THE APPLICABILITY OF STRUCTURAL LIGHTWEIGHT CONCRETE FOR THE CONSTRUCTION OF HIGHWAY BRIDGES IN VIRGINIA

by

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Virginia Highway Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways and the University of Virginia)

Charlottesville, Virginia

June 1973
VHRC 72-R42

PREFACE

This report was prepared for two purposes: (1) To assess the technical and economical status of structural lightweight concrete in the construction industry, and (2) to provide information that would enable the Virginia Highway Research Council to decide whether or not to recommend that the Virginia Department of Highways consider the use of structural lightweight concrete in bridge structures.

The information presented herein was collected from a literature search and from telephone conversations with a number of persons experienced in the use of lightweight concrete. Parts of the information taken from the literature search were excerpted verbatim; other parts were modified and adapted to this report. Telephone interviews were with prestressers, designers, academicians, staff members of professional societies, and others.

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INTRODUCTION

In many areas of the country, the supply of conventional aggregates suitable for use in structural quality concrete is becoming or has already become depleted. The seriousness of this situation is compounded because many aggregate sources are now or will shortly become unavailable because of economic reasons, zoning restrictions, pollution control, or appreciating land values. Whether or not the foregoing statement applies in the state of Virginia, the fact remains that manufactured lightweight aggregate is being used in increasing amounts in structural quality concrete in the building industry, as opposed to practically no use in the Virginia highway industry. The Virginia Department of Highways has used very little lightweight concrete, with one notable exception — the deck on the experimental structure called the "Petersburg Bridge". *

With the increasing usage of precast and preassembled items, the reduction in shipping costs and handling difficulties provided by lightweight concrete becomes an increasingly important matter for consideration. The increased haul distances dictated by the decreased aggregate supply result in increased costs which would be reduced by the reduced weight of the concrete even on cast-in-place jobs.

The modern lightweight aggregate industry was started in 1917 after Stephen J. Hayde, a contractor and brick maker, faced the problem of abnormal bloating of some of his brick (Expanded Shale, Clay, and Slate Institute 1971). This bloating was found by Hayde to be caused by shale expanding when subjected to high temperatures during the burning process. It occurred to him that this bloated material, which was being discarded, had potential for use as a lightweight aggregate. In 1918, Hayde was granted a patent on a process for manufacturing lightweight aggregates.

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* The "Petersburg Bridge" is a 100-ft. aluminum triangular girder span on Rte. 36 over the Appomattox River at the north city limits of Petersburg. Project Number 0036-123-071, B601.

The early application of this lightweight aggregate was not in the building industry, but in the construction of a few concrete ships during World War I and in more than a hundred concrete ships and barges during World War II. The concrete ship building industry is of little importance now, other than to illustrate the fact that high quality structural concrete could be made with lightweight aggregate (Expanded Shale, Clay, and Slate Institute 1971).

Today, lightweight concrete has become an important material in the structural concrete industry. It is used on a wide scale in the USA, USSR, and many other countries. It has been successfully used for a wide range of applications paralleling those of normal structural concrete, but different in several significant aspects.

This report is restricted to information on the higher quality lightweight concretes suitable for structural applications, including prestressing; thus, it deals with concrete containing expanded aggregates having a unit weight of 85 to 120 pcf and capable of developing compressive strengths ranging from about 2,500 to 6,000 psi (see Figure 1). Emphasis is placed on concretes with a compressive strength range of 4,000 to 6,000 psi at 28 days.

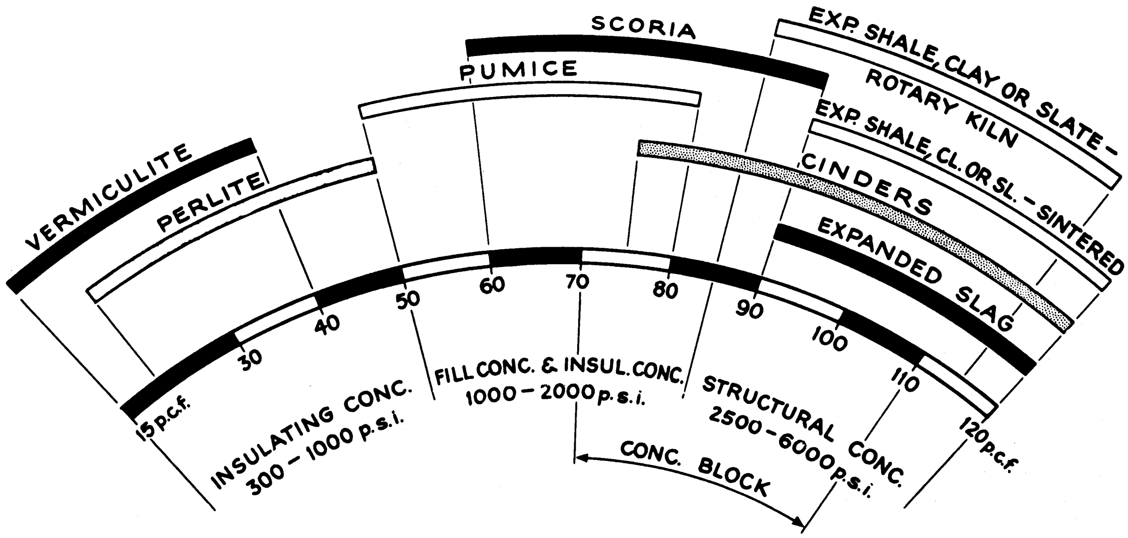

Figure 1. Weight spectrum of lightweight concretes.

