Report of the FIP Commission on

Prestressed Lightweight Concrete*

SYNOPSIS

The report discusses prestressed lightweight concrete, made with high-quality structural lightweight aggregates such as expanded shales, clays and slates, and capable of developing cube strengths from 280 to 500 kg/cm² (4000 to 7000 psi) at unit weights of 1400 to 2000 kg/m³ (85 to 120 pcf). Satisfactory values of shrinkage and creep are obtainable. Modulus of elasticity is approximately half that of normal concrete at the same strength. Fire resistance and thermal insulation are significantly better than for normal weight concrete. Specific applications are listed.

INTRODUCTION

Prestressed lightweight concrete is rapidly emerging as an important sector of the structural concrete industry. It possesses unique properties, similar in many ways to those of prestressed normal concrete, but differing in significant aspects. It is most wisely used when it is treated as a new material in its own right, and its special properties are fully considered in design and construction and utilized in performance.

Theme III of the Fourth Congress of FIP (Rome-Naples, 1962) awoke widespread interest in prestressed lightweight concrete, as a result of which a special FIP Commission was formed and charged with preparing this report.

This report is purposely restricted to lightweight concrete that is suitable for prestressing. For the purpose of this report, the following definitions have been adopted.

(1) *Structural lightweight-aggregate concrete.* Concrete containing expanded or porous aggregates having a unit weight of 1400 to 2000 kg/m³ (85 to 120 pcf) and capable of developing compressive strengths generally ranging from 280 to 500 kg/cm² (4000 to 7000 psi). When prestressed, this is called prestressed lightweight-aggregate concrete.

(2) *Normal concrete.* This is conventional concrete made with sand and gravel, or sand and crushed rock, aggregates, having a unit weight of 2200 to 2500 kg/m³ (135 to 150 pcf) and, for purposes of comparison in this report, having a compressive strength of 280 to 500 kg/cm² (4000 to 7000 psi).

Prestressed lightweight-aggregate concrete is currently used on a wide scale in the USA and USSR, and there is small but significant and expanding use in Australia, Canada and Great Britain. In 1964, approximately 1,000,000 m³ (1,000,000 yd.³) of prestressed lightweight-aggregate concrete were used through-

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out the world. It has been used satisfactorily both in factory production of standardized structural elements and for individual major structures requiring a high degree of technical performance and reliability. It has been successfully used for a wide range of applications paralleling those more commonly produced in prestressed normal concrete.

The design of prestressed lightweight-aggregate concrete is based on the same premises as that of prestressed normal concrete. It is essential, however, that full consideration be given to the specific properties and behaviour of prestressed lightweight-aggregate concrete.

Prestressed lightweight-aggregate concrete is absolutely dependent upon the availability of structural lightweight aggregates of high quality. Such aggregates, suitable for use in prestressed concrete, are produced in more than sixty plants in the USA, Canada, Australia and Great Britain. Substantial supplies of this type of aggregate are produced in the USSR. New lightweight-aggregate plants are being actively promoted for many of the West European countries. Several are scheduled to go into operation in the very near future. Intense interest in lightweight-aggregate plants exists in a number of other countries.

Since lightweight aggregates are usually a manufactured product, the properties and qualities are inherently subject to close control and constant improvement. Thus it is to be anticipated that material of even higher quality will become available for prestressed lightweight concrete. At the same time, improvement in the relative economics and the increasing experience in actual use presage a rapid growth in volume and importance for prestressed lightweight concrete.

PROPERTIES OF PRESTRESSED LIGHTWEIGHT-AGGREGATE CONCRETE

This summary of properties is purposely restricted to high-quality aggregate and high-strength mixes suitable for use with prestressing. All the properties of lightweight-aggregate concrete are affected to some extent by the moisture condition of the concrete. Both coated (i.e. pre-sized) and crushed expanded clay, shale and slate aggregates are considered together as no clear line of demarcation in properties can be found.

In the study of the properties of some forty different structural lightweight aggregates produced in the USA, Canada and Australia, it was found that they fall within a range; thus a broad band is a truer representation than a single line (see Appendix). A corollary result of the test programme has been that normal sand and gravel, and sand and crushed rock, aggregates also exhibit a rather wide range of values for each property.

(1) *Unit weight.* The range is 1400 to 2000 kg/m^3 (85 to 120 pcf), which is 60 to 80% of that of normal concretes of the same strength. The unit weight submerged is approximately 50% of that of normal concrete.

(2) *Compressive strength.* With minor increase in cement content, this is about the same as for normal concrete, up to a maximum of about 500 kg/cm^2 (7000 psi). With some lightweight aggregates no increase in cement is necessary, but with others an increase is definitely required.

(3) *Shear (diagonal tension).* At normal working stress this is about the same as for normal concrete, but at ultimate strength the shear in

diagonal tension for structural lightweight-aggregate concrete is between 65 and 100% of that for normal concrete. The diagonal tension strength of structural lightweight-aggregate concrete is characterized by its tensile splitting strength rather than by its compressive strength.

(4) *Tensile splitting strength.* This varies with different aggregates, from less than to more than that of normal concretes for dry or partially dry conditions. Low values may be due to a differential moisture content at the interior and exterior portions of the concrete member. However, in the wet condition, it is approximately the same as for normal concrete. The use of natural sand fines improves the tensile splitting strength of lightweight concrete in the dry condition. Tests in the USSR indicate that the axial tensile strength of lightweight-aggregate concrete is not less than that of normal concrete.

(5) *Modulus of rupture.* Like the tensile splitting strength, the modulus of rupture is about the same as for normal concrete in the moist condition, but reduced in the partially dry condition.

(6) *Bond.* Pull-out tests generally show the bond strength to be similar to but slightly less than for normal concrete at ultimate strength.

(7) *Transmission length.* This 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 because of the lower modulus of elasticity of structural lightweight-aggregate concrete.

(8) *Modulus of elasticity.* The range for structural lightweight-aggregate concrete is 140,000 to 210,000 kg/cm^2 (2,000,000 to 3,000,000 psi)—extreme range of 115,000 to 280,000 kg/cm^2 (1,600,000 to 4,000,000 psi)—which is only about half to two-thirds of that for normal concrete. Although the modulus of elasticity of lightweight-aggregate concrete is so much less than that of normal concrete, the dead-load deflexion of a prestressed lightweight-aggregate concrete beam will be only 15 to 25% greater than that of a prestressed normal concrete beam of the same dimensions.

(9) *Creep.* For simplicity of design procedures, the ratio of creep strain to instantaneous strain has often been considered a constant. However, much research has indicated that this ratio varies widely, even for a single type of concrete. Therefore, for the purposes of this report, creep has been defined as the deformation with time of concrete under sustained compressive loading.

For high-quality structural lightweight-aggregate concrete, the creep is only slightly greater than for normal concrete. Research on the long-term behaviour of columns shows that the long-term shortening for lightweight concrete is, for all practical purposes, the same as for normal concrete of the same compressive strength. The creep of structural lightweight-aggregate concrete is approximately proportional to the ratio of applied stress to the strength at the time of loading or the creep per unit stress is approximately proportional to the applied stress. The USSR reports that creep growth takes place in the early months, 60 to 80% occurring in the first two months. The USA similarly reports that significant creep deflexions will not occur after 90 days.

(10) *Shrinkage.* This depends upon the quality of the lightweight-aggre-

gate concrete. For high-quality structural lightweight-aggregate concrete, tests in the USA show values of shrinkage slightly greater than for normal concrete. Steam curing reduces the shrinkage of structural lightweight-aggregate concrete by 20% or more. However, the USSR reports considerably more shrinkage (up to 190%) when the aggregate used is all lightweight; with silica sand fines and lightweight coarse aggregate, this is reduced to about 140% of that for normal concrete.

(11) *Total loss of prestress.* This is about 110 to 115% of the total losses for normal concrete when both are subjected to normal curing; 124% of the total losses for normal concrete when both are subjected to steam curing. However, total prestress loss for lightweight-aggregate concrete under steam curing is approximately the same as for normal concrete under normal curing. Steam curing reduces the total prestress loss by 30 to 40% compared with normal curing.

(12) *Thermal insulation.* This is a basic property of lightweight-aggregate concrete. The much greater thermal insulation of lightweight-aggregate concrete has a decided effect on prestressing applications, because of the following factors:

(a) greater temperature differential in service between the side exposed to sun and the inside may cause greater camber (see discussion on volume change);

(b) better response to steam curing;

(c) greater suitability for winter concreting;

(d) better fire resistance.

The thermal conductivity of structural lightweight-aggregate concrete is approximately 40% of that of normal concrete: its thermal transmittance is about 50%.

(13) *Acoustical properties.* This also is a basic property of lightweight-aggregate concrete not affected by prestressing but one which does influence its application. Lightweight-aggregate concrete has satisfactory sound absorption and sound transmission insulation from a practical stand-point.

