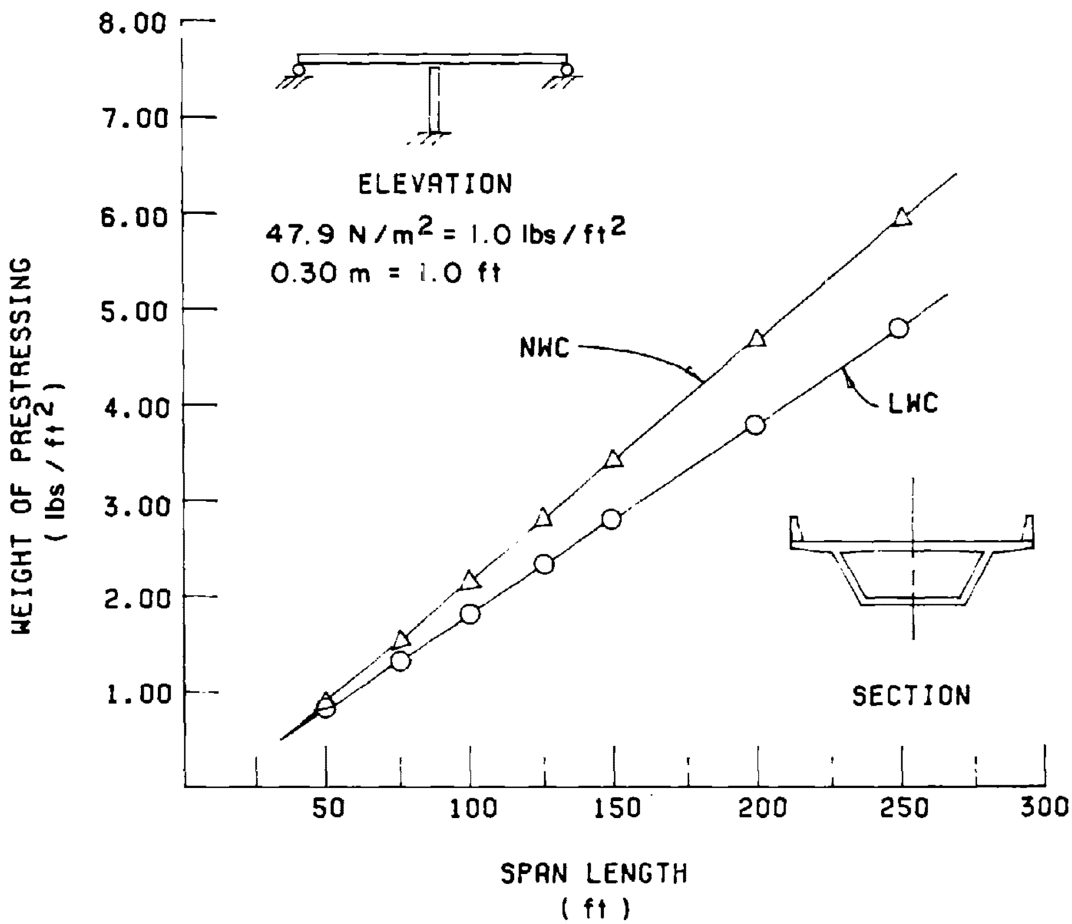



Figure 26. Weight of longitudinal prestressing steel for single-cell box girders.

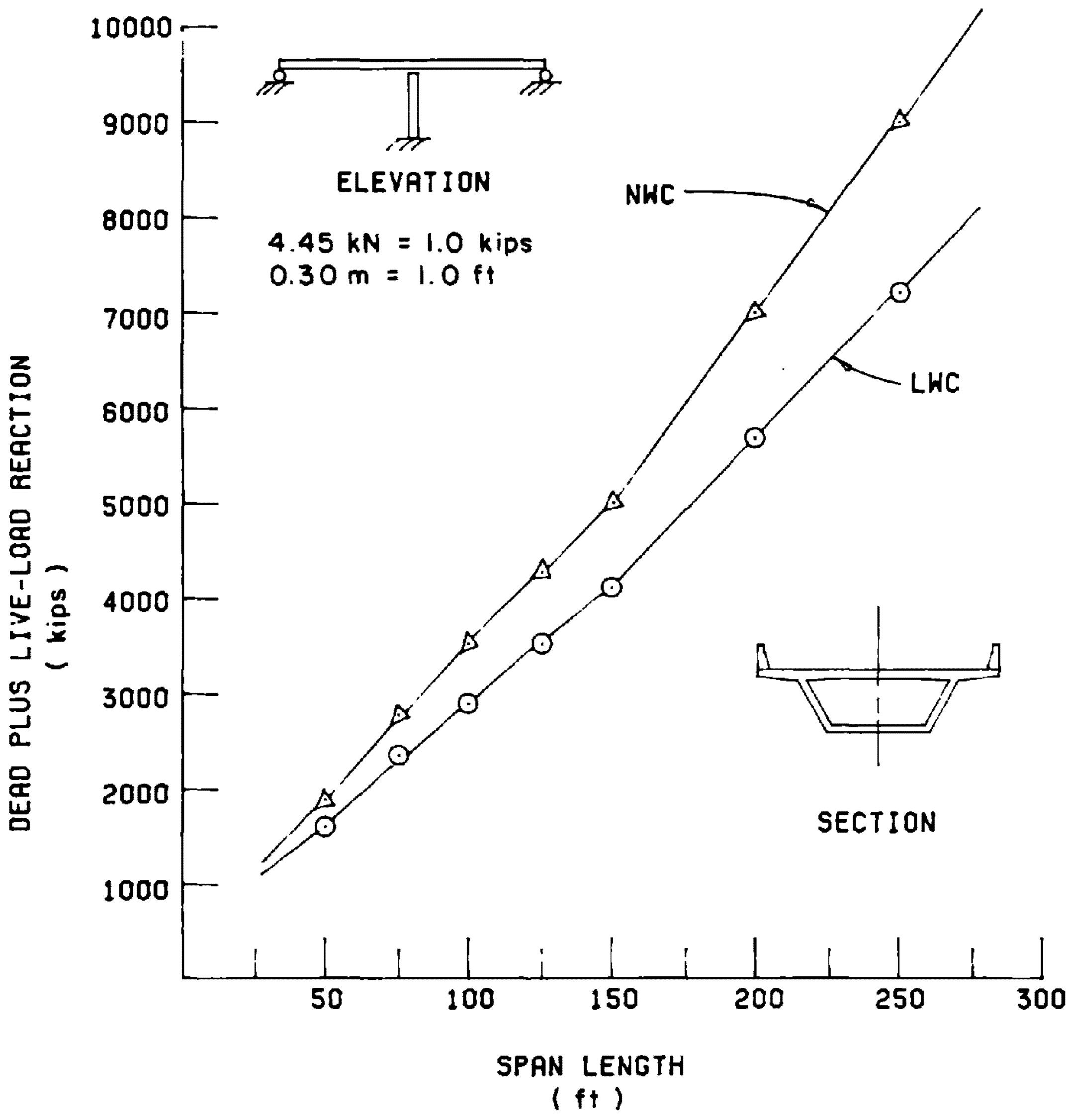



Figure 27. Dead plus live-load reaction for single-cell box girders.

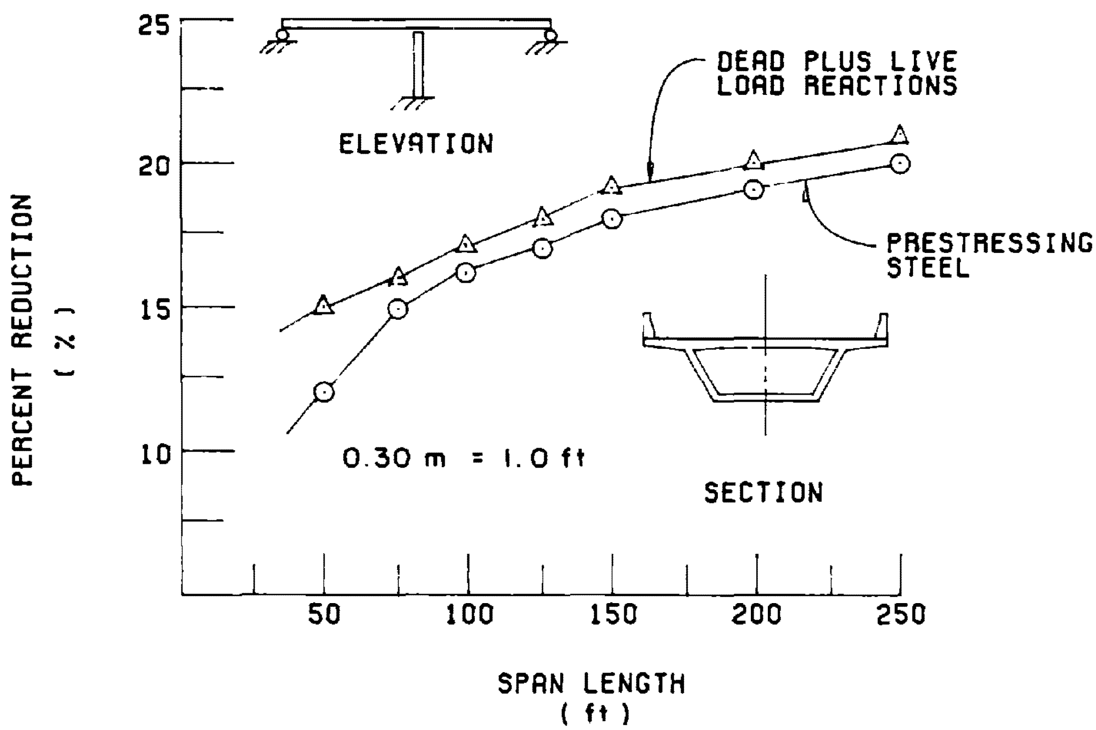



Figure 28. Percent reduction in load reactions and prestressing steel using lightweight concrete.

$30/ft ($98/m) for prestressed concrete piles 40 ft (12 m) in length, normal-weight concrete at $280/yd$^3$ ($366/m$^3$) in-place, and lightweight concrete at $280 and $320/yd$^3$ ($366 and $418/m$^3$) in-place respectively, the total cost per square foot of deck area for various span lengths is computed and shown in figure 29. It can be seen from the graph that if the unit cost of the two concretes are equal ($280/yd$^3$ or $360/m$^3$) lightweight concrete is the more economical material. However, the unit price of lightweight concrete will generally be higher than normal-weight concrete. Referring to figure 29 and interpolating, it is seen that a unit cost of about $305/yd$^3$ ($400/m$^3$) would make lightweight concrete competitive. Thus in order to be competitive, the lightweight-concrete in-place cost for single-cell box-girder bridges must not be more than about 10 percent that of normal-weight concrete. However, if the concrete cost is confined to the price of the out-of-the-truck concrete, which is typically 15 to 20 percent of the in-place cost, the 10-percent increase of in-place cost would be equivalent to 50-percent increase in out-of-truck cost. The required poundage of prestressing steel is about 7 percent less than that required by normal-weight concrete. Thus, in determining the potential cost advantages, a complete cost analysis should be made to compare the two concretes.