The earlier part of this paper deals with processes for manufacturing lightweight aggregates and with the chemical and physical properties of lightweight aggregates and lightweight aggregate concrete. The later part discusses the utilization of structural lightweight concrete in the construction industry and the local economics and technology of the material as it applies to bridge decks and bridge girders.

Most of the large ready-mix concrete producers and all the prestressers in Virginia use or have used lightweight aggregates in their concrete. Thus, there appears to be no distribution problem throughout the state, however, the quantity available at any one time at any one location might present a problem at present. There are at present a number of lightweight aggregate producers in Virginia or ones that ship into the state, so no one producer appears to enjoy a dominant competitive position in the market.

PROCESSES FOR MANUFACTURING LIGHTWEIGHT AGGREGATES

Rotary Kiln

Shales and slates are crushed and screened before being fed into the upper end of an inclined rotary kiln, whereas clay is usually extruded or pelletized before burning. In either case, the material travels slowly to the hot zone, where it reaches a temperature of 1,800° to 2,200°F. At these temperatures the material is in a plastic state and internally released gases expand to form it into a lightweight cellular structure. Following expansion, the material is discharged and cooled at a controlled rate. In some operations the material then is crushed, screened, and stockpiled.

Sintering

In the sintering process, the raw material is crushed and screened. It then is mixed with a small amount of fuel, such as finely ground coal or coke, and spread evenly over a traveling grate. The grate passes under an ignition hood where the fuel is ignited, and the fuel continues to burn as the grate moves over blowers. As the heated material becomes plastic, gases forming within the mass are entrapped and create a cellular structure. The clinker formed is allowed to cool; it then is crushed and screened for use.

Water Treatment

In the water treatment process expanded slag is produced by applying controlled amounts of water to molten blast-furnace slag. This is done either by a machine method in which the molten slag is agitated in a machine with a controlled amount of water; or by the water jet process, in which jets of water under high pressure are forced into the molten mass. The expanded slag then is crushed and screened to the required aggregate sizes.

PROPERTIES OF LIGHTWEIGHT AGGREGATE AND STRUCTURAL LIGHTWEIGHT AGGREGATE CONCRETE

For lightweight aggregates more consideration is given to such factors as the bulk unit weight, absorption, particle shape, size, and surface texture than is generally necessary for normal weight aggregates. In general, those characteristics that influence the properties of normal weight concrete also influence the properties of structural lightweight concrete.

The requirements for lightweight aggregates for use in structural concrete are outlined in ASTM C330-69, "Standard Specification for Lightweight Aggregates for Structural Concrete". This specification covers both natural and manufactured lightweight aggregates, however the discussion (PCI 1967; Haddad and Freedman 1967; Lewis 1966) on properties to follow will include only those that are manufactured by the three processes previously discussed.

Lightweight Aggregate

1. Unit Weight — The unit weight of loosely packed lightweight aggregates ranges between 35 to 70 lb./cu. ft. depending on the type of aggregate, its specific gravity, gradation, and shape. The unit weight of normal weight aggregates varies between 90 and 110 lb./cu. ft.

ASTM C330 limits the dry, loose unit weight of lightweight aggregates for use in structural concrete to a maximum of 70 lb./cu. ft. for fine aggregate, 55 lb./cu. ft. for coarse aggregate, and 65 lb./cu. ft. for combined fine and coarse aggregates. The loose unit weight of a combination of lightweight coarse aggregate and natural fine aggregate suitable for structural concrete in Virginia is estimated to be around 75 to 80 lb./cu. ft.

2. Absorption — Lightweight aggregates can absorb 5% to 20% water by weight of dry material, depending on the pore structure of the aggregate, based on a 24-hour absorption test. Prewetted and saturated aggregates are generally used to help control the moisture uniformity of the mixes. Under outdoor storage in stockpiles, the moisture content will rarely exceed two-thirds of the 24-hour absorption value. Uniformity of absorption is more important than the amount of absorption in batching lightweight aggregate concrete.

Normal weight aggregates usually absorb 1% to 2% water. In Virginia, the absorption seldom exceeds 1%. Normal weight aggregates usually contain some interior moisture at the time of batching and absorb very little water during the mixing operation.

3. Shape, Size, and Surface Texture — The shape of most structural grade aggregates is either cubical or rounded. Some, however, are angular.