(14) *Permeability.* Structural lightweight-aggregate concrete is impermeable 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 internal porosity of the aggregate particles. The material has been used successfully in shipbuilding in the USSR, USA and other countries.

(15) *Water absorption.* For structural lightweight-aggregate concrete, this is in the range of 12 to 22% by volume (average 17%) compared with 12% for normal concrete.

(16) *Abrasion resistance.* This is generally less than for normal concrete, particularly where the abrasion is local and concentrated, as in highway kerbs. For general wear, as in pavements, careful attention to obtaining a well proportioned concrete mix, and proper placing, finishing and curing will provide entirely satisfactory service.

(17) *Resistance to freezing and thawing.* This is generally equal to that obtained for good-quality, air-entrained, normal concrete. Air-entrainment is shown to be very important in all but exceptionally high-density, high-strength mixes. Lightweight concrete is reported to be more suitable for winter concreting because it has less heat loss during transport and better reaction to steam curing.

(18) *Marine durability.* This is generally believed to be approximately the same. Some authorities believe it

may even show increased durability.

(19) *Atmospheric durability.* This is believed to be about the same as that of normal concrete.

(20) *Corrosion.* The cover to the reinforcing steel for structural lightweight-aggregate concrete is generally specified as the same as for normal concrete. There is no evidence of any material difference in corrosion protection of lightweight-aggregate and normal concrete of the same strength, i.e. with approximately the same cement and water contents in the mix.

The USSR reports that the use of 2% $NaNO_3$ (by weight of cement) in the mix will give improved corrosion protection. Research studies are now under way at the Building Research Station, England, on zinc coating of tendons, phosphate coatings and the use of corrosion-inhibiting slurries, such as sodium nitrite and sodium benzoate, for use with both normal and lightweight concretes.

(21) *Fire resistance.* This is approximately 20 to 50% better than for normal concrete, partly because of lightweight-aggregate concrete's greater resistance to the transmission of heat. Increased thickness of cover increases the fire resistance in proportion to the ⅔ power of thickness.

Lightweight-aggregate concrete provides good thermal insulation over the tendons and also resists heat transmission through the slab.

Structural lightweight-aggregate concretes made with different aggregates performed remarkably alike under identical test conditions.

(22) *Fatigue.* Such tests as have been performed to date show equal or better behaviour by structural lightweight aggregate concrete. Tests were 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. Failures occurred along inclined sections, indicating the need for more shear reinforcement in structures subject to repeated loads than that required for static load design.

Experience with conventionally reinforced structural lightweight-aggregate concrete ships has demonstrated the ability to withstand many reversals of loadings produced by storms at sea.

(23) *Coefficient of thermal expansion.* For structural lightweight-aggregate concrete, the range is 7 to 9.5×10^{-6} per deg C (4 to 5.5×10^{-6} per deg F), which is a narrower range than normal concretes show. The average for an all-lightweight-aggregate concrete is 8 (4.5 per deg F), whereas with 30% replacement of the lightweight fines by natural sand it is 9 (5 per deg F), compared with 10 (5.5 per deg F) for normal concrete. Although structural lightweight-aggregate concrete expands only 85% as much as normal concrete, there have been no difficulties in service either with reinforcement or in composite construction of lightweight-aggregate concrete with normal concrete.

(24) *Poisson's ratio.* This runs from 0.17 to 0.21 for the great majority of concretes. A value of 0.2 may be used for design.

(25) *Alkali-aggregate reaction.* A limited number of tests have shown no reaction.

(26) *Dynamic behaviour under impact stresses.*

(a) *Pile-driving stresses.* The lower modulus of elasticity reduces the maximum compressive stress by 18% and the maximum tensile stress by 22%.

The stress wave velocity in structural lightweight-aggregate concrete is about 20% less than normal concrete, the length of stress wave is about the same.

(b) *Seismic resistance* appears generally slightly more favourable because of the greater resilience. The period of vibration of the structure may be lengthened and the response is likely to be somewhat lower. If its ultimate strain is also greater (see item 27 below), it will have significantly better seismic resistance.

(c) *Shock and energy absorption* is believed to be considerably increased compared with normal concrete.

(d) *Vibration damping* may be more effective because of the numerous discontinuities formed by differential shrinkage between the paste and the aggregate, and earlier crack formation.

(e) *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.

(27) *Ultimate strength.* Current research on lightweight columns indicates that structural lightweight-aggregate concrete may have greater ultimate strain than conventional concrete of the same compressive strength; and thus greater ultimate strength capacity.

UTILIZATION

Prestressed lightweight-aggregate concrete has been widely utilized in certain building applications and, to a lesser extent, in almost every application for which prestressed normal concrete has been employed. The most beneficial applications are those in which the unique properties of prestressed lightweight aggregate concrete are fully utilized, and it is selected not merely as a lightweight substitute for prestressed normal concrete but as a new material in its own right.

The fields in which prestressed lightweight aggregate has gained wide acceptance and in which it has proved its economy and structural benefits in extensive use are roofs, walls and floors of buildings. For these uses, the reduced dead weight with its lower structural, seismic and foundation loads, the better thermal insulation and better fire resistance have usually been the determining factors in the selection of prestressed lightweight-aggregate concrete.

There are a number of newer applications of the material which appear to offer exciting possibilities. Many of these are based on its energy-absorption properties and reduced modulus of elasticity, others on its thermal properties, and still others on its greatly reduced submerged weight.

Prestressed lightweight-aggregate concrete has been widely used in composite action with normal concrete. All possible combinations have been tried and have proved successful structurally. These combinations are:

(a) prestressed lightweight-aggregate concrete joists and beams with deck slab of normal concrete cast in situ;

(b) prestressed lightweight-aggregate concrete joists and beams with deck slab of lightweight-aggregate concrete cast in situ;

(c) prestressed normal concrete beams with in situ lightweight-aggregate concrete.

It has generally been found that combinations (a) and (b) are most efficient because of the relative moduli of elasticity. However, (c) has proved suitable in many cases, including a major bridge structure.

Table I lists the uses to which prestressed lightweight concrete has been put, together with the form or section for each, a brief statement as to present volume of use, a list of those advantages or properties which lead to its selection, and, finally, a list of any factors adverse to that particular use.

MANUFACTURE AND CONSTRUCTION

The techniques and procedures required for manufacture and construction of prestressed structural lightweight-aggregate concrete are very similar to those used for prestressed normal concrete. Experience has indicated the following specific recommendations.

For mix design and compaction, to achieve best strength and other properties

(1) The use of natural sand of normal weight to replace a part or all of the lightweight fines will generally give more consistent and slightly improved results with only small increase in unit weight. Replacement of 30% of the fines together with an increase in the proportion of coarse aggregates is often sufficient. Drying shrinkage is usually reduced and the tensile splitting strength in the dry condition is usually improved.

(2) The use of water-reducing and strength-accelerating admixtures (but no $CaCl^2$).

(3) The use of air-entrainment to prevent segregation and to increase resistance to freezing and thawing.

(4) Careful selection and handling of the lightweight aggregates.

(5) Proper design and control of the concrete mix.

(6) The mix should be consolidated and compacted by adequate vibration. It is important to avoid over-vibration as this may cause segregation.

(7) In the USSR, supplementary compaction by pressure is also used on certain precast elements such as roof slabs.

For curing

(1) Steam curing at atmospheric pressure is widely employed and generally improves properties, especially by reducing drying shrinkage and creep. Extensive tests show the optimum cycle for low-pressure steam curing is:

Delay or holding period 3 to 5 hr.
Rise in steam temperature
22°C per hr. (40°F per hr.)
Maximum sustained temperature
65°C (150F)
or 60 to 70°C (140 to 158°F)
Period of curing at maximum
temperature 11 to 14 hr.

Lightweight-aggregate concrete gains heat more slowly, and holds it longer, because of its insulating qualities; thus, for the same 28-day strength, lightweight-aggregate concrete benefits more from steam curing at an early age, such as 18 hr., than does normal concrete. Shorter delay periods, higher maximum temperatures and shorter curing times at maximum temperature may be used to achieve a shorter production cycle, but will generally result in a reduction of ultimate compressive strength and other properties.

(2) Steam curing at high pressure (autoclaving) is especially beneficial in reducing volume change, but so far has proved practicable for prestressed work only with small elements such as railway sleepers and small roof slabs.

Table I—Utilization of Prestressed Lightweight Concrete.