## STEEL PLATE GIRDERS

Preliminary designs were made to determine the weight of structural steel required for two-span, continuous-plate girder bridges. The structural system consisted of 36-ksi (250-MPa) structural steel girders with 4,000-psi (28-MPa) composite concrete decks. The working stress method was used to size the steel girder members. Three different studies were made.

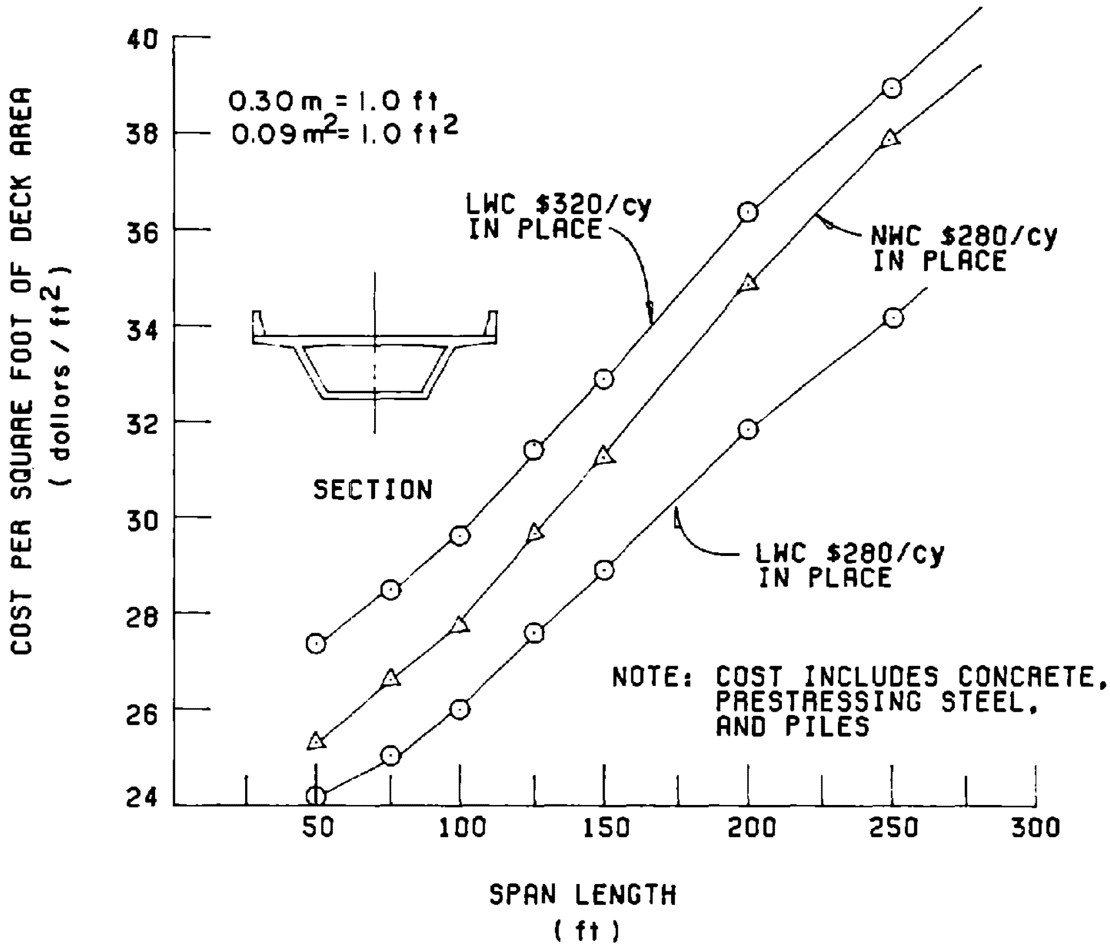



Figure 29. Cost comparison between lightweight concrete and normal-weight concrete with variable unit concrete cost.

In the first study the weight of structural steel was determined for a hypothetical 40-ft (12-m) roadway, which was designed to accommodate three lanes of HS-20 loading. The preliminary designs were made for span lengths of 50, 100, 150, and 250 ft (15, 30, 46, and 76 m) using lightweight and normal-weight-concrete decks. The results of these studies are shown in figure 30. It can be observed in figure 30 that the lightweight-concrete deck requires an average of about 14 percent less structural steel.

The second and third studies were based on a design of a normal-weight-concrete deck supported on steel plate girders. A scenario was assumed where the concrete deck was removed to accommodate either a loading capacity increase, from HS-20 to HS-25, or a 12-ft (3.7-m) roadway widening to add one lane of traffic. Results of these studies are given in figures 31 and 32.

Figure 31 shows the additional structural steel required when a normal-weight-concrete deck is replaced with a similar deck, but for higher load rating, from HS-20 to HS-25. It can be seen that the additional steel required for the increased loading is substantially different depending on whether lightweight or normal-weight concrete is used. The replacement of the normal-weight deck with a lightweight deck entails little or no additional structural steel or modification to the substructure, and should be considered in such replacement projects.

Referring to figure 32, it can be seen that additional structural steel is required if either a normal-weight or lightweight-concrete deck is used to widen an existing roadway by 12 ft (3.7 m), increasing the number of traffic lanes from 3 to 4. However, the additional steel required using lightweight concrete could be reduced by as much as 50 percent.

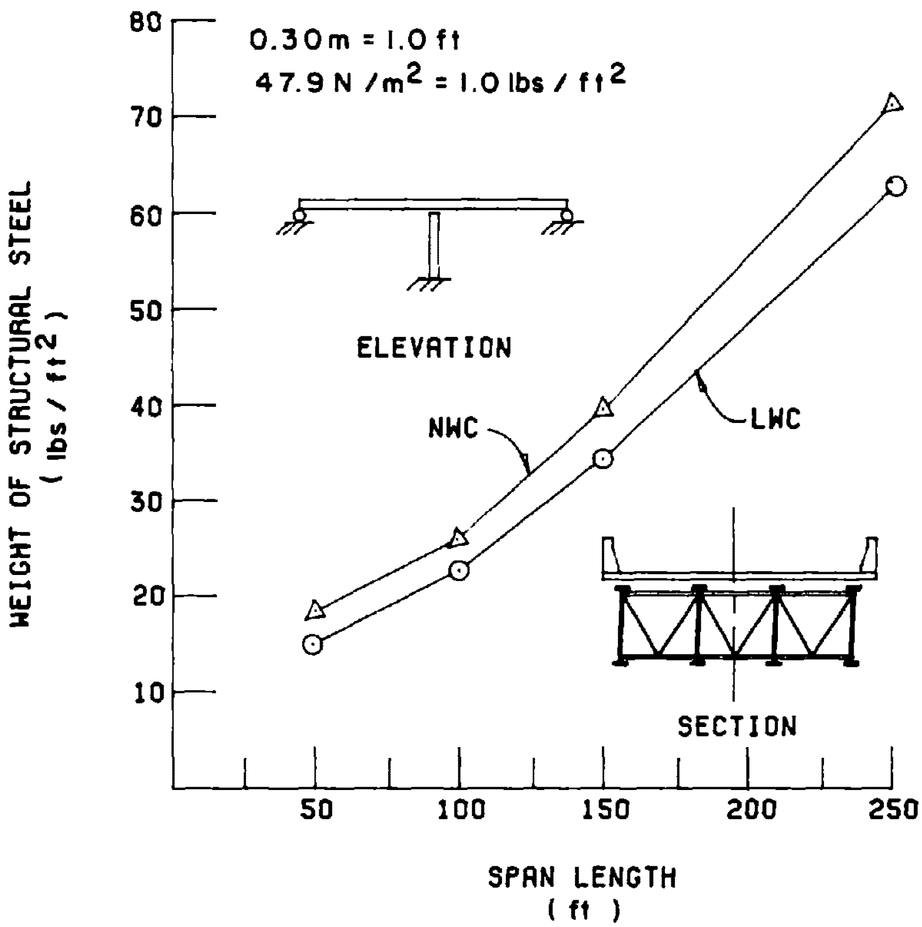



Figure 30. Weight of structural steel for steel plate girder bridges.

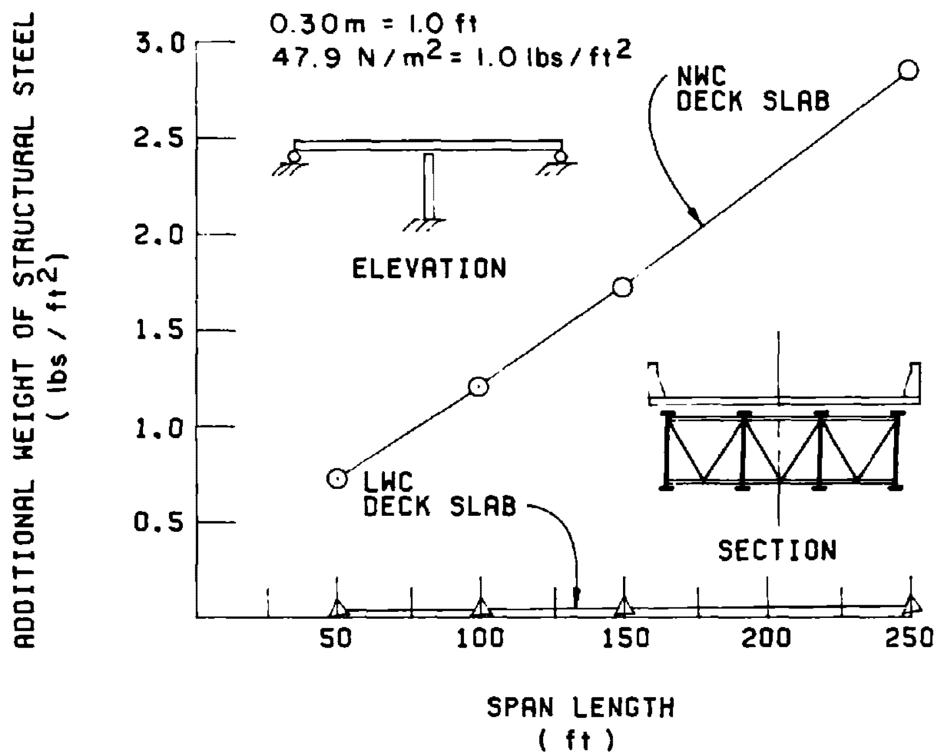



Figure 31. Additional structural steel required to increase load capacity from HS-20 to HS-25.