The maximum size of the coarse aggregates is seldom greater than 3/4". Aggregates of angular shape and rough-texture surfaces generally require a greater percentage of fines for workability than those with more cubical shapes and smoother textures.

Structural Lightweight Aggregate Concrete

Fresh Concrete

1. Unit Weight — The unit weight of fresh structural concrete may range from 85 to 120 lb./cu. ft., which is about 60% to 80% that of normal concrete of the same strength.

2. Workability and Finishability — Lightweight concrete mixtures can be proportioned to have the same workability, finishability and general appearance as a properly proportioned normal weight concrete mixture. Since air entrainment improves workability, it should be used in lightweight concrete mixes regardless of the anticipated exposure.

3. Slump — Due to the lighter weight of the aggregate, lightweight concrete does not slump as much as normal weight concrete with the same workability. Air entrained lightweight concrete with a slump of 2" to 3" can be placed under conditions that would require a slump of 3" to 5" for normal weight concrete. It is not usually necessary to exceed slumps of 4" in normal placements. With higher slumps, the large aggregate particles tend to float to the top, making finishing difficult.

4. Entrained Air — Air entrainment, besides helping to protect concrete against damage from freezing and thawing cycles, also improves workability. It reduces the amount of bleeding and segregation, and may compensate for minor grading deficiencies in the aggregates. Thus, entrained air is recommended in all lightweight concrete whether or not freeze-thaw resistance is a factor. Air contents are generally between 4 1/2% and 9%.

5. Vibration — Vibration is effective in consolidating both lightweight and normal concrete. About the same frequencies (70,000 or more VPM) are recommended for both. The length of time for proper consolidation varies, depending on the mix characteristics. Excessive vibration causes segregation by forcing large aggregate particles to the surface.

Hardened Concrete

1. Compressive Strength — With minor increases in cement content, the compressive strength is about the same for lightweight concrete as for normal concrete, up to a maximum of about 6,000 to 7,000 psi. The rate of strength development is approximately the same for both types.

Sometimes concretes made with certain types of lightweight aggregates show a "strength ceiling" beyond which an increase in cement content will produce no noticeable increase in strength. The strength ceiling is influenced mainly by the coarse aggregate, and it may be increased by reducing the maximum size of the aggregate.

2. Tensile Splitting Strength — Moist cured specimens of lightweight and normal weight concretes of equal compressive strength have approximately equal tensile strengths. The splitting tensile strength of air dried lightweight concrete generally is less than that of moist cured concrete and varies from about 70% to 100% that of normal weight concrete of equal compressive strength. The replacement of lightweight fines by natural sand usually increases the tensile strength.

3. Modulus of Elasticity — The modulus of elasticity of lightweight concrete is generally between 1.5 million and 2.5 million psi, depending on the compressive strength, type of lightweight aggregate, and sand content. Normal weight sand is often used with lightweight aggregate to increase the modulus of elasticity. Generally, the modulus of elasticity of lightweight concrete is 20% to 50% lower than that of normal weight concrete of equal strength. Although the modulus of elasticity is considerably less than that of normal concrete, the dead load deflection of a prestressed lightweight concrete beam will be only 15% to 25% greater than that of a normal prestressed concrete beam of the same dimensions.

4. Poisson's Ratio — The Poisson's ratios for lightweight and normal weight concretes are approximately equal. The value is generally between 0.15 and 0.25 depending upon the aggregate, moisture condition, and age of concrete.

5. Bond — For equal compressive strength, pull-out tests generally show the bond of strength of lightweight concrete to be similar to or up to 20% less than that for normal concrete at ultimate strength.

6. Drying Shrinkage — The drying shrinkage of lightweight concrete made and cured at normal temperature ranges from slightly less than to about 30% more than that of some normal weight concretes. Atmospheric steam cured lightweight concrete has a lower drying shrinkage than normally cured lightweight concrete. The drying shrinkage of concretes made with some lightweight aggregates may be reduced by partial or full replacement of lightweight fines by natural sand.

7. Creep — The creep of lightweight concrete ranges from about the same as to 50% more than that of some normal weight concretes. Creep of lightweight and normal concrete is dependent upon the magnitude of stress, strength of concrete, age at loading, time after loading, method of curing, and moisture condition of the concrete. Higher strength lightweight concretes show 20% to 40% less creep than lower strength lightweight concrete when loaded at the same age. Partial or full replacement of the lightweight fines with natural sand fines may effectively reduce creep. The creep of atmospheric steam cured lightweight concrete is about 25% to 40% less than that for moist cured similar concrete. It is recommended that when a precise knowledge of creep is needed, tests be performed.

8. Permeability — Structural lightweight concrete is impervious to water to the same degree as normal concrete because this property is dependent upon the quality of the cement paste and is not affected by the internal porosity of the aggregate particles. The material has been used successfully in shipbuilding in the USA, USSR, and other countries.