Type of application	Present volume of use	Form or section employed	Properties and advantages leading to selection compared with normal concrete	Adverse properties
Flooring	Substantial	Precast flat slabs. Precast cored slabs. Precast T slabs, single or double. Precast joists with in situ slab. Lift slabs. In situ composite deck slab on prestressed lightweight joists. In situ post-tensioned slab (or slab and beam) floors	Lower dead weight. Reduced seismic loads. Reduced structure and foundation loads. Easier handling and erection. Better fire resistance. Lower transport costs	Slightly greater camber and deflexion
Roofing	Very large and widespread	Precast T slabs, single and double. Precast and in situ shells and folded plates. Cellular composite slabs. Precast slabs for cable-suspended roofs. Canopy roofs for grandstands and aircraft hangars. Roof trusses. Precast flat slabs, solid or cored	Lower dead weight. Reduced seismic loads. Reduced structural and foundation loads. Better fire resistance. Better heat insulation. Reduced condensation. Lower thermal movements. Lower transport costs and erection costs	Slightly greater camber and deflexion
Walls for buildings	Substantial	Solid panels. T panels. Sandwich panels. Cellular-composite panels. Panels with special architectural finish	Prestressing of wall panels prevents cracking, makes thinner sections practicable, and facilitates handling and erection. Lower dead weight. Reduced seismic loads. Reduced structural and foundation loads. Better heat insulation. Better freeze-thaw durability. Lower thermal movements. Easier handling and erection. Better fire resistance. Less condensation	
Bridge beams	Some, including some large and important structures	Suspended span. I beams composite with in situ deck. T beams. Box beam girders. Hollow-core slabs. Segmental sections	Reduced dead weight. Reduced seismic loads. Reduced structural loads. Reduced foundation loads. Easier handling and erection. For segmental beams, low modulus of elasticity permits better distribution of bearing pressures on adjoining faces when 'dry' joints are used. Better fire resistance (some installations in fire hazard areas)	Low modulus of elasticity. Greater camber. Lower diagonal tension
Bridge decks	Some use	Precast slabs. In situ deck slab composite with prestressed lightweight I beams	Lower dead weight	
Foot-bridges	Considerable	I beams. T beams. 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	Some	Bearing piles. Fender piles. Dolphin piles. Batter piles. 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 deflexion and energy absorption. Better ability to deform without cracking during driving when obstructions are encountered	More subject to spalling from abrasion and local impact

Table I (cont.)

Type of application	Present volume of use	Form or section employed	Properties and advantages leading to selection combined with normal concrete	Adverse properties
Crane beams and elements of industrial building	Some	I beams. Rectangular beams. Box sections	Lower dead weight. Reduced structural loads. Energy absorption. Fire resistance	Greater camber. Lower diagonal tension. Greater deflexion under live load
Seismic-resistant and shock-absorbent structures	A few under investigation	Beams. Framed structures	Energy absorption. Lower modulus of elasticity. Lower dead weight means lower seismic loads	
Guard rails and fenders	A few	Rectangular beams	Energy absorption. Greater deflexion under impact. Fire resistance (as compared with timber)	Spalling under local impact and abrasion on edges
Poles	Experimental and some production	Tapered. Constant section. Hollow core	Reduced weight for transport and erection. Reduced seismic loads. Greater deflexion under load	
Railway sleepers (ties)	Experimental and some production		Reduced weight for handling and installation. Better energy absorption. Greater deflexion reduces 'centre binding'	Inserts may require somewhat larger embedment or anchoring
Floating structures	Some	Precast elements. Cast in situ	Reduced weight where wall thickness is determined by cover over steel and by placing, watertightness, and stiffness requirements. Greater durability anticipated. Better energy absorption. Reduced permeability anticipated. Submerged weight of lightweight aggregate concrete is only one-half that of normal concrete. Underwater tensile strength about same as for normal concrete	

(3) Electro-thermal curing is practiced in the USSR. The cycle is a rise in temperature for 2 to 4 hr., followed by curing for 12 hr. at a temperature of 70 to 95°C (158 to 203° F), the higher temperatures being used where the unit is stressed directly against its mould.

(4) Supplementary moist curing, after steam curing, will reduce drying shrinkage. However, it is not normally used except for very critical structural members.

For prestressing

(1) Owing to the somewhat longer transmission length, slow release of pre-tensioning tendons by means of hydraulic jacks is preferable to sudden release by burning.

(2) With post-tensioning, care must be taken to achieve dense concrete in the anchorage zone and to provide adequate local reinforcement to prevent spalling. In some isolated cases, normal concrete has been employed for the end-blocks, these being precast as a short section and then set in the forms. However, this has not normally proved necessary.

For problems of surface finish

(1) Lightweight-aggregate concrete is more apt than normal concrete to form air-bubble pockets on the vertical and return faces. External vibration and careful use of mould lubricants will minimize these.

(2) Deck or surface finishing should follow closely behind placing and

care must be taken not to 'drag' the coarse aggregate out of the mix.
(3) Over-vibration should be avoided, as this tends to bring the coarse aggregate to the surface.

For architectural treatments and textures

(1) Lightweight-aggregate concrete is generally adaptable to a wide range of architectural finishes, paralleling those applied to normal concrete.
(2) Light sand-blasting of lightweight-aggregate concrete gives a bush-hammered effect at a fraction of the cost.
(3) White cement is often used with lightweight-aggregate concrete, although the basic colour of the aggregate may show. The use of white natural sand (quartz sand) with white cement and lightweight coarse aggregate will generally give a very satisfactory colour.
(4) Acid-etching and exposed-aggregate finishes are commonly used.
(5) Where ceramics, quartz or other facing materials are used in conjunction with lightweight-aggregate concrete structural elements, and the composite section is prestressed, careful consideration must be given to the different moduli of elasticity in order to ensure the proper location of the tendons.

For storage, transport and erection

(1) Excessive and prolonged soaking of surfaces during storage and transportation should be avoided as this may cause subsequent shrinkage problems after erection.
(2) Impact on corners and edges should be avoided as some lightweight-aggregate concretes are more subject to spalling than normal concrete.
(3) Thin elements (such as roof slabs) should be protected from differential exposure to sun's heat in prolonged storage, as this may cause differential camber.
(4) In general, because of their lighter weight, prestressed lightweight-aggregate units are easier to transport and erect.

High-strength lightweight-aggregate concrete

Whilst this field has not been thoroughly explored, in general the same techniques as used with normal concrete are effective, particularly those which reduce drying shrinkage.

Strengths of 500 to 700 kg/cm^2 (7000 to 10,000 psi) have been obtained with no-slump concrete consolidated by prolonged vibration or shock, a high cement content (550 kg/m^3) (930 lb./yd.^{3}), and no entrained air. This gives a unit weight in the range of 1750 kg/m^3 (105 pcf), and a modulus of elasticity of 210,000 kg/cm^2 (3,000,000 psi). Such methods have not yet been generally applied in manufacture but are indicative of potential developments.

SERVICE REPORTS

Thorough evaluation of the adequacy of prestressed lightweight concrete for widespread structural utilization must be based on continuing inspections and analyses of its actual behaviour in service. Prestressed lightweight concrete has been used on a major scale for approximately ten years and has generally proven excellent structural adequacy and performance. In a number of cases, it has been exposed to severe overloads or adverse conditions far beyond those considered in design, and has performed much better than anticipated.

In the few specific cases in which problems have developed, these have turned out under analysis to be due to poor design or poor workmanship; in general, failure to under-stand fully the special properties of this material. Much can be learned from study of these problems and failures, but they must be considered in proper perspective against a background of many thousands of successful applications.

Durability

Resistance to freezing and thawing. Reports from the USSR, USA and Canada generally indicate better resistance to freezing and thawing than for normal concrete. Air entrainment is considered necessary for best durability. The USSR reports that the higher frost resistance is due to the porous structure.

Marine exposure. Experience with structural lightweight-aggregate concrete ships and barges from both world wars shows generally excellent durability, despite the small cover provided over the reinforcing steel. One well studied case is the ship Selma, which has been beached for over 40 years at Galveston, Texas, in semi-tropical sea water. Although there is only 1 cm (0.4 in.) of cover of expanded-shale-aggregate concrete over the reinforcing steel, substantial portions of the ship remain in excellent condition. This outstanding performance is believed to be due to the low water/cement ratio of the concrete, rich cement content and good consolidation.

Prestressed lightweight-aggregate concrete piles have been in service in the USA since 1955 and recent inspection showed excellent condition.

Reports from the USSR indicate better marine durability of lightweight-aggregate concrete because of lower permeability to water resulting from its inherent structure.

Behaviour in actual fires

There have been numerous severe fires involving conventionally reinforced lightweight-aggregate concrete and these have generally borne out the predicted results from fire tests, that the better thermal insulation gives increased fire resistance compared with normal concrete.

There is only one documented case of an actual fire of severe intensity involving prestressed lightweight-aggregate concrete. This occurred in 1959 in Charlotte, North Carolina. The double-tee floor units were made with expanded-shale coarse aggregate, and natural-sand fine aggregate. A 7.5 cm (3 in.) thick topping of normal concrete was applied after erection. Shortly after the building had been completed, a tanker truck containing high-octane petrol crashed into the building and the fire burned fiercely for more than one hour. All exposed steel in the structure was twisted and destroyed, as were window sashes, and metal stairs, and hardware. Window glass melted, and the brick on the front wall was badly cracked.