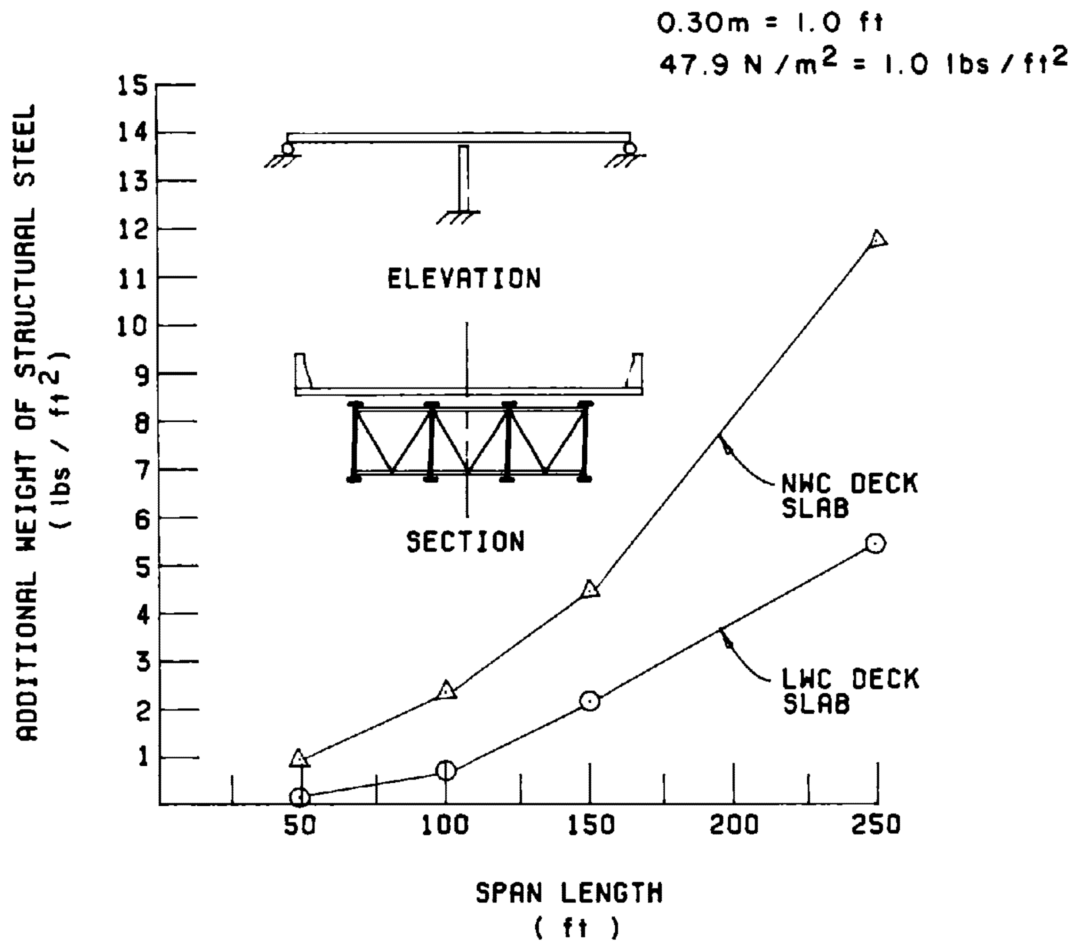



Figure 32. Additional structural steel required to increase roadway by one lane.

AASHTO I-GIRDERS

A study was made to determine the poundage of prestressing steel required for AASHTO I-girders, assuming a continuous 2-span system, 5,000-psi (35-MPa) concrete and a 40-ft (12-m) wide deck accommodating 3 lanes of traffic. Span lengths of 50, 75, 100, 150, and 175 ft (15, 23, 30, 46, 53 m) were considered. The geometric shape of both concrete designs for each span length was identical, and the entire girder and deck were assumed to have the same unit weight.

Results of the study, shown in figure 33, indicate that the difference in the weight of prestressing steel between lightweight and normal-weight-concrete structures increases with increasing span length, from 13.6 percent for a span of 50 ft (15 m) to 20.0 percent for a span of 150 ft (46 m).

SEGMENTAL BOX GIRDER

The use of lightweight concrete can be economical for segmental box girder bridges. Typical dead-load to dead-load plus live-load ratios average about 0.70 to 0.85 for this type of structure. Long-span segmental box-girder bridges constructed by the balanced-cantilever method normally have haunched girders to reduce the dead load during construction, resulting in an economical design.

Figure 34 shows the results of a study to determine the amount of prestressing steel required for segmental box-girder bridges constructed by the balanced cantilever method, using lightweight and normal-weight concretes.

As the span length increases, the weight difference of required prestressing steel for the two concretes remains relatively constant at about 21 percent. This is significant as the cost of prestressing steel is a major cost item for segmental box-girder

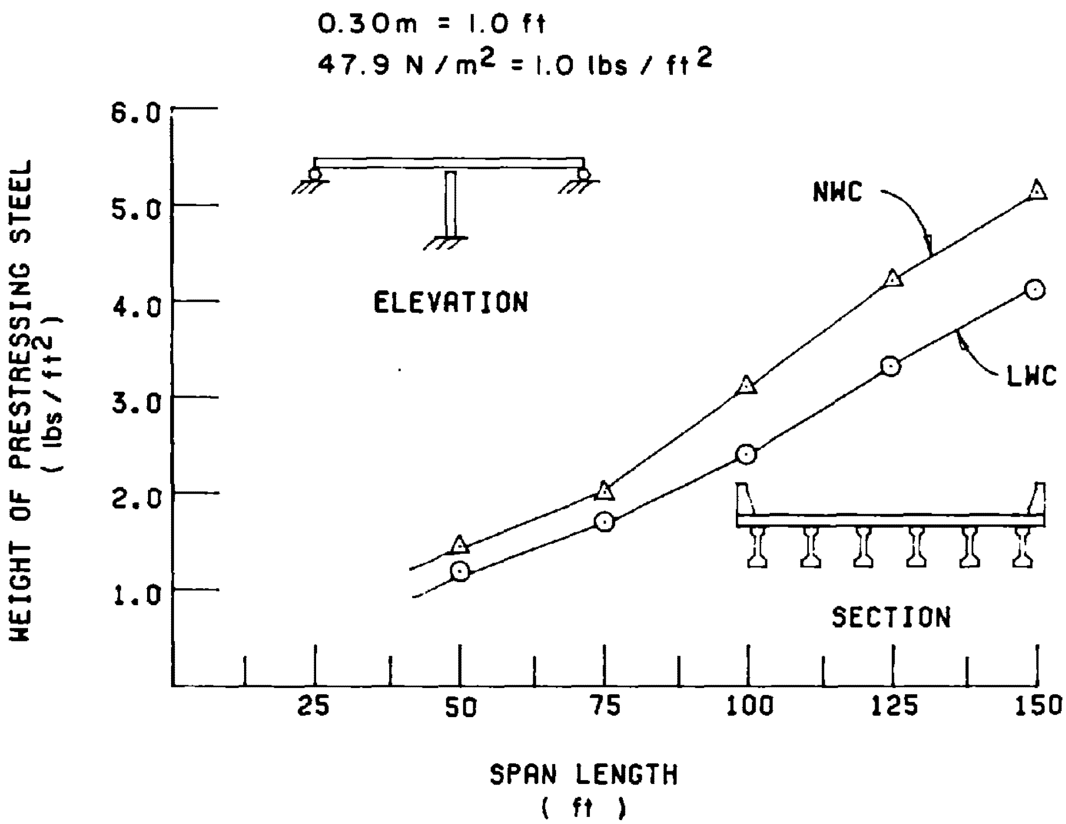



Figure 33. Weight of prestressing steel for AASHTO I-girder.

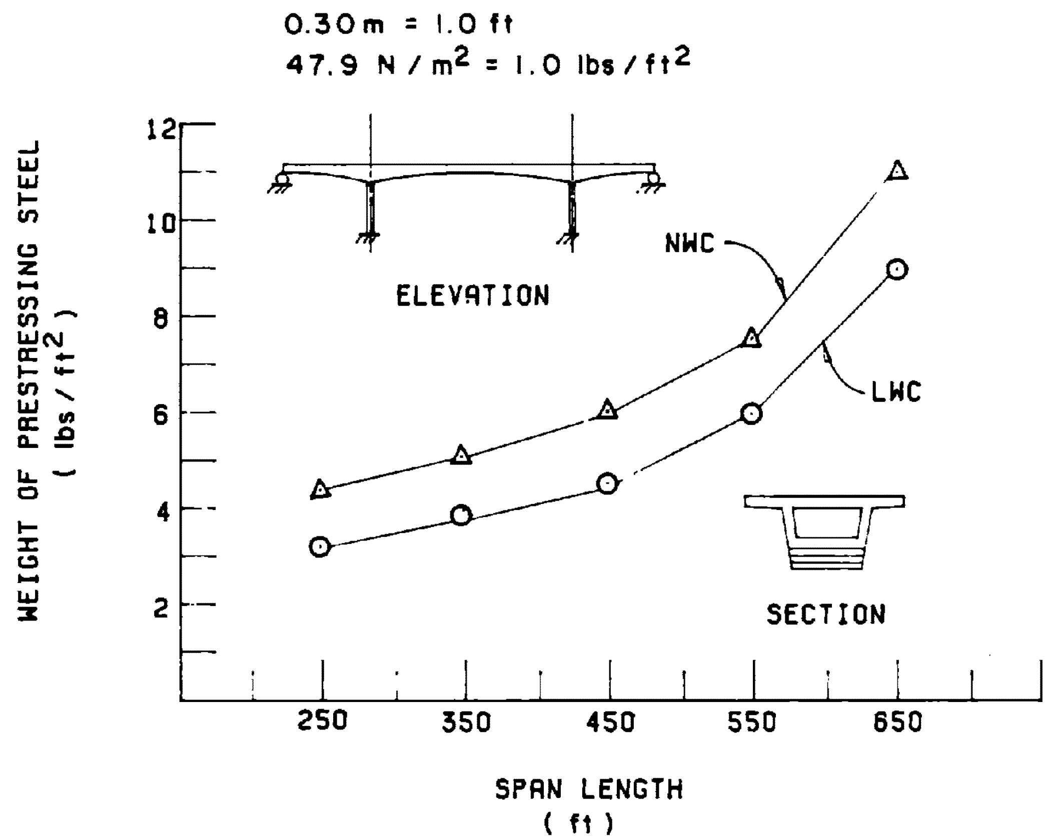



Figure 34. Weight of prestressing steel for segmental-cantilever box-girder bridge.

bridges. The required substructure quantities of foundation concrete, reinforcing steel and piles would also be reduced by approximately 20 percent. Another important aspect is the construction time required to complete the superstructure. Lightweight segments can be made longer, reducing construction time.