9. Freeze-thaw Resistance — The resistance of lightweight concrete to damage from freezing and thawing is dependent upon the same factors that affect the freeze-thaw resistance of normal weight concrete — entrained air, water-cement ratio, and moisture condition.

Use of intentionally entrained air increases the freeze-thaw resistance of the concrete, especially if the aggregates are in a saturated condition at the time of mixing. The resistance to freezing and thawing of many air entrained lightweight concretes is equal to or greater than that of many air entrained normal weight concretes. The amount of intentionally entrained air required for adequate durability of lightweight concrete is about the same as that required for normal weight concrete.

The effect of the water-cement ratio on the durability of lightweight concrete is approximately the same as for normal weight concrete — reducing the water-cement ratio improves durability.

Tests have indicated that the freeze-thaw resistance of structural lightweight concrete of compressive strengths less than 5,000 psi may be increased through the partial or full replacement of fine aggregates by normal weight sand.

The moisture condition of lightweight aggregates at the time of mixing has a significant effect on the freeze-thaw resistance of concrete.

10. Resistance to Deicer Scaling — Lightweight aggregate concrete can be made resistant to the effects of deicing chemicals by using entrained air, a low water-cement ratio, and adequate curing followed by several weeks of air drying prior to the application of the chemicals.

11. Thermal Expansion — The coefficient of thermal expansion for structural lightweight concrete varies from 3.6 to 6×10^{-6} in./in./F., depending upon the aggregate type and amount of natural sand. The range for normal weight concretes is 3.5 to 7×10^{-6} in./in./F., depending upon the mineralogy of the aggregate.

12. Abrasion Resistance — The compressive strength of concrete is the most important single factor related to abrasion resistance. However, because of the porous structure of lightweight aggregates, the resistance of each thin wall or shell to load and/or impact may be low compared to the point load and impact resistance offered by a solid particle of similar composition. Therefore, the abrasion resistance of all lightweight aggregate concretes may not be suitable for steel-wheeled or exceptionally heavy industrial traffic. The use of natural sand in lightweight concrete improves resistance to abrasion.

13. Fatigue — Such tests as have been performed to date show equal or better fatigue behavior by lightweight aggregate concrete as compared to normal weight concrete. In tests conducted by the American Association of Railroads on prestressed lightweight aggregate concrete box beams, repeated loadings to 2,000,000 cycles did not reduce the static capacity appreciably. Tests in the USSR have shown an endurance coefficient about the same as for normal concrete.

14. Use of Normal Weight Fine Aggregates — Normal weight fine aggregates are often used to replace, partially or completely, the lightweight fine aggregates in lightweight concrete mixtures, principally for economy. Partial or complete replacement of lightweight fines with a good normal weight sand generally improves properties such as strength, workability, finishability, durability, and modulus of elasticity and generally decreases the water required for a given slump. However, it also has a detrimental effect in that the unit weight increases from 10 to 18 pcf.

Prestressed Concrete

1. Transmission Length — The transmission length of lightweight concrete is about the same as for normal concrete, since it is the cement paste which affects the bond. There may be a slight increase in transmission length when using lightweight concrete because of the lower modulus of elasticity.

2. Total Loss of Prestress — The total loss of prestress of lightweight concrete is about 110% to 115% of the total loss for normal concrete when both are subjected to normal curing, and 125% of the total loss for normal concrete when both are subjected to steam curing. Steam curing of lightweight concrete reduces the total prestress loss by 30% to 40%, compared with normal curing.

3. Corrosion Resistance — The cover over the steel for structural lightweight concrete is generally specified to be the same as for normal concrete. There is no evidence of any significant difference in corrosion protection from that of normal concrete of the same strength, i.e., with approximately the same cement and water contents in the mix.

4. Pile Driving Stresses — The lower modulus of elasticity of lightweight concrete reduces the maximum compressive stress by 18% and the maximum tensile stress by 22%, as compared to normal weight concrete.

5. Subsidence of Foundations — Prestressed lightweight aggregate concrete is generally better able to adjust to subsidence, both sudden and that occurring over a period of time, than is normal weight concrete.

Summary of Important Disadvantages and Advantages

A summary of the important problems with the properties of lightweight aggregates would include (Marek et. al. 1972).

1. The lack of uniform aggregate properties from one raw material deposit to another.

2. The need for better control of unit weight.

3. The need for improved control of absorption to a lower and narrower band.

4. The need for greater uniformity in compressive and flexural strengths, resistance to shear, and elastic modulus.

Of course, the one great advantage of lightweight aggregate is its relatively low unit weight.

In comparison to normal weight structural concrete, adverse properties of lightweight structural concrete would include:

1. A reduction in shear strength (diagonal tension).

2. A greater propensity for spalling, abrading, and damage from impact.

3. In prestressed girders, a slight increase in camber and deflection.

The advantages of lightweight structural concrete over normal weight structural concrete would generally include:

1. A lower dead weight that reduces structural and foundation loads, allows for easier handling and erection, and provides lower transportation costs.