The prestressed floor-slab units spalled to a depth of 2.5 cm (1 in.), but were otherwise sound. The asphalt tile flooring on the other side was not burned. Test loads afterwards showed the floor able to carry its design load safely without excessive deflexion.

Volume-change problems

These are the problems associated with creep, shrinkage and change of temperature. They are similar to those encountered in prestressed normal concrete, but may be more severe and troublesome in lightweight-aggregate concrete because of its lower weight, lower modulus of elasticity and lower shear strength. Since live load is a higher portion of total load when lightweight concrete is being used, this means that the initial camber in an unloaded condition is usually greater. Creep and shrinkage of high-quality structural lightweight-aggregate concretes are generally of the same order of magnitude as with normal concrete, but with some aggregates and some methods of curing, they may be slightly greater. The modulus of elasticity being only 60% or so of that of normal concrete, the net effect is greater camber at the time of construction.

Subsequently, several factors may combine to increase the camber. Because of the better thermal insulation of lightweight concrete, the temperature on the top side of roof members may have much greater variation than the underside, particularly if the top is covered with black roofing. This tends to increase the camber in the daytime; the prestress tends to prevent full recovery in the night. Because there is less water penetration with some lightweight-aggregate concretes, differential shrinkage of roof members in service may be greater.

As camber grows, the eccentricity of the prestress increases, giving a permanent set to the camber. As the camber increases, the ends rotate, causing considerable additional tension and shear stresses in the ends of the members near the bearings.

All these factors can be successfully overcome with proper design, but they cannot be ignored. They are similar to the same processes occurring with prestressed normal concrete, but they may be of the order of 50% greater in magnitude.

(1) In one case, the precast, prestressed T-members were taken directly from production (i.e. in a moist condition) and placed on the roof of a building in the middle of winter in order to close it in and permit inside construction to continue. Roofing was placed immediately, and the inside of the building was heated. This drove all the moisture to the top flange of the roof units, while the stems of the T's dried out. The differential shrinkage caused excessive camber which, combined with creep, reached as much as 3.7 cm (1.5 in.) in a 10 m (33 ft.) span.

The solution has turned out to be to store the prestressed members so as to allow a substantial portion of the shrinkage and creep to take place before erection.

(2) In two other cases, prestressed lightweight-aggregate roof members were covered with black material; in one case, black roofing—in the other, black asphalt. No provisions were made for end rotation. The sun's heat in the day caused upward camber; the prestress prevented full return at night. Cracks developed in the stems of the T's near the bearings in one case. In the other case, adequate mild-steel reinforcing prevented cracking of the stems of the T's, but the beam on which they sat developed cracks.

The correction and solution are the installation of neoprene bearing pads near the edge of the bearing seat so as to prevent concentration of bearing stresses. The need for adequate mild steel in the stems of the T's near the bearings is definitely shown.

(3) Perhaps the most notorious case of difficulty occurred with the first prestressed lightweight-aggregate bridge members made in the USA in 1953, and shipped and installed across the Kenai River in Alaska. These units were flat-slab deck units*, with the prestress designed for normal concrete. Since the elements were to be shipped 2,000 miles

Editor's note: the units in distress were post-tensioned I-girders of lightweight concrete; these supported the flat-slab deck units.

from the point of manufacture, the manufacturer requested and received permission to substitute lightweight-aggregate concrete, but no compensatory change was made in the prestressing force. The units as designed had inadequate mild steel at the ends, according to present-day codes and recommendations. No neoprene or rubber bearing pads were provided.

Shrinkage and creep at the time of manufacture were reportedly greater than is now achieved with best practice, and the modulus of elasticity was low. So, as shipped, the units had considerable camber. The units were transported by truck, then ship and then truck to the site. During this, they were constantly wet on the top, generally dry underneath. Thus differential shrinkage and multiple handling increased the camber.

After installation, an attempt to correct the camber was made by asphalt paving. The problems were aggravated by the black surface, with temperature differential and moisture gradient.

The actual live load that occurred in this remote location was negligible. Camber continued to grow, the ends continued to rotate. Finally after 8 years of service, the ends had cracked to the extent that the deck had to be replaced.

This type of problem is now solved by better design, which includes an evaluation of camber-deflexion through the early years of service, better detailing of the mild steel at the bearings, and the use of neoprene bearing pads.

Behaviour in pile-driving

Prestressed concrete piles have been manufactured and driven in lengths up to 40 m (130 ft.). The use of lightweight-aggregate concrete reduced the weight that must be lifted. The deflexions during lifting were about the same as for normal-weight concrete, the lower weight about balancing the lower modulus of elasticity. Prolonged driving with steam pile-hammers gave results similar to those obtained with normal concrete piles.

In one important installation in which prestressed sheet piles of both normal and lightweight-aggregate concrete were driven through buried timbers and riprap, it was noted that the prestressed lightweight piles were able to take much more distortion without cracking.

Abrasion and wear

Properly and carefully made deck slabs of prestressed lightweight-aggregate concrete have demonstrated their ability to withstand heavy traffic, perhaps the most notable example being the Oakland Bay Bridge, San Francisco. Decks of concrete ships made with lightweight-aggregate concrete have similarly withstood wear, vibration and alternating stresses.

However, lightweight-aggregate concrete is subject to local 'plucking' and spalling under localized impact, such as occurs with the kerbs and median barriers of bridges. Similarly, in the case of the Oakland Bay Bridge, prestressed lightweight-aggregate concrete deck elements showed plucking at one spot at the bottom of a vertical curve, where the trucks applied power suddenly for the uphill climb; the remainder of the entire deck showed no such wear. A thin coat of epoxy surfacing has restored this and appears as a good solution for points of extreme localized abrasion or impact.

ECONOMY

The extensive use of prestressed lightweight-aggregate concrete is absolutely dependent upon the availability of high-quality lightweight aggregates. By far the most important sources of lightweight aggregates suitable for use with prestressing are expanded clays, shales and slates produced by the rotary kiln method. Sintered expanded clays, expanded slags and aggregates made from sintered pulverized fly ash have been used to a lesser extent. Natural lightweight aggregates similar to pumice have generally been inadequate in quality and consistency, but a few such natural sources located in Nevada, Hawaii, Japan and the Armenian SSR apparently have properties comparable with those of the expanded clays and are used and suitable for prestressed members of medium quality.

Whilst the establishment of a plant for producing structural lightweight aggregates requires a large capital expenditure, these aggregates can be widely utilized in conventionally reinforced lightweight-aggregate concrete as well as in prestressed lightweight-aggregate concrete. Experience has shown that the availability of lightweight aggregates of a uniformly high quality gives a rapid stimulus to demand. In those countries now producing, the use is rapidly expanding, necessitating the development of additional plant capacity.

The demand for lightweight aggregates is not necessarily dependent upon low cost. On the contrary, the major demand for structural lightweight aggregates has resulted from the beneficial properties of the resultant lightweight concrete. Thus lightweight-aggregate concrete, including prestressed applications, has an opportunity for substantial growth even in those countries where natural sand and gravel aggregates are available and cheap.

The cost differential between normal aggregates and lightweight aggregates varies considerably from place to place, but in general, high-quality lightweight aggregates cost up to approximately twice as much as normal aggregates. This additional cost may frequently be over-balanced or offset by direct and indirect economic advantages. In some regions, structural lightweight aggregates actually cost less than normal aggregates.

Direct advantages

(1) Reduced dead weight—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 whch means lower transport cost, especially in long-distance hauls. In some instances, the reduced weight permits units to be sent by lorry 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 to the over-all economy.
(5) Lower weight for erection, which often permits the use of standard rather than special equipment, and facilitates handling and erection of units.
(6) Greatly reduced weight in submerged or floating installations.
(7) Thermal insulation is made integral with the structural element.

Indirect advantages

(1) The reduced dead weight, accruing from lower unit weight and

reduced cover for fire resistance, means reduced lateral loads for seismic design.

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

(3) The reduced dead weight means lower foundation loads, permitting 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% by the use of lightweight concrete.

(4) Saving in other elements of the structural frame through the reduced dead weight of prestressed lightweight elements.

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

(6) Winter concreting may be facilitated through better retention of heat.

At present, the economic situation as regards prestressed lightweight-aggregate concrete is in a state of rapid change or evolution. There is a tremendous actual and planned growth in the production of high-quality lightweight aggregates while, at the same time, deposits of natural normal-weight aggregates close to the point of use are being depleted and the cost of normal aggregates is moving upwards. Meanwhile, better techniques and control of structural lightweight aggregates and of their use in prestressed work is permitting increasingly wide utilization of this new material.

Already in a few specific cases, lightweight-aggregate concrete is being used for the entire production of the prestressing plant, the direct and indirect savings having proved lightweight to be economical for all phases of the plant's production. In a much larger number of cases, lightweight constitutes 50% of the prestressing plant's production.

Prestressed lightweight-aggregate concrete, having proved its structural and technical capabilities, is rapidly emerging as an economical material for a wide variety of uses and should therefore undergo a rapid growth in use in the near future.