## CABLE-STAYED BRIDGES

Long-span cable-stayed bridges with concrete superstructures were studied to compare the steel cable weight for using normal-weight and lightweight concrete. Span lengths of 500, 1000, and 1500 ft (150, 300, 450 m) were considered (figure 35). The difference becomes greater as the span length is increased.

Because of the high dead-load to live-load ratio that is typical of long-span cable-stayed bridges, considerable material savings can be achieved in the cables, tower, and substructure by the use of lightweight concrete. Construction time of the superstructure would be reduced if segment lengths are increased by reducing material weight.

## REDUCTION IN STEEL BY USING LIGHTWEIGHT CONCRETE

From the data presented in the previous graphs it is evident that considerable savings in structural or prestressing steel can be realized by the use of lightweight concrete.

The following tabulation shows the approximate reduction in percentage in structural or prestressing steel for the bridges included in this study:

| | Structural Steel | Prestressing Steel |
|---|---|---|
| Single-cell box girder | NA | 16.6 |
| Steel plate girder | 13.7 | NA |
| AASHTO I-girder | NA | 18.6 |
| Segmental box girder | NA | 21.4 |
| Cable-stayed girder | NA | 13.5 |

0.30 m = 1.0 ft
47.9 N / m$^2$ = 1.0 lbs / ft$^2$

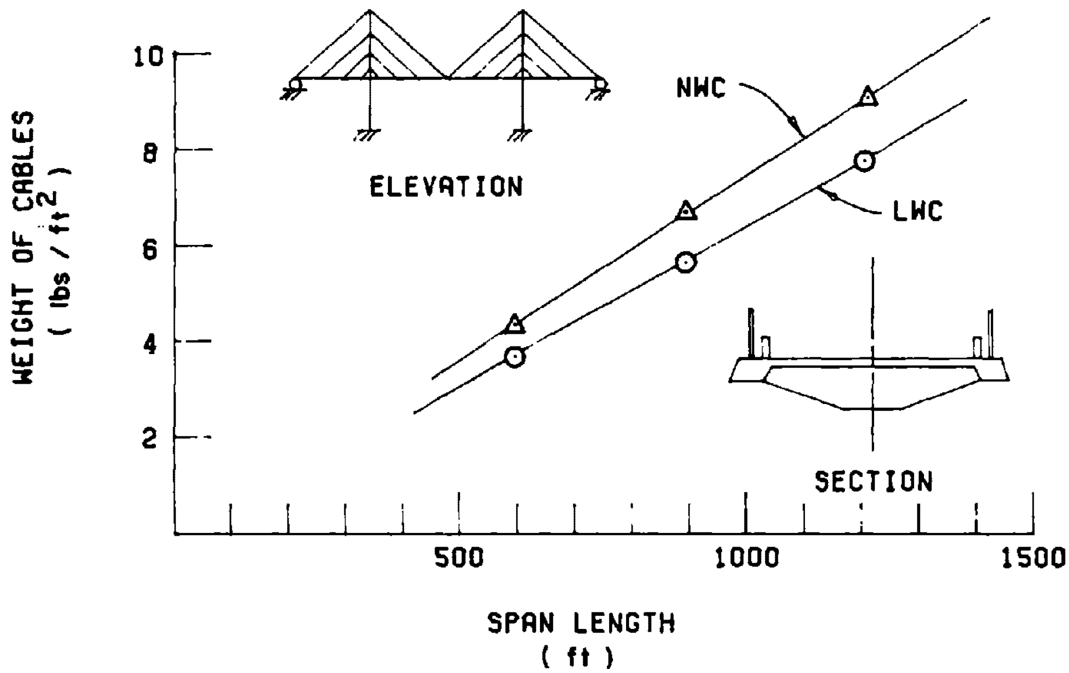



Figure 35. Weight of longitudinal cable stays for cable-stayed bridges.

## DISCUSSION

This report covers an industry which is at least 60 years old, and spans a vast geographical area. Lightweight aggregates are used for varied purposes, from insulating concrete to high-strength structural concrete. The following discussion pertains to some important facts and issues concerning the use of lightweight concrete in bridge construction.

### ADVANTAGES OF LIGHTWEIGHT CONCRETE

The only consistent reason for the use of lightweight concrete is the reduction of weight. In the case of the San Francisco-Oakland Bay Bridge, weight reduction had produced considerable savings in the suspension cables and structural steel of the trusses. In the construction of AASHTO I-girders and other structural elements, the savings as the result of reduced weight appeared in the cost of pretensioning and posttensioning tendons and in transportation and handling costs, as well as in the size piers and the foundations of a bridge. In the Parrots Ferry Bridge, a long-span segmental cantilever bridge, considerable savings were achieved in the post-tensioning costs, a major cost item in this type of structure. In steel-girder bridges, lighter deck weight means not only less steel, but possibly shallower sections. This could have the far-reaching effect of reducing profile grades, pier heights, and other affected elements of the construction.

In bridge rehabilitation, the weight-reducing advantage of lightweight concrete permits some roadway widening and increased live loads. The case of the redecking of the Woodrow Wilson Bridge in Washington, D.C. is an excellent example of the use of lightweight concrete in permitting some deck widening without the strengthening of the steel supporting structure.

There is little indication that the lightweight concrete was used in bridges for other than economic reasons, for example, for superiority in performance. It could be inferred from statements of some State transportation officials that a lightweight aggregate would be preferred if the area does not produce satisfactory normal-weight aggregates.

## DISADVANTAGES OF LIGHTWEIGHT CONCRETE

Bridge engineers tend to be conservative in accepting new materials until the experience of others proves successful. The need for special quality control and training of inspection personnel are extra burdens for a small staff to handle, and the reason for change cannot be too compelling if existing methods and local materials are producing good results. The scarcity of lightweight-aggregate plants in some parts of the country and the attendant cost of transportation of the material to a project are deterrents against its use.

## ADEQUACY OF SPECIFICATIONS

Specifications for lightweight concrete, which are available from AASHTO, ASTM, and ACI, must be considered minimum requirements, and additional information often needed by a designer must be obtained from publications and other sources.

Several States, including New York, Missouri, and Maryland, have prepared specifications and special provisions on lightweight concrete for their own use. There is a need for specification guidelines for the use of the nation as a whole. Such guidelines should cover every facet of lightweight concrete, such as materials, quality and construction control, and construction procedures.

Much of the difficulty experienced with lightweight concrete appears to be caused by the failure to recognize the differences between this material and normal-weight concrete. Water content of the mix and the porous nature of the aggregate are among the factors that are not sufficiently recognized or understood. Specifications emphasizing such differences could be very helpful to both designer and quality control engineers.

The successful experiences with the lightweight-concrete roadway decks for the bridges described in this report were due to good project specifications, attention to quality control, trained personnel, and an effective maintenance program.

The guide specifications, included as appendix 2, are a compilation of materials by ACI and the bridge departments of various States and are believed to contain elements essential to the preparation of a set of state-of-the-art specifications for the use of lightweight concrete in bridges.

## MATERIAL AND STRUCTURAL PROPERTIES OF LIGHTWEIGHT AGGREGATE

The properties of lightweight aggregate have been discussed in an earlier section of this report. None of these properties, if properly specified and tested, prevent this material from being used in making acceptable structural concrete for bridges.

Adequate compressive strengths can be achieved with proper mix design. Other design information derived from tests by a certified laboratory, such as creep, shrinkage and modulus of elasticity, is usually available from the aggregate or concrete suppliers.

Some have questioned the durability, wear resistance and long-term freeze-thaw qualities of lightweight concrete. No evidence was found that these properties differ from those of normal-weight concrete. In fact, there is evidence that these properties could be better for lightweight concrete, especially if the normal-weight concrete is of poor quality. This leads to the suggestion that the designer might consider specifying lightweight concrete if natural aggregates are not of high quality. Although lightweight aggregates vary depending on the raw material source, they are usually of a more consistent quality than some natural aggregates. Specified material tests will provide the necessary quality characteristics.

In making this study, it has been brought to our attention that lightweight concrete exhibits a brittle characteristic under impact, and may not be suitable for use as traffic barriers. Since information is lacking, this appears to be a good topic for further research.

PRESTRESSING OF LIGHTWEIGHT CONCRETE

After World War II, the then young prestressed concrete industry, in seeking a competitive edge for their product, recognized that the use of lightweight concrete would significantly reduce the high cost of prestressing steel and dead weight. Lightweight concrete was incorporated in prestressed concrete design, particularly in slabs and beams for buildings. Some T-beams and girders were also produced for bridges.

When the prestressed AASHTO I-girder was developed in the 1950's, several States built these precast girders with lightweight concrete, primarily to reduce weight for transporting over highways. Currently these lightweight girders have not been built in large numbers, possibly because normal-weight concrete is more economical and causes less operational problems at precasting plants. Recently, however, the success of the lightweight, prestressed deck slabs used in redecking the Woodrow Wilson Bridge has secured for this material a place in the vast bridge rehabilitation program.

The lightweight prestressed superstructures in the Napa and Parrotts Ferry Bridges have shown no unusual problems not found in normal-weight concrete bridges of similar design. Lightweight superstructures have an advantage in earthquake regions because of the reduced dead load of the superstructure.

The requirements of lightweight concrete with respect to prestressing are not particularly stringent. Primarily, recognition must be given to its lower modulus of elasticity and its shrinkage and creep values since these are the factors that determine prestress loss and the overall behavior of the structure. The use of these factors in analysis and related computations is routine and similar to those for normal-weight concrete.

The tendon-anchoring region in posttensioned lightweight-concrete beams and slabs deserves special attention. The anchors exert considerable tensile stresses in the concrete, and lightweight concrete, being weaker than normal-weight concrete, will have a greater tendency to crack in the region of anchors. This region will require special attention in design and construction.

## COST ANALYSIS

It is generally agreed that for the same volume lightweight aggregate and lightweight concrete costs more than normal-weight aggregate or concrete. Before comparing costs of various alternate materials, the acceptability of lightweight concrete for the purpose intended must first be established. With this decision made, the unit cost information of the acceptable materials can be obtained from suppliers, or from past experience with the product. Because of the limited experience with lightweight concrete in some areas, a wide range of unit cost information can be expected, making it difficult to arrive at reasonable values. Unit costs, however, are only part of a cost analysis. Estimating the total cost of the bridge is the objective.

Comparing costs of completed new or rehabilitated structures can be a complex process. The analysis must also take into consideration the types of structures, the transportation of material, and the equipment required. The amount of competition in furnishing material, and contractor interest and experience can be crucial elements affecting cost. If the project is a bridge replacement, the use of lightweight concrete might meet upgrading requirements of an old bridge, thus avoiding the cost of a new structure and traffic delays.