2. For segmental beams, the low modulus of elasticity permits better distribution of bearing pressures on adjoining faces when dry joints are used.

3. In piling, the reduced submerged weight means greater capacity for design loads. Better deflection and energy absorption allows lightweight concrete to better withstand deformation without cracking (Marek et. al. 1972) during driving when obstructions are met.

UTILIZATION OF STRUCTURAL LIGHTWEIGHT CONCRETE

The largest use to date of prestressed lightweight concrete is for the roofs, walls, and floors of buildings. The lower weight has also been the determing factor in the selection of lightweight concrete for prestressed bridge girders, bridge decks, and particularly the suspended span of cantilever-suspended span bridges. The reduced weight leads to a saving in the structural frame itself and particularly to a savings in foundations. The latter savings have been cited as a major economic advantage. The reduced weight also facilitates transportation of prefabricated elements. In a number of instances studied in California, the saving in transportation cost just about balanced out the increased cost of the lightweight aggregate when the transport distance was 100 miles; beyond that, the use of prestressed lightweight concrete offered a saving. Moreover, since the maximum hauling weight is often limited, use of lightweight concrete may make it possible to haul a larger unit. Similarly, in erection, where crane capacities are limited, use of lightweight concrete permits larger single elements to be erected.

Table 1 lists the highway oriented uses to which prestressed lightweight concrete has been put together with the type of member for each, a brief statement as to present (1966) volume of use, a list of those advantages or properties which led to its selection, and a list of any factors adverse to that particular use.

The extensive use of structural lightweight aggregate concrete is absolutely dependent upon the availability of high-quality lightweight aggregates. The demand is not necessarily dependent upon low cost, because the major demand for structural lightweight aggregates has resulted from the beneficial properties of the resultant lightweight concrete. Thus, it would appear that lightweight aggregate concrete, including prestressed applications, has an opportunity for substantial growth even in those localities where natural aggregates are available and cheap.

The cost differential between normal and lightweight aggregate varies considerably from place to place, but in general good lightweight aggregates cost around three times as much as normal aggregates. Following is a list of the direct and indirect economic advantages of using structural lightweight aggregate concrete.

Direct Advantages (PCI 1967)

(1) Reduced dead weight is of special advantage where the dead load is a high percentage of total load, as in roofs, foot bridges, etc.

(2) Reduced thickness of cover for same fire rating. Greater fire resistance.

(3) Lower modulus of elasticity for better absorption of dynamic shock and seismic loads — important in many applications.

(4) Reduced weight for transportation, which means lower transport cost, especially in long distance hauls. In some instances, the reduced weight permits units to be sent by truck where they would otherwise exceed the road limits. The reduced weight may permit the transport and thus the use of larger individual precast units, with a considerable benefit in overall economy.

(5) Lower weight for erection, which often permits the use of standard rather than special equipment and facilitates the handling and erection of units.

(6) Greatly reduced weight in submerged or floating installations.

Indirect Advantages

(1) The 30% reduction in dead weight can reduce the requirements for prestressing steel by 10% to 18%.

(2) The reduced dead weight means lower foundation loads, which permits the use of smaller footings, or a reduction in number of piles, as the case may be. For example, pile requirements may be reduced by 20% to 25%.

TABLE 1

Utilization of Prestressed Lightweight Concrete

Type of Application	Present Volume of Use	Form or Section Employed	Properties and Advantages Leading to Selection	Adverse Properties
Bridge Girders	Medium usage, including some large and important structures.	Suspended span. I-girders with composite cast-in-place deck. Tee-girders. Box beam girders. Hollow-core slabs. Segmental girder sections.	Reduced dead weight seismic structure, and foundation loads. Easier handling and erection. For segmental girders, low modulus of elasticity permits better distribution of bearing pressures on adjoining faces when using dry joints. Better fire resistance.	Low modulus of elasticity. Greater camber. Reduced shear and diagonal tension strength.
Bridge Decks	Medium use	Precast slabs. Cast-in-place composite deck slab on prestressed lightweight I-girders.	Lower dead weight. Better resistance to freeze-thaw and deicing salts.	Susceptibility to local "plucking".
Footbridges	Heavy usage	I-girders. Tee-girders. Box beams.	Low dead weight of particular importance where dead weight is a major portion of total design load and where design load is seldom realized in service. Easier erection.	
Piling	Medium usage	Bearing, fender dolphin, batter and sheet piles.	Reduced submerged weight means greater capacity for design loads; also less bending stress in batter piles. Reduced weight for transport and handling, especially important with very large piles. Better deflection and energy absorption. Better ability to deform without cracking during driving when obstructions are encountered.	More subject to spalling from abrasion and local impact than normal weight concrete.

(3) Saving in other elements of the structural frame accrue from the reduced dead weight of prestressed lightweight elements.

(4) A reduction in depth of beam for the same span may be possible in some cases. (However, where live load deflection controls design, a substantial saving in depth may not be possible.)