AREAS FOR ADDITIONAL RESEARCH AND DEVELOPMENT

The following areas for investigation have been raised as being particularly needed or as giving especial promise.

(1) The tensile strength and diagonal tension strength of lightweight-aggregate concrete need further investigation. The tensile strengths are believed to be limited by the differential shrinkage between paste and aggregate. Possible means of reducing this are: sealing the surface of the concrete, as by an epoxy; special coatings of aggregate particles; and using expansive cement (see item 2 below). Another means would be the careful adaptation or matching of the cement paste to the particular type of aggregate involved, based on a study of the character of the micro-cracks.

(2) The use of expansive cement in conjunction with lightweight aggregate could be mutually beneficial. The expansive cement should reduce the shrinkage in the paste. The absorbed water contained in the lightweight aggregate provides a good source of curing water at proper locations in order to enable expansive cement to develop its full reaction, with beneficial effects of increased strength, reduced moisture gradients in large members during

curing, and reduced shrinkage. Structural lightweight aggregates appear almost ideal for use with expansive cement because they combine high porosity and water retention with high strength and relatively high stiffness of the aggregate particles.

(3) High compressive strength. An investigation of this should be co-ordinated with the work of the FIP Commission on High-Strength Concrete. Compressive failure of lightweight-aggregate concrete is believed to be essentially a tensile failure. Possible avenues of approach are:

(a) the use of smaller maximum size aggregate and higher cement content;
(b) steaming at higher temperatures and for longer periods to reduce shrinkage;
(c) the use of triaxial prestress —the use of high-strength wire spirals combined with extra-high axial prestress might induce sufficient transverse or binding prestress to have a significant effect;
(d) further pursuit of high-strength mix design;
(e) embedment of fibres or needles which might have proportionally greater beneficial effect with lightweight-aggregate concrete.

(4) Behaviour under shock, dynamic and seismic loadings. This is a particularly promising line of approach and might well be co-ordinated with the FIP Commission on Prestressed Seismic Structures.

(5) Analysis and investigation of new applications for which prestressed lightweight concrete can be beneficially applied. Such new applications might utilize the low modulus of elasticity and energy-absorption properties as well as the low unit weight. Suggested areas are:

(a) machinery structures and foundations;
(b) pavements and runways—the low modulus of elasticity and lower coefficient of thermal expansion should result in less change in prestress during service.

(6) Areas for research on basic properties where further and better information is believed to be needed include:

(a) ultimate design in flexure;
(b) design of eccentrically and concentrically loaded columns;
(c) ultimate strain;
(d) coefficient of thermal expansion and contraction.

(7) Continuing inspection and reports on the performance and behaviour of prestressed lightweight concrete under service conditions, with particular emphasis on its behaviour under the following conditions:

(a) sea water and marine exposure;
(b) earthquake;
(c) fires;
(d) exposure to freezing and thawing, with and without exposure to sea water;
(e) overload and impact;
(f) durability in corrosive environments under exposure to various chemicals, etc.

(8) Investigation of the influence of different types of cement upon the properties of lightweight-aggregate concrete with specific reference to the interaction between the particular type of cement and particular aggregates involved.

(9) Development of a strength theory for lightweight-aggregate concrete.

CONCLUSION

It is believed that this report will have shown adequately the great potential for expanding the manufacture and use of prestressed lightweight concrete. In a recent article, Engineer I. G. Ivanov-Dyatlov states: "From studies of the technology of manufacture, the structural-mechanical properties, shrinkage, creep, water impermeability, heat resistance, and fatigue, it has been shown that high-quality expanded-clay-aggregate concretes are suitable for building the most demanding structures." Much work remains ahead in further research, development and application, but sufficient knowledge and experience exists to justify the assertion that prestressed lightweight concrete is already of major significance as a new and reliable material for wide structural use.

APPENDIX

PHYSICAL PROPERTIES OF STRUCTURAL LIGHTWEIGHT AGGREGATE CONCRETE

The data presented are based on the study of forty lightweight-aggregate concretes and a limited comparison is afforded with five normal concretes containing sand and gravel or crushed-rock aggregates. In general, the various concretes had slumps varying from 2.5 to 10 cm (1 to 4 in.) and air contents varying from 4 to 7%.

It should be noted that the various graphs shown are not meant to be used as precise measures of each property but merely give an approximate and reasonable assessment for guidance.

The data from which these charts were prepared were based upon cylinder strengths. As presented herein,

(Cont. on p. 87)

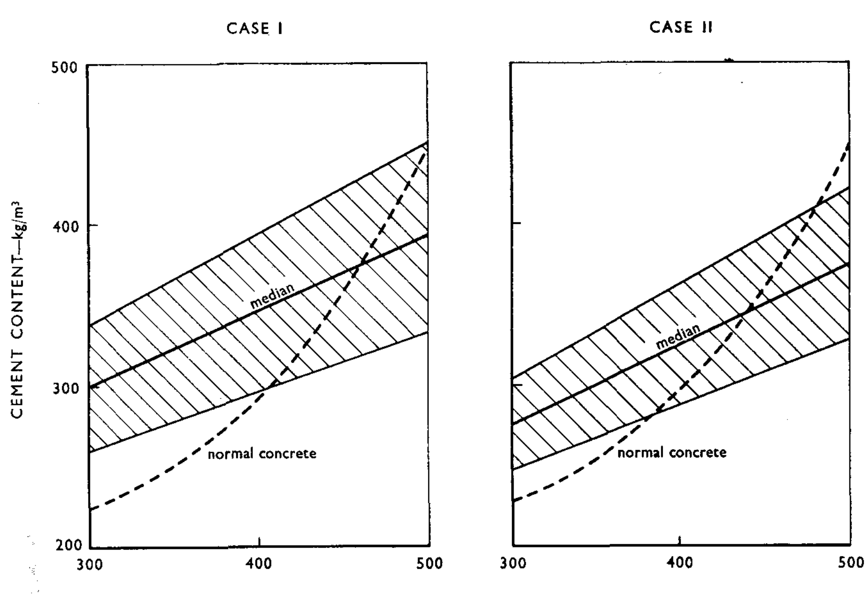

Fig. A1—Relation between cement content and compressive strength.

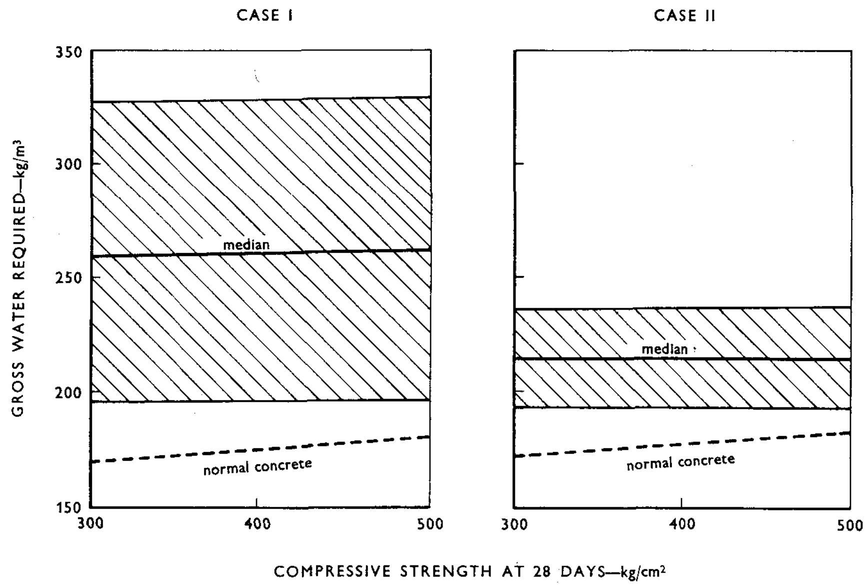

Fig. A2—Relation between gross water requirement and compressive strength.