Sometimes the alternate design approach produces better results. One example which occurred a few years ago was the rehabilitation of the Newburgh-Beacon Bridge across the Hudson River in New York State. Proposals called for the widening of the roadway deck on an existing steel bridge with minimum revision to the steel superstructure. Contract documents were prepared for filled-steel grid or lightweight-concrete deck solutions, both considered equal alternates. The estimate for both alternates was $45 million. The low bid received was $43 million with a second bid for about the same price. Both were for lightweight concrete. The lowest bid for the filled-steel grid was $57 million.

This experience indicates that if equally acceptable materials are available, then the additional cost in preparing alternate designs could be offset many times by the savings from the keener competition they generate. Arbitrary selection of material based on meager cost information to save design cost can be counter-productive and lead to the construction of an uneconomical structure.

# FINDINGS AND RECOMMENDATIONS

## FINDINGS

- Lightweight concrete is being used to provide an economical solution in rehabilitating and upgrading existing bridges, especially where they involve an increase in the load rating or a widening of the roadway.

- Experienced quality control and technical personnel are essential to produce structural lightweight aggregates and concrete.

- The rotary-kiln is the preferred method of producing structural lightweight aggregate.

- The raw materials used to produce structural lightweight aggregate are currently limited to shale, clay, and slate.

- The compressive strength of structural lightweight concrete is commonly specified at 4,000 psi (28 MPa) for nonprestressed and 5,000 psi (35 MPa) for prestressed, but 7,000 psi (48 MPa) or more has been obtained in recent bridge projects.

- Lightweight aggregate usually costs more per unit volume than normal-weight aggregate because of energy and other production costs; however, comparisons should be based on the overall construction costs of a bridge, which take into account the cost-saving effects of lightweight concrete on other parts of the bridge.

- Water contained in the pores of lightweight aggregate improves internal curing of the concete by making this water available for cement hydration.

- Lightweight aggregate, made under controlled conditions, is a uniform quality product, free from many impurities found in natural aggregate.

- Natural sand is preferred in structural lightweight concrete despite its increased weight because of the advantages of higher strength and lower cost.

- There is evidence that lightweight concrete is more tolerant of deicing salts, but no explanation of the phenomenon is available.

- Review of the bridges visited, and contacts with State and industry representatives, have produced evidence that good lightweight concrete has better durability than some normal-weight concrete; but the evidence is inconclusive.

- Analytical studies show cost savings are achieved by the use of lightweight-concrete elements in the superstructure of long-span bridges.

- Analysis shows construction time savings by the use of lightweight concrete for segmental construction, because lighter weight permits unit segment lengths to be increased.

- Empirical formulas presently used for design should be extended to include lightweight-concrete strengths beyond 5000 psi.

- At least one State has discontinued the use of structural lightweight concrete because of its poor performance; another has limited its use to special projects.

RECOMMENDATIONS

- Training courses or seminars for design, construction, and maintenance personnel are needed to increase the knowledge, understanding, and acceptability of the use of lightweight concrete in bridge construction.

- AASHTO and the individual States should institute an effort toward the preparation of a lightweight-concrete design guide, specifications, and a field-control manual to facilitate the use of this material.

- In the rehabilitation of bridges originally built with normal-weight-concrete decks, consideration should be given to replacement with lightweight-concrete decks to upgrade load capacity and increase roadway width.

- Shale, clay, and slate should be exclusively used as the raw material to produce structural lightweight aggregate, and should be processed only by the rotary-kiln method.

- Future research should be conducted in areas mentioned in the findings as having inconclusive information, namely: durability, tolerance to deicing salts, impact characteristics, skid resistance, and adherence to overlay systems.

## APPENDIX 1

## ROTARY-KILN LIGHTWEIGHT AGGREGATE PLANTS

| Address | Plant Locations |
|---|---|
| Amlite Corporation*<br>P.O. Box 128<br>Glasgow, Virginia 24555 | Snowden, Virginia |
| Arkansas Lightweight Aggregate Corp.<br>P.O. Box 1567<br>West Memphis, Arkansas 72301 | West Memphis, Arkansas |
| Barrett Industries*<br>Route 3, Box 211B1<br>San Antonio, Texas 78218 | San Antonio, Texas |
| Big Rivers Industries, Inc.<br>P.O. Box 66377<br>Baton Rouge, Louisiana 70806 | Erwinville, Louisiana |
| Buildex, Inc.<br>P.O. Box 15<br>Ottawa, Kansas 66067 | Ottawa, Kansas<br>Morguette, Kansas |
| Carolina Stalite Company<br>P.O. Box 1037<br>Salisbury, North Carolina 28144 | Gold Hill, North Carolina |
| The Carter-Waters Corporation<br>P.O. Box 19676<br>Kansas City, Missouri 64141 | Centerville, Iowa<br>Dearborn, Missouri |
| Chandler Materials Company<br>5805 East 15th Street<br>Tulsa, Oklahoma 74112 | Tulsa, Oklahoma<br>Choctaw, Oklahoma |
| Dakota Block Company*<br>P.O. Box 2920<br>Rapid City, South Dakota 57709 | Rapid City, South Dakota |
| Delta Industries, Inc.<br>Jackson Ready-Mix Concrete<br>P.O. Drawer 1291<br>Jackson, Mississippi 39205 | Jackson, Mississippi |

| | |
|---|---|
| The Featherlite Corporation<br>P.O. Box 1029<br>Austin, Texas 78767 | Austin, Texas |
| Galite Corporation<br>(Subsidiary of Big Rivers Industries)<br>O.O. Box 468<br>Rockmart, Georgia 30153 | Rockmart, Georgia |
| Hydraulic Press Brick Company<br>P.O. Box 7<br>Brooklyn, Indiana 46111 | Brooklyn, Indiana<br>Cleveland, Ohio |
| Kanta Products, Inc.*<br>P.O. Box 96<br>Three Forks, Montana 59752 | Three Forks, Montana |
| Lehigh Portland Cement<br>Lehigh Lightweight Aggregates<br>7617 Little River Turnpike<br>Annandale, Virginia 22003 | Woodsboro, Maryland |
| Lightweight Processing Company<br>715 North Central Avenue<br>Glendale, California 91203 | Ventura, California<br>Frazer Park, California |
| Norlite Corporation<br>P.J. Keating Company<br>P.O. Box 367<br>Fitchburg, Massachusetts 01420 | Cohoes, New York |
| Port Costa Materials Company<br>P.O. Box 5<br>Port Costa, California 94569 | Port Costa, California |
| Solite Corporation<br>P.O. Box 27211<br>Richmond, Virginia 23261 | Green Cove Springs, Florida; Albemarle, North Carolina; Cascade, Virginia; Mt. Marion, New York; Avonia, Virginia; Brooks, Kentucky |
| Texas Industries, Inc.<br>P.O. Box 400<br>Arlington, Texas 76010 | Streetman, Texas<br>Clodine, Texas |
| Tombigbee Lightweight Aggregate Corp.<br>Drawer V<br>Livingston, Alabama 35470 | Livingston, Alabama |

| | |
|---|---|
| Utelite Corporation<br>P.O. Box 387<br>Coalville, Utah 84017 | Coalville, Utah |
| Vulcan Materials Company<br>Southern Division<br>P.O. Box 7324-A<br>Birmingham, Alabama 35253 | Birmingham, Alabama |

Canada

| | |
|---|---|
| Cindercrete Products, Ltd.<br>Box 306<br>Victoria and Fleet Streets<br>Regina, Saskatchawan, Canada S4P 3A1 | Regina |
| Genstar Building Materials<br>Aggregate Divisions - Calgary<br>P.O. Box 5338 Station A<br>Calgary, Alberta, Canada T1H 2N8 | Calgary, Alberta<br>Edmonton, Alberta |
| Koldonan Concrete Products, Ltd.<br>221 Panet Road<br>Winnipeg, Manitoba, Canada R2J 0S4 | Winnipeg, Manitoba |

*Uses most aggregate for own products.

APPENDIX 2

# STRUCTURAL LIGHTWEIGHT-CONCRETE BRIDGE GUIDE SPECIFICATIONS*

## STRUCTURAL LIGHTWEIGHT AGGREGATE

Lightweight aggregate shall be an expanded shale, clay, or slate produced by the rotary-kiln process, and shall be ________ or approved substitute, and shall meet all the requirements of AASHTO M 195 and ASTM C330.[2, 3] In case of conflict, AASHTO M 195 shall govern.[2] Nonstructural lightweight aggregates such as pumice or scoria shall not be acceptable. ASTM-C330 certification shall have been verified by an independent testing laboratory within 2 years of the submission of data to the engineer.[3] The lightweight-aggregate producer shall furnish test reports from an independent testing laboratory certifying that concrete made from the aggregate and containing approximately 6 percent air content shall have a minimum durability factor of 85 percent when tested in accordance with ASTM C666.[24]

Coarse lightweight aggregate shall conform to the grading requirements of 3/4 in (19 mm) to No. 4 (or 1/2 in (13 mm) to No. 4, or 3/8 in (10 mm) to No. 8) of ASTM C330.[3] In addition, the resistance to degradation of the coarse aggregate, when tested by the Los Angeles abrasion method of ASTM C131, shall not exceed 50 percent.[25]

## STRUCTURAL LIGHTWEIGHT CONCRETE

Cement, aggregates, water, and admixtures shall be proportioned in accordance with ACI 211.2 "Recommended Practices for Selecting

*These guide specifications are compiled from standard specifications by ACI and various State bridge departments.

Proportions for Structural Lightweight Concrete."[4] Minimum cement content shall be 705 pcy (418 kg/$m^3$). The water added (net) to the mix using saturated aggregate shall not cause the w/c ratio to exceed 0.45. Water-cement ratios shall be established by trial mixes in accordance with ACI 211.2.[4]

Air entrainment shall be a minimum of 6 percent and a maximum of 9 percent (entrapped plus entrained). Air content shall be determined by the volumetric method described in ASTM C173.[23]

Slump shall be 3 1/2 $\pm$ 1 in (89 $\pm$ 25 mm). Maximum fresh unit weight (for control and acceptance) shall not exceed 120 pcf (1,922 kg/$m^3$). The air-dry in service unit weight shall average less than 115 pcf (1,842 kg/$m^3$). Equilibrium unit weight shall be measured in accordance with ASTM C567 with the exception that the air-dry density shall be determined at 60 days.[6]

Mix design data, creep, and shrinkage on lightweight concrete produced from the approved lightweight aggregate shall be made available to the engineer for prior approval. The manufacturer of the lightweight aggregate proposed for the project shall make available to the engineer results of tensile strength tests conducted in accordance with ASTM C496.[7] The tensile splitting strength obtained on concrete composed of coarse lightweight aggregate and natural sand should yield values in excess of 0.85 times those called for in ACI 318-83 for the compressive strength called for in the specification.[9] The tests should give values exceeding 0.75 times those called for in ACI 318-83 when the concrete is composed of fine and coarse lightweight aggregate (i.e., natural sand is not included).[9] A linear interpolation between 0.75 and 0.85 can be used when natural sand is included with fine, lightweight aggregate.