LIGHTWEIGHT CONCRETE AND THE BRIDGE INDUSTRY IN VIRGINIA

As an aid to achieving an assessment of the applicability of structural lightweight concrete to Department needs, telephone interviews were conducted with a number of Department personnel and other people familiar with the material. Some of the disciplines represented by those interviewed were: precaster-prestressers, structural designers, materials engineers, lightweight aggregate producers, and staff members of professional organizations dealing with structural concrete. The questioning was directed to the technological and economical aspects as presently related to the bridge industry in Virginia. Comments from the interviews will be divided under the general headings of Economics and Technology.

Economics

Lightweight aggregates delivered to the ready mix plants cost about $12 to $12.50/ton. This price is approximately four times that of normal weight aggregate. Lightweight concrete ranges from $5 to $7.50 more per cubic yard than normal weight concrete. For 5,000 psi quality concrete, the cost of lightweight concrete consisting of lightweight coarse aggregate and normal fine aggregate is approximately $25.50 per cubic yard.

Depending upon the cost of normal weight aggregate, the smaller the differential between that and lightweight, the more apt the consumer is to use lightweight aggregates, assuming all other factors are equal (which they apparently are not, as will be discussed subsequently).

In citing his experience with prestressed lightweight concrete, one prestresser remarked that the costs of lightweight and normal weight concretes were about the same. The reason cited was that the economy produced by the reduced amount of steel and the reduced shipping and erection costs of lightweight concrete is about offset by the higher cost of the material and the increased level of technology needed in properly handling lightweight concrete during the mixing and placing operations.

Technology

Nearly all persons interviewed commented upon the need for more and a higher level of technology when dealing with lightweight concrete than when dealing with normal weight concrete. In relation to this need, absorption and specific gravity are the two properties most often cited as troublesome. These two properties manifest themselves as problems in the development of a consistent yield of concrete. Because these properties can vary with the aggregate source, the aggregate size and surface textures, the moisture content of aggregate, and between shipments of aggregate from the same supplier, problems with yield are fairly common.

Air contents of 6% to 8% are used in order to facilitate dealing with the problem of harshness of lightweight mixes, and air contents in this range do not aid in attaining higher strength.

Prestressers questioned cited unit weights of lightweight concrete of 125 to 130 lb. per cubic yard. These mixes are with lightweight coarse aggregate and a natural fine aggregate. The combination of lightweight coarse and fine aggregate is seldom used by Virginia prestressers. Normal weight structural concretes run from about 150 to 160 lb. per cubic yard with 155 lb. per cubic yard being fairly common. It is generally assumed in the concrete industry that for equal volume lightweight concrete provides about a 17% to 20% reduction in weight.

Problems in achieving compressive strengths above 5,000 psi were reported by the prestressers. One, however, reported getting into the 6,000 psi range by using a cement factor of 9 sacks per cubic yard. One designer said that he considered the weight reduction of 5,000 psi lightweight concrete to be unable to offset the problems of handling the material and of the added cost; however, he said that in the 3,000 - 4,000 psi range the advantages of lightweight concrete were more favorable.

In regard to prestressed concrete members, differential camber was reportedly greater when lightweight concrete was used.

The lighter weight for hauling and erecting is highly desirable for those concerned in moving concrete, whether it be hardened or unhardened. The nailability and drill-ability of lightweight concrete are better than in normal weight concrete.

When considering bridges, and in particular the AASHO I-Beam sections of approximately 90 - 100 feet, the ratio of dead load to total load is about 75% up to 90% (the ratio increases with an increase in span length). In shorter spans (40 - 50 feet) the ratio is closer to 50%. Thus, it may be seen that the greater advantage lies with reducing the dead load of the longer members; for example:

(a) Assume a 90 - 100 foot I-beam:

Dead Load = 350 lb./ft.^{2}
Live Load = 100 lb./ft.^{2}
Total Load = 450 lb./ft.^{2}

Use Lightweight Concrete: Reduce Dead Load by 20%

Dead Load = 280 lb./ft.^{2}
Live Load = 100 lb./ft.^{2}
Total Load = 380 lb./ft.^{2}

$$\text{Reduction } \frac{450 - 380}{450} = 15.8\%$$

(b) Assume a 40 - 50 foot I-beam:

$$
\begin{array}{ll}
\text{Dead Load} & = 100 \text{ lb./ft.}^2 \\
\underline{\text{Live Load}} & \underline{= 100 \text{ lb./ft.}^2} \\
\text{Total Load} & = 200 \text{ lb./ft.}^2
\end{array}
$$

Use Lightweight Concrete: Reduce Dead Load by 20%

$$
\begin{array}{ll}
\text{Dead Load} & = \ 80 \text{ lb./ft.}^2 \\
\underline{\text{Live Load}} & \underline{= 100 \text{ lb./ft.}^2} \\
\text{Total Load} & = 180 \text{ lb./ft.}^2
\end{array}
$$

$$\text{Reduction } \frac{200 - 180}{200} = \frac{20}{200} = 10\%$$

In this very general example, there is approximately a 50% greater reduction in the weight of the longer members when lightweight concrete is used. The length and weight restrictions applied to hauling precast members (and any other material) over Virginia highways play an important role in any decision between lightweight and normal concrete. Table 2 compares the lengths and weights of several normal and lightweight prestressed concrete members in relation to the length and weight restrictions imposed by the Code of Virginia. While the data in the table cannot be precise due to the assumption of the particular unit weights and the net length of members to be 100 feet, the table indicates that in the shorter spans, where design span lengths govern, a weight advantage of nearly 20% is gained by using lightweight concrete. In the larger spans, where hauling weights are the governing factor, an increase in length of up to 18 feet is gained by using lightweight concrete.