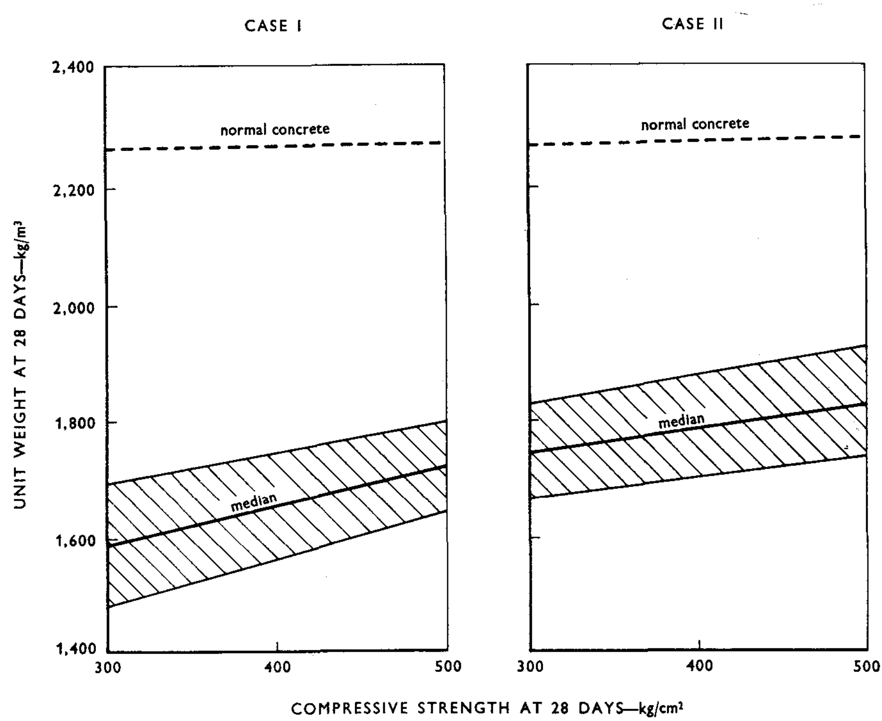

Fig. A3—Relation between unit weight and compressive strength. The unit weight is that of hardened concrete cured by steam at atmospheric pressure or given normal curing (for 7 days at 23° C (73.4° F) and 100% relative humidity followed by drying at 23° C (73.4° F) and 50% relative humidity, ASTM C330).

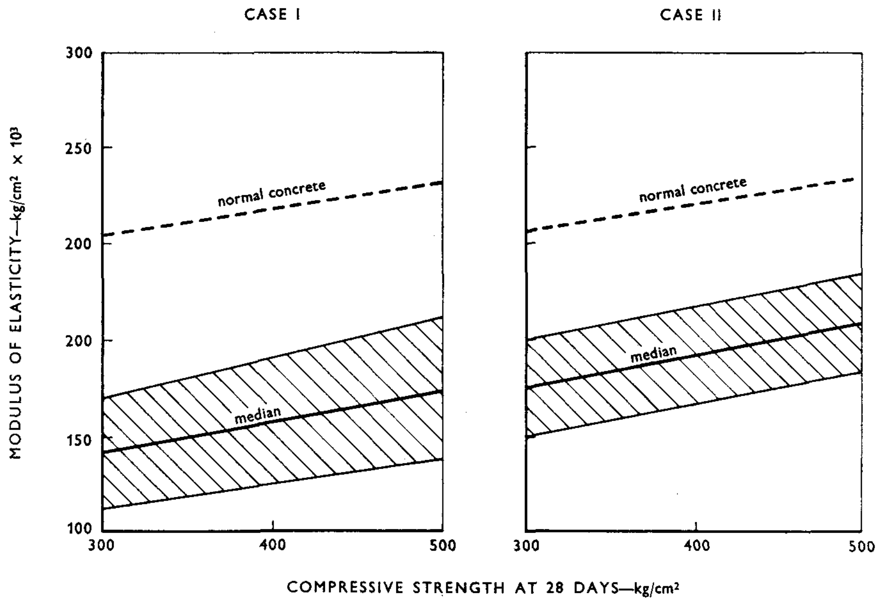

Fig. A4—Relation between modulus of elasticity and compressive strength. The modulus of elasticity quoted is the chord modulus as determined by ASTM C469–61T.

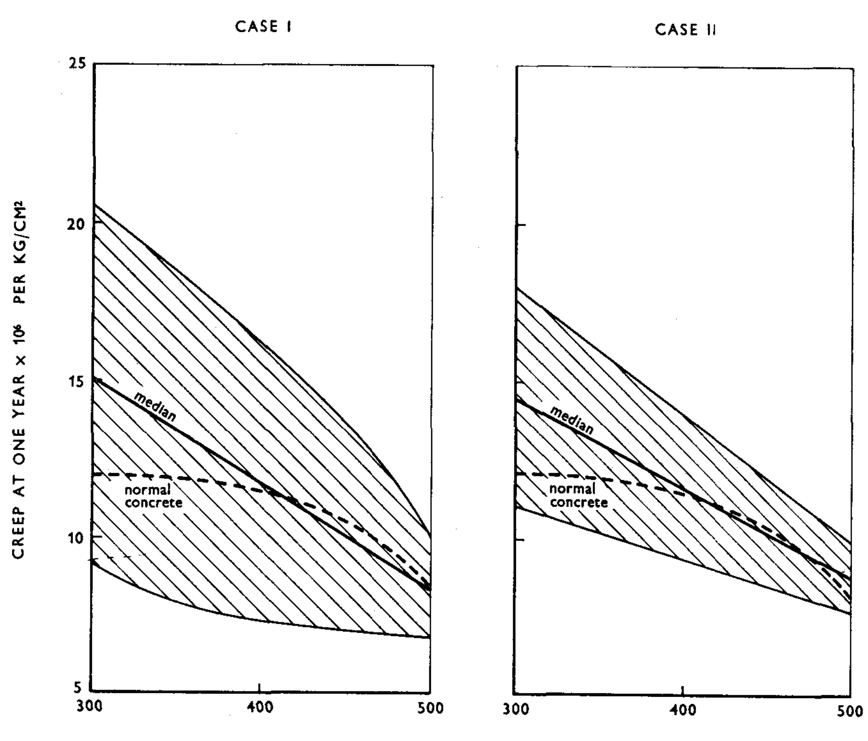

Fig. A5—Relation between creep and compressive strength. Normal curing.

they have been converted to equivalent cube strengths by arbitrarily dividing by 0.85.

In Figs. A1 to A17 the area shaded represents the range of 40 structural lightweight-aggregate concretes. The median of the range is shown in each case. The broken line is a typical value for a normal concrete made with Elgin sand and gravel.

In Figs. A1 to A5 and A8 to A11, reference is made to "Case I and Case II". Case I is concrete made with 100% lightweight aggregate. Case II is concrete made with lightweight coarse aggregate but with normal sand fines.

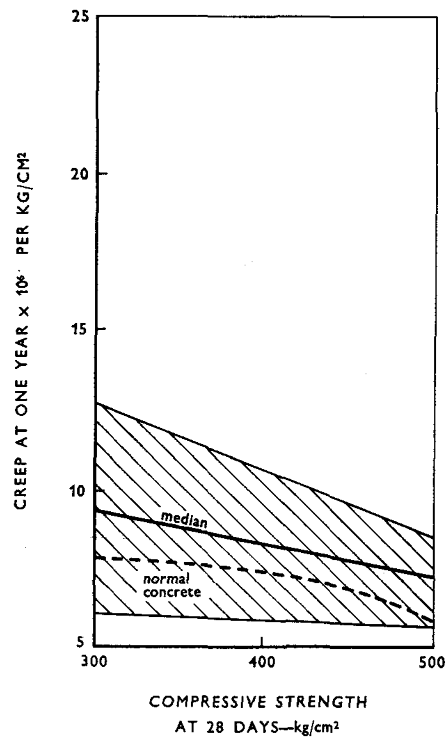

Fig. A6—Relation between creep and compressive strength. Steam curing at atmospheric pressure, maximum temperature 65° C (150° F). (Note that the comparison normal concrete has less creep than other normal concretes.)

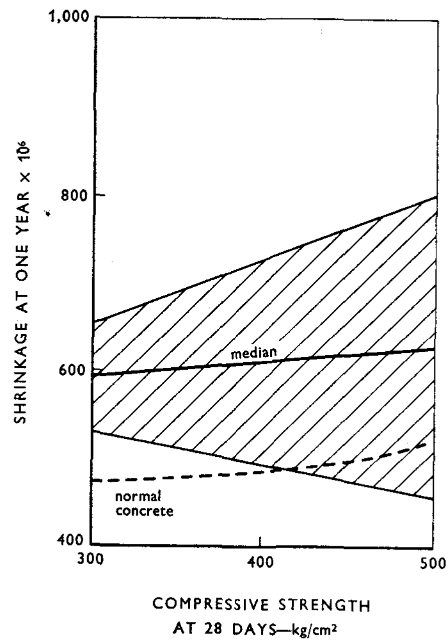

Fig. A7—Relation between shrinkage and compressive strength. Steam curing. (Concrete is allowed to harden for 4 hr.; then steam is introduced at a temperature rise of 22° C (40° F) per hr. to a maximum temperature of 60–70° C (140–160° F). After 12 hr. at maximum temperature specimens are allowed to cool for 2 hr. before they are demoulded.)