Concrete Test Cylinders

Concrete cylinders for determining compressive strength shall be fabricated and cured in accordance with the procedures outlined in ASTM C31.(27) Testing procedures for compressive strength determination shall be in accordance with ASTM C39.(28) The contractor shall provide molds approved by the engineer for casting test cylinders. Cardboard molds will not be acceptable. The contractor shall provide curing boxes that meet the requirements of ASTM C31.(27)

Test Cylinders for Quality Control

These will be cast by the engineer in sets, each set consisting of three individual cylinders. The casting frequency will be one set for each 50 $yd^3$ (38 $m^3$), or fraction thereof, actually placed. A minimum of one set will represent each day's concrete placement. Unless otherwise specified, test cylinders for quality control purposes will be tested by the engineer no sooner than the 29th curing day subsequent to placement.

If the average compressive strength of any 10 consecutive quality control cylinder set falls below _____ psi (____ $MN/m^2$), the contractor shall correct the concreting operations in a manner acceptable to the engineer to produce concrete conforming to these specification requirements. Any costs associated with the corrections shall be borne by the contractor.

Two companion cylinders for each 100 $yd^3$ (76 $m^3$) or fraction thereof, shall be tested in accordance with the requirements of ASTM C567 with the exception that the air-dry unit weight shall be determined at an age of 60 days.(6)

## PREQUALIFICATION OF STRUCTURAL LIGHTWEIGHT CONCRETE MIX PROPORTIONS

After the materials have been accepted for this work, the contractor will determine the proportions for concrete and equivalent batch weights to produce concrete with a compressive strength of ____ psi (____ $MN/m^2$) at 28 days.

### Trial Mixes

The contractor will determine the proportions on the basis of trial mixes conducted with the materials to be used in the work in accordance with ACI 211.2 "Recommended Practices for Selecting Proportions for Structural Lightweight Concrete."(4) The corresponding cement content for each trial batch shall be determined by means of a yield test in accordance with ASTM C138.(29)

### Proportions

The engineer shall be provided a copy of the trial mix design that includes the following:

- The weight in pounds (kg) of fine and coarse aggregate (saturated surface-dry condition), per cubic yard ($m^3$) of concrete.
- The cement content in pounds per cubic yard ($kg/m^3$).
- Amount of water in pounds per cubic yard ($kg/m^3$).

These values shall be used to manufacture all lightweight concrete for this project. The proportions shall not be changed unless the engineer is informed at least 3 working days prior to the change being made. Further, the contractor shall detail to the engineer his reasons for making the changes.

## Batch Weights

The engineer will approve the batch weights. Since the proportions are designated in terms of aggregates in saturated surface-dry conditon, the equivalent batch weights used by the contractor shall be corrected periodically to account for the moisture content of the aggregate at the time of use.

## Strength of Concrete Mixture

Where a concrete production facility has appropriate testing records on a concrete similar to that proposed for the project, the concrete proportions may be submitted for approval in accordance with the procedures of ACI 318-83 Article 4.3.(9) Where no prior data on similar concrete is available, the concrete shall be proportioned in accordance with the procedures and requirements of ACI 318-83 Article 4.4.(9) Evaluation and acceptance of concrete shall be in accordance with ACI 318-83 Article 4.7.(9)

## Workability

The concrete shall be of such consistency and composition that it can be worked readily without segregation of materials or the collection of free water on the surface. Subject to the limiting requirements above, the contractor shall, if the engineer requires, adjust the proportions of cement and aggregates so as to produce a mixture which will be easily placeable at all times, due consideration being given to the methods of placing and compacting used on the work.

## PLACING STRUCTURAL LIGHTWEIGHT CONCRETE

Stockpiles of lightweight aggregates shall be continuously and uniformly sprinkled with water for 8 hours by means of a sprinkler system approved by the engineer. The occurrence of a steady rain of comparable intensity will permit the turning off of the sprinkler system, at the direction of the engineer, until the rain ceases. At the end of the wetting period, or after the rain ceases, the stockpiles shall be allowed to drain for a period of 12 to 15 hours immediately prior to use, unless otherwise determined by the engineer.

Lightweight coarse aggregates, together with approximately 2/3 of the total mixing water, shall be introduced into the mixer and mixed for a minimum of _____ minutes. The fine aggregate, cement, admixtures, and remaining mixing water shall then be added and mixed completely.

Structural lightweight concrete shall not be placed when the temperature of the concrete mixture is 90 °F (32 °C) or greater. No placement of structural lightweight concrete will be allowed if weather forecasts indicate that air temperatures of 100 °F (38 °C) or greater will occur within 4 hours of the proposed placement time.

The contractor may place concrete at night with the prior permission of the engineer. Night placement will be restricted to those times, in the engineer's opinion, during which daytime temperatures are too high to result in acceptable concrete placements during daylight hours. All extra costs attributable to nighttime placement operations will be borne by the contractor. Permission to perform nighttime placements may be rescinded by the engineer (Structures) at any time, with no advance notice.

Handling and Placing

Concrete shall be transported from the place of mixing to the point of deposition as rapidly as practicable. Methods which will prevent the separation or loss of ingredients shall be employed. Concrete shall not fall freely more than 4 ft (1.2 m). Depositing a large quantity at any point and working it into final position will not be permitted. Aluminum equipment will not be permitted to come in contact with concrete.

Chuting

If concrete is conveyed by chutes, the plant shall be of sufficient size and design to ensure a continuous flow. Chutes shall be metal (except aluminum will not be permitted) or metal lined. The angle of the chute with the horizontal as well as the shape of the chute will be such as to allow transportations of the concrete without separation of the ingredients. The delivery end of the chute shall be as close as possible to the point of the deposit. If the operation is intermittent, the chute shall discharge into a hopper. The chute shall be thoroughly flushed with water before and after each run. Water used for this purpose shall be discharged outside the deck placement area. Chutes shall be properly baffled, or hooded, at the discharging end to prevent aggregate separation.

Pumping

Pumping will be permitted provided the lightweight aggregate used in the concrete is vacuum or thermally saturated to minimize slump loss during pumping. The saturation and pumping systems must be approved by the engineer.

Compacting

Concrete shall be thoroughly compacted during and immediately after deposition by vibrating the concrete internally with mechanical vibrating equipment. The type of vibrator and the extent of operations shall be approved by the engineer. A sufficient number of vibrators shall be employed so that, at the required rate of placement, thorough consolidation is achieved throughout the entire volume of concrete. Extra vibrators shall be available for emergency use and for use when other vibrators are being serviced.

Continuous Placement

Concrete shall be deposited continuously and as rapidly as practicable until a given placement section is completed. Construction joints not indicated on the plans will not be permitted without the express written consent of the engineer, under such conditions as he may require.

Concrete shall be placed continuously between expansion joints and stringer relief joints. Other construction joints will not be permitted.

## Curing

Curing shall be done by the continuous saturation method. The use of impervious curing covers which do not require wetting will not be permitted. No waivers will be granted. In areas where there is no ready water supply the contractor will be required to transport sufficient water needed to keep the blankets saturated for the required curing period. Membrane curing compound will not be permitted. The completed bridge deck may be subjected to its full legal load upon attainment of ____ psi (____ $MN/m^2$) compressive strength, but under no circumstances sooner than after 7 curing days have passed.

## Field Tests

During the progress of construction, the engineer will make test cylinders to determine whether the concrete which is being produced compares to the quality specified by the plans of specifications. The contractor shall cooperate in the making of such tests, allowing free access to the work for the selection of samples and storage of specimens and in affording protection to the specimens against injury or loss through his operations.

Samples of concrete for test specimens shall be taken at the mixer or, in the case of ready-mixed concrete, from the transportation vehicle during discharge. Such specimens shall be molded immediately after the sample is taken, placed in a protected spot and kept under moist curing conditions at approximately 70 °F (21 °C) for a maximum of 72 hours, whereupon they shall be removed to the testing laboratory.

Should the strengths shown by the test specimens fall below the values specified by the plans or specifications, the engineer shall have the right to require changes in proportions to apply on the remainder of the work.

Manufacturer's Representative

The manufacturer of the lightweight aggregate shall have a service representative at the site for the initial placement of structural lightweight concrete and available for subsequent support. The manufacturer's representative shall be given the authority by the contractor to assist in all aspects of lightweight concrete mixing and placement operations and provide liaison with the concrete supplier as approved by the engineer. A technical report shall be submitted to the engineer by the lightweight-aggregate supplier regarding any observations or test results relative to the concreting practices at the work site.

APPENDIX 3

# SUGGESTED
# STRUCTURAL LIGHTWEIGHT-CONCRETE BRIDGE
# FIELD CONTROL PROCEDURES

## GENERAL

Field control of structural lightweight concrete follows all the rules and principles of normal-weight concrete with the following major exception: the internal pores of a particle of structural lightweight aggregate may have a variable degree of saturation that must be compensated for in batch weights to produce a concrete of uniform fresh density containing a consistent absolute volume of lightweight aggregate. The following recommendations for field control of structural lightweight concrete include some of the recommendations of:

- ACI 304.5R-82 "Batching, Mixing, and Job Control of Lightweight Concrete."[30]
- ACI 211.2-81 "Standard Practice For Selecting Proportions for Structural Lightweight Concrete."[4]
- ACI 213R-79 "Guide for Structural Lightweight-Aggregate Concrete."[1]
- Field service recommendations of lightweight-aggregate manufacturers who provide field control personnel.

## PRINCIPLES OF PROPORTIONING AND ADJUSTING STRUCTURE LIGHTWEIGHT CONCRETE

Proportions for exposed bridge deck concrete should be selected to make the most durable concrete with the required engineering properties. Prior experience that has provided durable bridge decks will provide guidance in approaching optimum combinations of materials, but final proportions should be established by laboratory trial mixes which are then adjusted to provide practical field batches. The principles and procedures for proportioning normal-weight concrete, such as the absolute volume method, should be applied. The local aggregate manufacturer should be consulted for the special proportioning considerations appropriate to lightweight-concrete bridge decks.

In utilizing the absolute-volume method, the volume of fresh concrete produced by any combination of materials is considered equal to the sum of the absolute volumes of cement, aggregate, net water, and entrained air. Proportioning by this method requires the determination of the as-batched moisture content and bulk, moist, specific gravity of the separate sizes of aggregates in a saturated surface-dry condition. The principle involved is that the "mortar" volume consists of the total of the volumes of cement, fine aggregate, net water, and entrained and entrapped air. This mortar volume must be sufficient to fill the voids in a volume of rodded coarse aggregate, plus sufficient additional volume to provide satisfactory workability.