The New York State Thruway Authority has been using lightweight aggregate concrete in the bridge decks of its heavily traveled structures for about 12 years — not for the weight reduction offered, but for a satisfactory coarse aggregate substitute in regions where troublesome limestones and dolomites are found.* With a C. F. of 6 2/3 to 7 and air contents of 8% to 10%, the Authority achieves compressive strengths of approximately 4,500 psi. Skid resistance is good, and abrasion resistance is as good as that obtained with the limestones and dolomites. Overall, the Authority is very happy with the performance of lightweight aggregate concrete in bridge decks. Its experience, however, has indicated the need for lightweight aggregate specifications somewhat more stringent than that of ASTM C-330 in order to prohibit the inclusion of lightweight aggregates of insufficient durability.

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* Telephone conversation with Mr. William Clark, Materials Engineer, New York State Thruway Authority.

TABLE 2

Maximum Beam Lengths and Weights for Design and Hauling

Beam Type	Span Range, Ft.	Permissible by Code or Design: Max. Length, Ft.	Permissible by Code or Design: Max. Weight, Lb.	Governing Factor	Comments
I-II	40-60	60 (60)	23,870 (19,250)	Design Length (Design Length)	(19% less Weight)
III	55-80	80 (80)	48,200 (38,870)	Design Length (Design Length)	(19% less Weight)
IV	70-100	82 (100)	70,000 (68,500)	Haul Weight (Haul Length)	(18' additional Length)
V	90-120	64 (80)	70,000 (70,000)	Haul Weight (Haul Weight)	(16' additional Length)
VI	110-140	60 (74)	70,000 (70,000)	Haul Weight (Haul Weight)	(14' additional Length)
B-I	up to 74	74 (74)	44,640 (36,000)	Design Length (Design Length)	(19% less Weight)
II	up to 86	86 (86)	57,350 (46,250)	Design Length (Design Length)	(19% less Weight)
III	up to 97	96 (97)	70,000 (57,250)	Haul Weight (Design Length)	(18% less Weight)
IV	up to 103	92 (100)	70,000 (61,650)	Haul Weight (Haul Length)	(8' additional Length + 12% less Weight)

NOTES:

(1) Lightweight concrete = 125 lb./cu. ft.
Normal concrete = 155 lb./cu. ft.

(2) 70,000 lb. assumed to be maximum net weight that can be legally hauled.

(3) Maximum legal net length of members is assumed to be 100 feet.
Length limitations in Virginia are as follows:

Roadway	Overall Length
2 Lane	90'
4 Lane (undivided)	100'
4 Lane (divided)	110'
Interstate (30 mi. limit)	125'

(Substract 10' to 15' from above lengths for truck cab to arrive at net length of members)

(4) Lightweight concrete values in parentheses.

(5) No consideration is given to the possibility of the volume of a member being reduced by using lightweight concrete since its own dead weight is reduced.

(6) Span capability varies with beam spacing and concrete strength.

When considering buildings, there are a number of properties of lightweight concrete besides reduced weight that are attractive to the designers, fabricators, and owners. Of course, weight reduction in the entire structure is probably the most important since the foundation system in buildings is more directly affected than it is in bridges. The immense loads, both dead and live, transmitted to the foundations of tall buildings are a primary design consideration. The extent to which the foundations of buildings can be spread is often constrained by the proximity to other buildings and utility lines. In bridges, this factor is usually much less critical.

Building designers are also interested in the acoustical and thermal properties of lightweight concrete. With respect to the latter, lightweight concrete permits considerably less heat loss and thus provides greater fire resistance than normal weight concrete. The greater fire resistance also reduces insurance costs on the building. This is an important factor in building construction, since it is a recurring cost of the life of the structure.

The aforementioned properties of lightweight concrete serve to indicate why it's becoming increasingly popular in the construction of buildings. The fact that these same properties are of little importance to bridge designers accounts in part for the reason why it has not had widespread acceptance in the bridge industry.