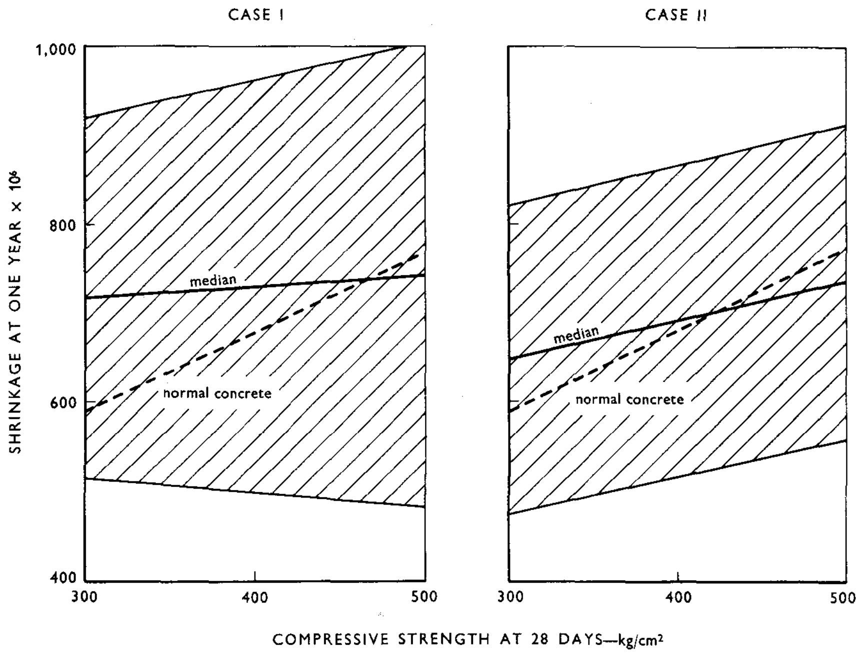

Fig. A8—Relation between shrinkage and compressive strength. Normal curing.

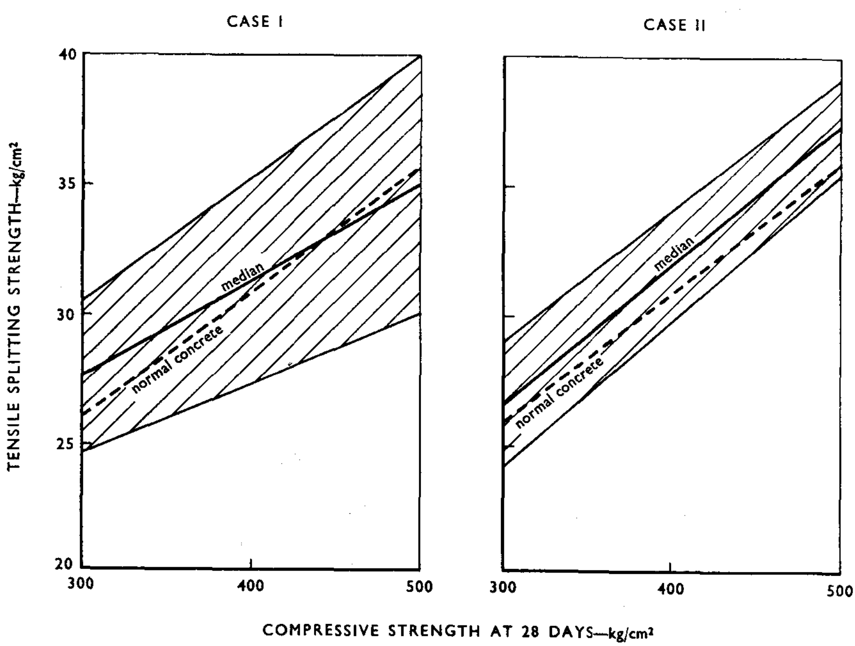

Fig. A9—Relation between tensile strength and compressive strength. Specimens are stored moist at 23° C (73.4° F) and tested moist. (For definition of tensile splitting strength see ASTM C496.)

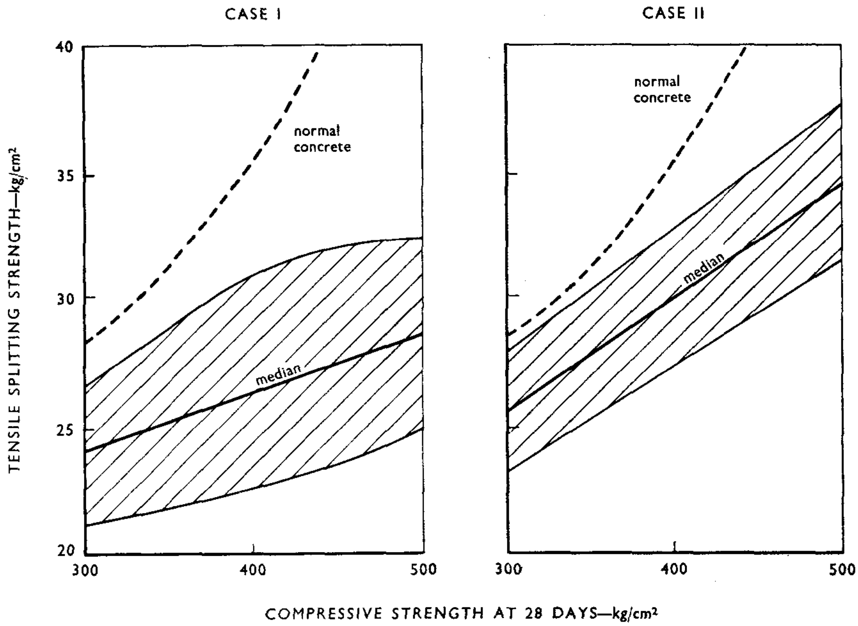

Fig. A10—Relation between tensile strength and compressive strength. After curing, the specimens are allowed to dry at 23° C (73.4° F) and 50% relative humidity and tested in this condition.

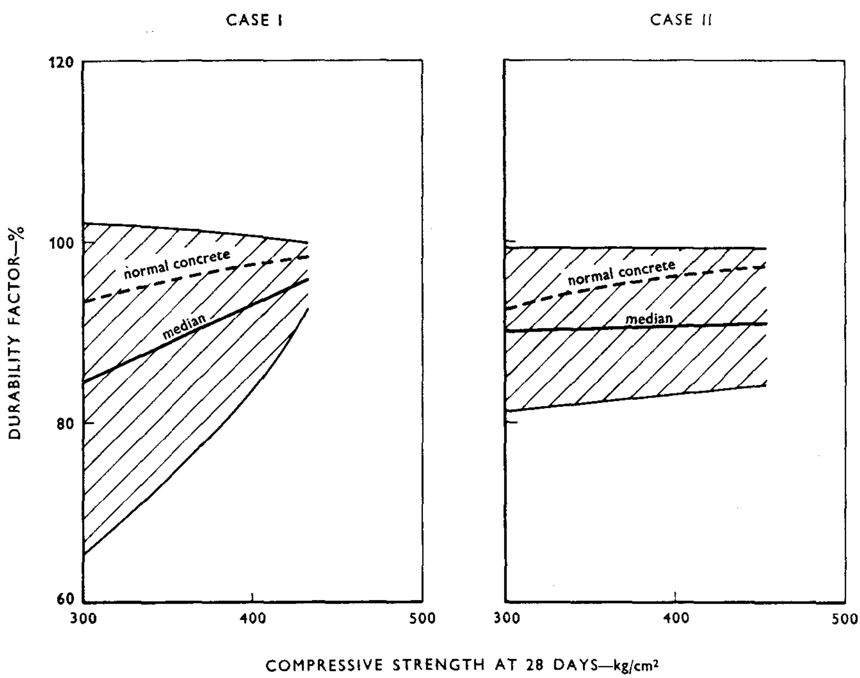

Fig. A11—Relation between durability factor (measure of resistance to freezing and thawing) and compressive strength. The durability factor is defined in ASTM C290—61T.

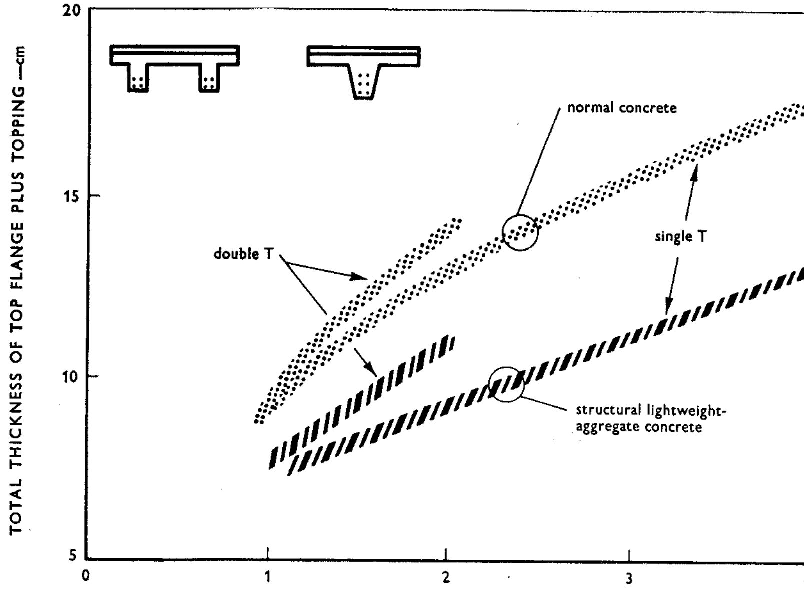

Fig. A12—The fire resistance of prestressed structural lightweight-aggregate concrete. Fire rating based on transmission of heat through top flange and topping as controlling factor.