Workability

Workability is an important factor in achieving a durable bridge deck surface with lightweight concrete, and slumps should generally be limited to a maximum of 4 1/2 in (114 mm). A lower slump of about 3 1/2 in (94 mm) imparts sufficient workability and also maintains cohesiveness and "body," thereby preventing the lighter coarse particles from working up through the mortar to the surface. (This is the reverse of normal-weight concretes where heavy, natural aggregate segregation results in an excess of mortar at the surface.) In addition to increasing the possibility of segregation, a slump in excess of 4 1/2 in (114 mm) will cause unnecessary finishing delays.

## Mixing Water

As with normal-weight concrete, the amount of water added to a lightweight concrete mix should be the minimum amount which will permit the concrete to be properly placed, consolidated, and finished. Excess water increases the possibility of segregation, lowers strength, reduces durability, increases shrinkage, and hampers finishing. In most conditions, slumps of 3 1/2 ± 1 in (94 ± 25 mm) will be satisfactory.

## Air Entrainment

As with normal-weight concrete, air entrainment is essential in a lightweight-aggregate bridge deck. Air entrainment enhances workability, improves resistance to freezing and thawing cycles and to deicer chemicals, decreases bleeding, and tends to obscure minor grading deficiencies.

The strength of lightweight-concrete mixes may be reduced by high air contents. However, at usual air contents (6 to 8 percent) the reduction is small if slumps are less than 5 in (127 mm) and cement contents used are as recommended.

It is recommended that lightweight-aggregate concretes which may be subjected to freezing and thawing, or to deicer salts, should contain 6- to 8-percent air when maximum aggregate size is 3/4 in (19 mm), 7 to 9 percent when maximum size is 3/8 in (10 mm). The volumetric method, as described in ASTM C173, is the only recommended method of measuring air in lightweight concrete.[26]

## CONCRETING OPERATIONS WITH STRUCTURAL LIGHTWEIGHT CONCRETE

### Mixing and Delivery of Ready-mixed Concrete

The fundamental principles of mixing and delivery of ready-mixed concrete as required by ASTM C94 apply to structural lightweight concrete as they do to normal-weight concrete.[31] It is also recommended that immediately prior to discharge, the mixer should be rotated approximately 10 revolutions at mixing speed to minimize segregation. Structural lightweight aggregates should be handled according to standard procedures that have been established in the ready-mixed concrete industry for normal-weight concrete.

### Placing

There is little or no difference in the techniques required for placing lightweight concrete from those utilized in properly placing normal-weight concrete. If placed by pumping, the aggregate must be vacuum or thermally saturated to minimize slump loss during pumping. ACI 304 discusses in detail proper and improper methods of placing concrete.[32] The most important consideration in handling and placing concrete is to avoid separation of the coarse aggregate from the mortar portion of the mixture. The basic principles required to secure a good lightweight-concrete job are:

- A workable mix utilizing a minimum water content.
- Equipment capable of expeditiously handling and placing this concrete.
- Proper consolidation.
- Good quality workmanship.

A well-proportioned lightweight-concrete mix can generally be placed, screeded, and floated with substantially less effort than that required for normal-weight concrete. Over-vibration or over-working is often a principle cause of finishing problems in lightweight concrete. Such abnormal practice only serves to drive the heavier mortar away from the surface where it is required for finishing, and to bring an excess of the lighter coarse aggregate to the surface. "Floating" of coarse lightweight aggregate can also occur in mixes of high slump.

## Finishing

Good bridge-deck surfaces are achieved with properly proportioned quality materials, skilled supervision, and good workmanship. The quality of the job will be in direct proportion to the efforts expended to assure that all of the above essentials are maintained throughout the construction. Proper finishing of lightweight-concrete slabs is described by ACI Committee 302.(33)

A good finish on lightweight-concrete bridge decks can be obtained as follows:

- Prevent segregation by: providing a well-proportioned and cohesive mix, keeping the slump as low as possible, and avoiding over-vibration.
- Time the finishing operations properly.
- Use magnesium, aluminum, or other satisfactory finishing tools.
- Perform all finishing operations after free-surface bleeding water has disappeared.
- Cure the concrete properly.

## Curing

On completion of the final finishing operation, moist curing of the concrete should begin as soon as possible. Durability and permeability characteristics of the concrete are decisively influenced by the extent of curing provided. In bridge construction practice, 7 days of moist, burlap-covered curing is generally considered adequate with a temperature in excess of 50 °F (10 °C). Structural lightweight concrete benefits significantly from the process of "internal curing" due to the availability and exchange of water between the moistened lightweight aggregate and the hydrating cement paste. To achieve the additional protection offered by "internal curing," the lightweight aggregate must have a moisture content in the vicinity of the 24-hour absorption.

## PRINCIPLES OF FIELD CONTROL OF STRUCTURAL LIGHTWEIGHT CONCRETE

Proportions which have been established for given conditions may require adjustment from time to time to maintain the specified proportions in the field. Knowledge that proportions are remaining essentially constant, or that they may be varying beyond acceptable limits, should be obtained by conducting tests for fresh unit weight of concrete (ASTM C138), air content (ASTM C173), and slump (ASTM C143).[29, 26, 34] These tests should be made at such uniform frequency as may be specified (a given number of tests per stated quantity of concrete, per stated time period, or per stated section of structure, etc.), but also should be made, for example, when moisture content of the aggregates may have changed appreciably, when the concrete shows change in slump air content or workability characteristics, or when there is an appreciable change in added water requirements.

A change in fresh unit weight of concrete, with batch weights and air content remaining constant, shows that the batch is over yielding (with lower unit weight) or under yielding (with higher unit weight). The over-yielding batch will have lower-than-planned cement content and the under-yielding batch will have higher-than-planned cement content.

At the job start, or preferably prior to the start of the project, the fresh properties of a representative sample of job mixed concrete: unit weight, air content, and slump, of a full-sized batch should be determined to verify that the concrete conforms to the laboratory mix. Adjustments, if necessary, may then be made immediately. In general, when variations in fresh unit weight exceed ±2 percent, an adjustment in batch weights may be required to restore the concrete properties specified. The air content of lightweight concrete should not vary more than ±1.5 percent from the specified value to avoid adverse effects on strength, workability, or freeze-thaw durability.

Correcting for Moisture Content

The principal factors necessitating modification of proportioning and control procedures for lightweight aggregate concrete, compared to normal weight concrete, are the greater absorptions and the higher rates of absorptions of most lightweight aggregates. The greater absorption is due to the cellular nature of lightweight aggregates.

Based on a 24-hour absorption test, lightweight aggregates generally absorb from 5 to more than 25 percent by weight of dry aggregate, depending on the size and pore structure of the aggregate. Normally, however, under conditions of extended dry outdoor storage in stockpiles, moisture content may be less than the moisture content determined by 24-hour immersion.

By contrast, normal-weight aggregates usually will absorb less than 3 percent of moisture. However, the moisture content in a normal-weight aggregate stockpile may be as high as 5 to 10 percent or more. The important difference is that the moisture content in lightweight aggregates is largely absorbed into the interior of the particles, whereas in moist normal-weight aggregates it is largely surface moisture.

Rate of absorption in lightweight aggregates is a factor which also has a bearing on mix proportioning, handling, and control of concrete, and depends on the volume, size and distribution of pores in the aggregate. It should be noted that water which is internally absorbed in the aggregate is not available to the cement as mixing water. On the other hand moisture in a damp or wet natural sand is surface moisture which is available in the cement.

The moisture content of a lightweight aggregate at some time after it comes into contact with water depends on both the time of exposure to water and on the initial moisture content of the aggregate. Initially damp lightweight aggregates will contain more internally absorbed water after a period of water immersion than similar, initially dry aggregates immersed for the same period. Thus, concrete made with initially dry lightweight aggregates will contain less total water than concretes made with similar aggregates that were damp for some time before mixing.

Moisture content of the aggregates at time of mixing has little effect on compressive strength of the concrete, provided the mix is adjusted to maintain constant cement and air contents, similar consistency, and a constant volume of both coarse and fine aggregates.

It is desirable that the aggregates be damp at the time of mixing to reduce the amount of water absorbed from the mix and so reduce the rate of loss of slump. Damp materials also show less tendency to segregate during storage and transportation than dry materials. When the moisture content of the aggregate is less than the 24-hour absorption, it is desirable to mix the aggregate with about 2/3 of the required mixing water for a short period prior to introduction of cement, air-entraining admixture, and balance of the mixing water. This minimizes slump loss and provides consistent fresh unit weight. The supplier of the particular aggregate should be consulted regarding the necessity for such predampening and for the mixing procedure. When lightweight aggregates have a moisture content approaching that obtained by a 24-hour immersion, their behavior in the concrete will demonstrate a very low rate of further absorption. In this condition, little absorption occurs and the lightweight concrete behaves similar to ordinary concretes. Checks of moisture content, gradation, and unit weight of the aggregate can readily be made, and these may reveal the cause of changes in concrete properties. If the moisture content has changed, the aggregate weight is adjusted to keep the weight of dry aggregate constant. If the density of the aggregate has changed, the weight of dry aggregate is adjusted to keep the volume of dry aggregate constant.

Unless concrete is allowed to lose moisture for a suitable period after curing, prior to exposure, concrete made with highly saturated lightweight aggregates that have a higher degree of saturation developed by vacuum or thermal saturation techniques may be more vulnerable to early freezing and thawing than concrete made with lightweight aggregates that contain a lower moisture content. When concrete temperatures are expected to be below freezing, the use of aggregates containing moistures significantly higher than that of a 24-hour immersion should be discontinued at least 2 weeks in advance of such a condition.

## PRINCIPLES OF ADJUSTING THE PROPERTIES OF STRUCTURAL LIGHTWEIGHT CONCRETE IN THE FIELD

Proportioning and/or adjusting lightweight-concrete mixes follows the procedures of the method of absolute volumes. In this method the volume displaced by each ingredient of the mix (except entrained air) is calculated as the weight in lbs (kg) of that ingredient divided by the product of 62.4 pcf (1,000 kg/m$^3$) and the specific gravity of that ingredient. Total volume of the mix is the sum of the displaced or absolute volume of each ingredient thus calculated, plus the volume of entrained and entrapped air determined by direct test.

Calculation of the absolute volume of cement and calculation of air as the percentage air determined by test, multipled by total volume, are the same for both lightweight-concrete and normal-weight concrete mixes. The volume displaced by normal-weight aggregates is calculated on the basis of the saturated surface dry weights of aggregates and the bulk specific gravities (saturated surface dry basis) as determined by ASTM C127 and C128.[35, 36] Volume displaced by water in normal-weight concrete mixes is therefore on the basis of "net" mix water. Net mix water is the water added at the mixer plus any surface water on the aggregates, minus any water absorbed by aggregates which have moisture contents less than the 24-hour immersion moisture content.