SUMMARY

The use of lightweight aggregate concrete in a structure is usually predicated on a lower overall cost. While lightweight concrete may cost more per cubic yard than normal weight concrete, the structure may cost less as a result of reduced dead weight. The additional cost of lightweight aggregate concrete in relation to normal weight concrete in Virginia appears to be between $5 and $7.50 per cubic yard. Economy then depends on attaining a proper balance among cost of concrete per given volume, unit weight, and structural properties. Normal weight concrete may cost less per cubic yard, but will be heavier, which results in greater dead loads, increased sizes in many sections, and therefore a possible increase in the amounts of concrete and reinforcing steel needed.

A summary of the advantages and disadvantages of using lightweight concrete in bridge decks and structural members are summarized in the following subsections.

1. Bridge Decks

The resistance to freezing and thawing and deicing salts is an important aspect of durability in concrete bridge decks. These two factors have been particularly troublesome in Virginia along with those of alkali-aggregate and decreased skid resistance from polishing-prone aggregates.

It has been shown that the freezing and thawing resistance of properly air entrained lightweight concrete is equal to or greater than that of many air entrained normal weight concretes (Haddad and Freedman 1971). For the purpose of reducing the problem of harshness in handling lightweight concretes, it is customary to use 6% to 8% air entrainment in the mixtures. The inclusion of air entrainment to alleviate this handling problem should also help ensure that the lightweight mixes will be properly air entrained from a durability standpoint.

Lightweight concrete's resistance to salt scaling is obtained in the same manner as for normal weight concrete — by the use of entrained air, a low water-cement ratio, good curing, and a week or two of drying before applying any salt (Haddad and Freedman 1971).

The permeability of normal and lightweight concretes is dependent upon the quality of the mortar and is not affected by the internal porosity of the aggregates (PCI 1967). The pore structure of most lightweight aggregates is characterized by isolated cells that inhibit the passage of moisture through the particles. The permeability of lightweight concrete should not be of major concern when the past successful use of it in ships is considered.

There is no indication of a problem from alkali-aggregate reactions with the use of lightweight aggregates.

The abrasion resistance of lightweight concrete has been shown to vary with the compressive strength of the concrete. However, it is generally somewhat less than that found in normal weight concrete. For use in pavements, satisfactory results can be obtained if the mix is properly proportioned, placed, finished, and cured (PCI 1967). Good skid resistance should be provided by the use of concrete incorporating silica fine aggregate and lightweight coarse aggregate. Limited tests on bituminous mixes incorporating lightweight coarse aggregates have shown that they will provide a relative high coefficient of friction (Maupin 1970). It is surmised that with continuing wear the lightweight aggregate rather than polishing like many natural aggregates, regenerates a fresh surface via fracturing or normal wear, which exposes new cellular walls to better enable tires to obtain a gripping action.

At present, the Virginia Department of Highways has one lightweight concrete bridge deck in its road system — the Petersburg Bridge. It has been in service approximately 12 years, has an ADT of around 5,000 (1971), is uncovered, gets regular salting, and is in good condition.* The design properties of this 4,000 psi concrete were C. F. = 7 - 7 1/2 sks per cubic yard, A. E. = 5 - 7%, and maximum slump = 4". Natural sand was used with a lightweight coarse aggregate.

The only disadvantage of using lightweight concrete in bridge decks would appear to be the added cost. This additional expense, if it actually exists, would be comparatively small when taken in relation to the overall cost of a structure.

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* Telephone conversation with Richmond District Bridge Engineer, J. A. Tavenner.

2. Precast and Prestressed Structural Members

In today's bridge construction, increasing use is being made of prefabrication and preassembly of bridge components. From this standpoint the lighter weight of the components made with lightweight concrete reduces their dead weight; may reduce the amount of reinforcement or prestress needed; and, to a minor extent, reduces the amount of concrete required. The savings in weight extends all the way through to the foundation. The lower weight also reduces hauling handling costs. At equal weights, an approximately 20% increase in span length can be had by using lightweight instead of normal weight concrete.

Certain properties of structural lightweight concrete members require special treatment. In particular, shear strength is reduced, the modulus of elasticity is reduced, and creep is generally increased.

RECOMMENDATIONS

As a result of a literature search and conversations with persons having experience with structural lightweight concrete, the following recommendations are offered.

1. Because lightweight aggregate concrete appears to have the physical and chemical properties needed in durable concrete bridge decks, the good experience of the New York State Thruway Authority, and the 12 years of good performance of the Petersburg Bridge, it is suggested that the Department, to gain important field experience for future reference, consider the use of lightweight coarse aggregate and silica fine aggregate in several bridge decks. It could be used in a two-stage construction sequence if a reduction of concrete cost was necessary.

2. Because of the potential advantages offered to the parameters of length and weight and the safety consideration of longer spans, it is suggested that in the design stages of precast or prestressed concrete structural members cost figures for the use of lightweight concrete be obtained from local fabricators and that a judgement as to its use being based essentially on economics. There do not appear to be any significant technical reasons why structural lightweight concrete cannot be used in view of its wide use for a number of years in the commercial building market, and in the bridge market too in some states. This experience would appear to offer proof that the capabilities of the material are sufficient for structural purposes.

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