Lightweight Aggregate Moisture Correction

It must be remembered that the principle of the water-cement ratio also applies to lightweight-aggregate concrete. When mixes are proportioned on a cement-content basis, the compressive strength associated with a certain cement content is obtained only at a given consistency. If it is found necessary to increase the slump, the increase in water content should be accompanied by a proportionate increase in cement content.

Total moisture in lightweight aggregate consists of internally absorbed moisture and, when the degree of saturation is very high, an additional amount of surface moisture. The ratio between the two is difficult to accurately determine under field conditions. Only the free surface moisture will affect the mixing water requirements. In field control, moisture corrections of the batch weights should be made on an oven-dry basis. The total moisture percentage as determined by drying a 500-g sample on a hot plate is to be used for adjustments of the batch weight. It is recommended that a certain portion of the added water be withheld on the first batch. In transit mix plants complete mixing of the first truck should be assured at the batch plant and final adjustments of the mixing water be made from the truck water system. Adjustments will serve as a guide for correcting the batch weights of subsequent batches.

ASTM C172 states that it is applicable to obtaining samples of fresh concrete from mixers, agitators, or dump trucks.[37] Samples from concrete that has been compacted or manipulated after its discharge from a mixer, agitator, or conveyance are not suitable for making acceptance tests for consistency, air content, or potential strength.

The method also requires that remixing of the sample shall be conducted at the place where tests are to be made or where specimens are to be molded. Testing should be done as close to the point of sampling as possible. The incorrect practice of sampling concrete at the discharge stream from a mixer or truck, or a pile, by means of a scoop or shovel, and then filling a test container (slump cone, air meter, bowl, cylinder or beam mold) with several such samples without the required remixing should not be condoned.

## Control of Fresh Field Density

A major objective of the control of lightweight concrete is the securing of a correct yield. By dividing the batch weight of materials per cubic yard ($m^3$), by the unit weight of the fresh concrete, the yield of the concrete can be computed on a cubic yard ($m^3$) basis. The control technician should, at all times, know the total weights of materials per cubic yard ($m^3$) including changes due to water added or withheld.

Data obtained in the determination of the weight per cubic foot of the fresh concrete by method ASTM C138 are used in calculating the yield of concrete.[29] Attention is invited to some precautions that should be observed in this test. When calibrating the measure with a glass plate it is necessary that the open upper end of the measure be in a plane. It is undesirable to heap the measure so much that coarse aggregate will be forced into the measure while mortar overflows down the outside of the measure. If it is necessary to add or remove concrete, the total concrete should be added or removed to maintain the same proportion of mortar and coarse aggregate. The optimum amount of concrete is such that, after the rodding and tapping operation, a very slight excess of less than 1/8 in (3 mm) will be removed by the glass plate.

A flat plate of glass, acrylic, or metal should be used for striking off the concrete. It has often been observed that, in practice, a rod, trowel, or straightedge is used instead of the specified plate to strike off the concrete, leaving the concrete high, resulting in a greater unit weight.

## PRACTICAL FIELD CONTROL PROCEDURES OF STRUCTURAL LIGHTWEIGHT CONCRETE

When it is desired to change the amount of cement, volume of air, or the percentage of fine aggregate in a mix, or when it is desired to change the slump of the concrete, it is necessary to offset such changes with adjustments in one or more other factors if yield and other characteristics of the concrete are to remain constant. The following paragraphs indicate some of the compensating adjustments, show the usual direction of adjustments necessary, and give a rough approximation of the amount of the adjustments per cubic yard of concrete. It should be noted, however, that the numerical values given are intended for guidance only; that they are approximations; and that more accurate values obtained by observation and experience with particular materials should be used wherever possible.

Before the start of placement of concrete, take the total batch weights of the material per cubic yard and divide by 27 in order to find the anticipated fresh density in pounds per cubic foot of the mix.

If the actual density obtained in the field differs from the anticipated by more than 2 pcf (32 kg/$m^3$) an adjustment should be made. As soon as the change becomes effective another density determination should be made to confirm the accuracy of the adjustment. Change in water requirement must be anticipated whenever these adjustments are made. Their magnitude can be estimated from experience with a given lightweight-concrete mix. In the event that air content is greater than 1 percent above or below that for which the mix was designed, corrections should be made in the amount of admixtures in order to obtain the desired air content.

Routine determinations of the unit weight are recommended for every 50 $yd^3$ (38 $m^3$). Additional determination should be made to control the results of eventual adjustments.

Accurate determination of the unit weight and air content is a most important tool in the control of lightweight concrete. Special attention should be given, therefore, to correct calibration of scales, unit-weight container, and air meter.

Proportion of fine aggregate, an increase in the percentage of fine to total aggregates, generally requires an increase in water content. For each percent increase in fine aggregate, increase water by approximately 3 pcy (48 kg/$m^3$). Increase in water content will require an increase in cement content to maintain strength. For each 3 pcy (48 kg/m$^3$) increase in water, increase cement by approximately 1 percent. Adjustment should be made in the coarse and fine aggregate weights as necessary to obtain desired proportions of each and to maintain required total effective displaced volume.

A change of 1 percent of air content accounts for an approximate change of 1 pcf (16 kg/m$^3$) in density of the mix. Therefore, high or low air contents will effect the density and the yield of the concrete. Proper correction of the air content will bring the density of the fresh concrete back to the desired level. If this does not happen corrections should be made as in paragraph above.

An increase in air content will be accompanied by an increase in slump unless water is reduced to compensate. For each percent increase in air content, water should be decreased by approximately 5 pcy (80 kg/m$^3$). A large increase in air content may cause a decrease in strength unless compensated for by additional cement. Adjustment should be made in fine-aggregate weight as necessary to maintain required total effective displaced volume.

An increase in slump is obtained by increasing water or air content. For each desired 1-in (25-mm) increase in slump, water should be increased approximately 10 pcy (160 kg/m$^3$) when initial slump is about 3 in (76 mm); somewhat more when initial slump is higher. Increase in water content will be accompanied by a decrease in strength unless compensated for by an increase in cement content. For each 10 pcy (160 kg/m$^3$) increase in nonabsorbed water, increase cement content approximately 3 percent. Adjustment should be made in fine-aggregate weight as necessary to maintain required total effective displaced volume.

Control of any type of concrete mix in the field requires recognition of changes due to variation in ambient temperature, temperature of ingredients, length of mixing and agitating time, and other causes. Discussion of such factors is beyond the scope of this report.

Minor variations in properties of the lightweight aggregate usually occur from shipment to shipment. For greater uniformity, it is therefore recommended that individual shipments from the lightweight-aggregate source be as large as is compatible with stockpile capacities. The loose unit weight of aggregate should be determined in accordance with ASTM C330, paragraph 7.[3]

Materials in the stockpiles should be kept moistened to not less than 70 percent of their 24-hour absorption. This may be done by several methods, such as running a sprinkler on the pile, but is best accomplished by spraying the material on the conveyor belt. The important point is having the moisture content uniform throughout the pile so that slump variations will not be encountered when batching and supplying concrete on the job. In order to obtain a uniform moisture content it is best to discontinue any wetting of the pile prior to batching the concrete, provided the material has sufficient moisture.

Avoid excessive handling of aggregate as this will tend to break down the aggregate, causing a finer gradation and resulting in a heavier material. Excessive handling and improper stockpiling may cause undue material segregation which creates weight and yield variations in concrete.

Stockpiling

To avoid segregation no aggregate should be handled or shipped in the dry condition. Stockpiled material will usually have sufficient moisture at a reasonably uniform moisture content. If the stockpiles are tunnelled by conveyors to bins, little trouble should be encountered. If clam shells are used to charge the bins use reasonable control procedures. If the weather has been very wet or very dry move back the outer layers of material and use the inside of the pile which is usually more uniform in moisture content. When long, dry spells are encountered stockpiles may need additional water. Stockpiles should be watered with a sprinkler days ahead of use so that moisture may equalize in the pile.

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# FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH, DEVELOPMENT, AND TECHNOLOGY

The Offices of Research, Development, and Technology (RD&T) of the Federal Highway Administration (FHWA) are responsible for a broad research, development, and technology transfer program. This program is accomplished using numerous methods of funding and management. The efforts include work done in-house by RD&T staff, contracts using administrative funds, and a Federal-aid program conducted by or through State highway or transportation agencies, which include the Highway Planning and Research (HP&R) program, the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board, and the one-half of one percent training program conducted by the National Highway Institute.

The FCP is a carefully selected group of projects, separated into broad categories, formulated to use research, development, and technology transfer resources to obtain solutions to urgent national highway problems.

The diagonal double stripe on the cover of this report represents a highway. It is color-coded to identify the FCP category to which the report's subject pertains. A red stripe indicates category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, and green for category 9.

*FCP Category Descriptions*

**1. Highway Design and Operation for Safety**

Safety RD&T addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act. It includes investigation of appropriate design standards, roadside hardware, traffic control devices, and collection or analysis of physical and scientific data for the formulation of improved safety regulations to better protect all motorists, bicycles, and pedestrians.

**2. Traffic Control and Management**

Traffic RD&T is concerned with increasing the operational efficiency of existing highways by advancing technology and balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, coordinated signal timing, motorist information, and rerouting of traffic.

**3. Highway Operations**

This category addresses preserving the Nation's highways, natural resources, and community attributes. It includes activities in physical maintenance, traffic services for maintenance zoning, management of human resources and equipment, and identification of highway elements that affect the quality of the human environment. The goals of projects within this category are to maximize operational efficiency and safety to the traveling public while conserving resources and reducing adverse highway and traffic impacts through protections and enhancement of environmental features.

**4. Pavement Design, Construction, and Management**

Pavement RD&T is concerned with pavement design and rehabilititation methods and procedures, construction technology, recycled highway materials, improved pavement binders, and improved pavement management. The goals will emphasize improvements to highway performance over the network's life cycle, thus extending maintenance-free operation and maximizing benefits. Specific areas of effort will include material characterizations, pavement damage predictions, methods to minimize local pavement defects, quality control specifications, long-term pavement monitoring, and life cycle cost analyses.

**5. Structural Design and Hydraulics**

Structural RD&T is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highway structures at reasonable costs. This category deals with bridge superstructures, earth structures, foundations, culverts, river mechanics, and hydraulics. In addition, it includes material aspects of structures (metal and concrete) along with their protection from corrosive or degrading environments.

**9. RD&T Management and Coordination**

Activities in this category include fundamental work for new concepts and system characterization before the investigation reaches a point where it is incorporated within other categories of the FCP. Concepts on the feasibility of new technology for highway safety are included in this category. RD&T reports not within other FCP projects will be published as Category 9 projects.