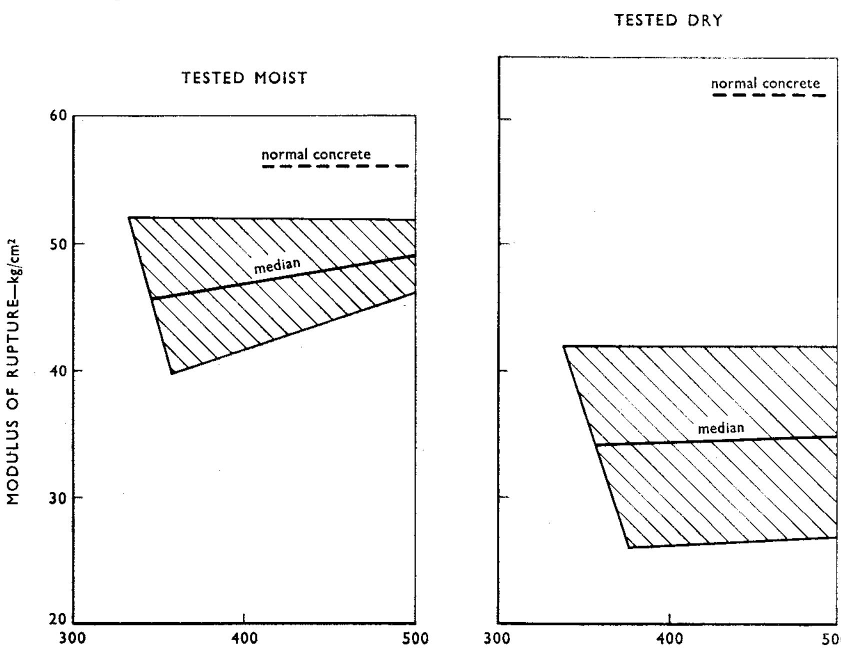

Fig. A13—Relation between modulus of rupture and compressive strength for concrete made with 100% lightweight aggregates. Normal curing. (For moist and dry conditions, compare Figs. A9 and A10. The modulus of rupture is the flexural strength as determined by the method given in ASTM C78.)

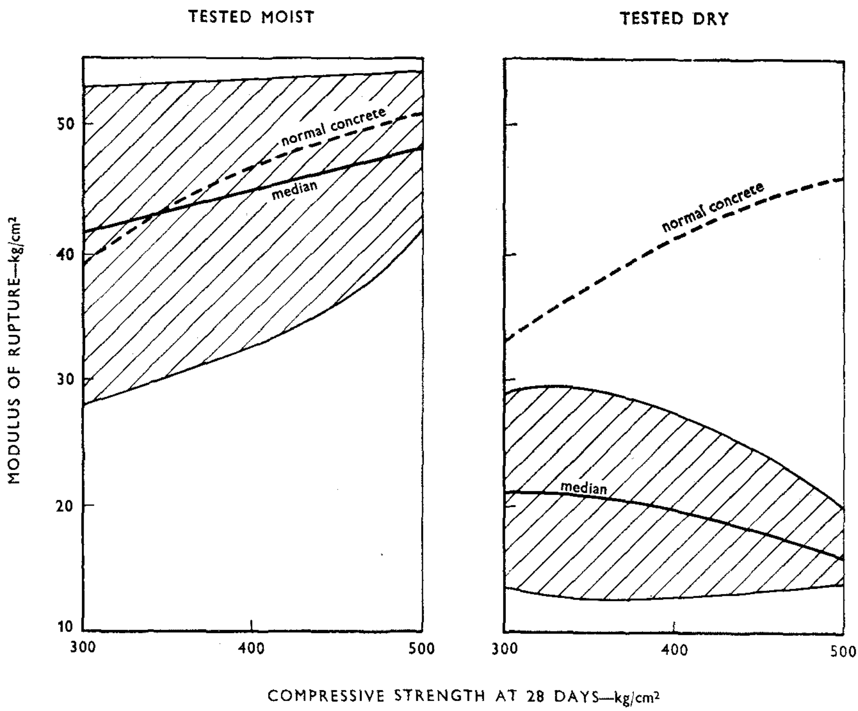

Fig. A14—Relation between the modulus of rupture and compressive strength. Steam curing at atmospheric pressure and maximum of 65° C (150° F).

TABLE II—Prestress Loss as Affected by Type of Curing*

Type of aggregate	Total prestress loss (%)			
	Normal curing		Steam curing at atmospheric pressure	Autoclave curing
	1 year	3 years		
Expanded shale produced in rotary kiln	22	24	21	7
Control specimens (normal-weight sand and gravel)	21	22	17	5

*Hanson, J. A., Journal of the Prestressed Concrete Institute, Vol. 9, No. 2, April 1964.

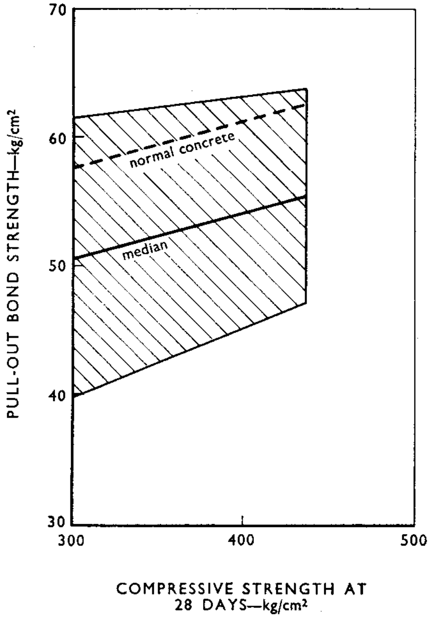

Fig. A15—Relation between pull-out bond strength and compressive strength.

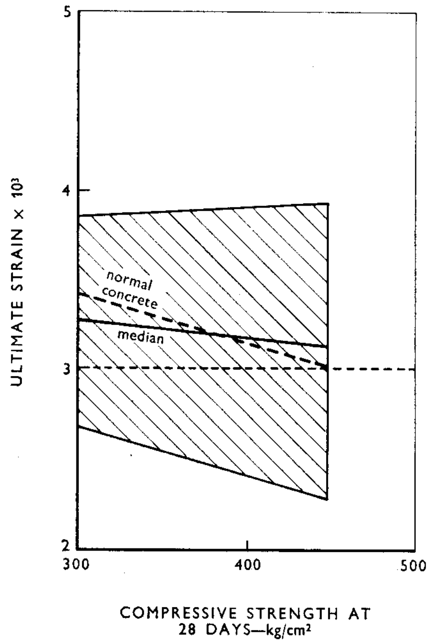

Fig. A16—Relation between ultimate strain and compressive strength.

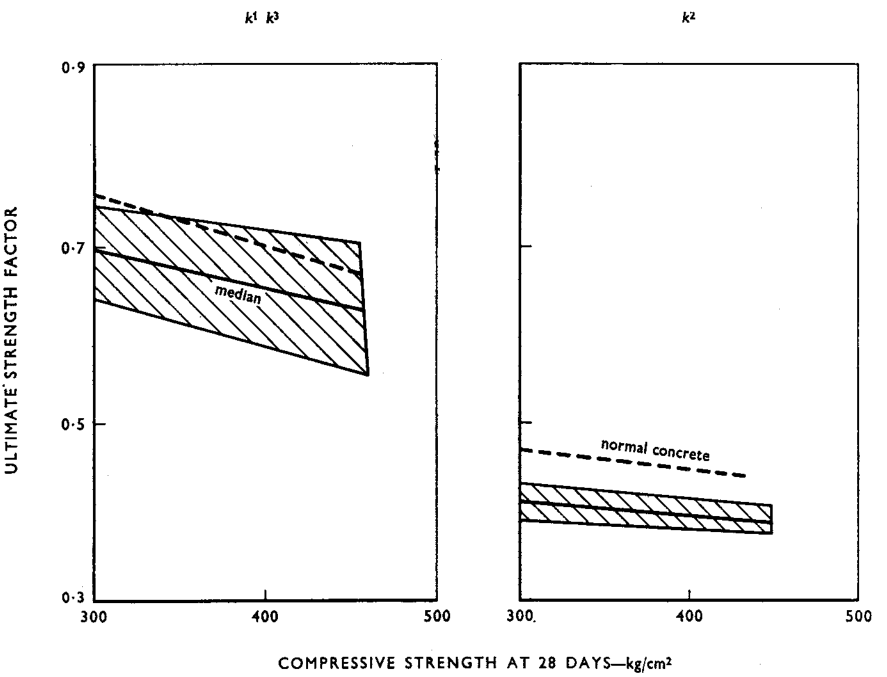

Fig. A17—Relation between ultimate strength factors (used in ACI Building Code ACI 318–63) and compressive strength.

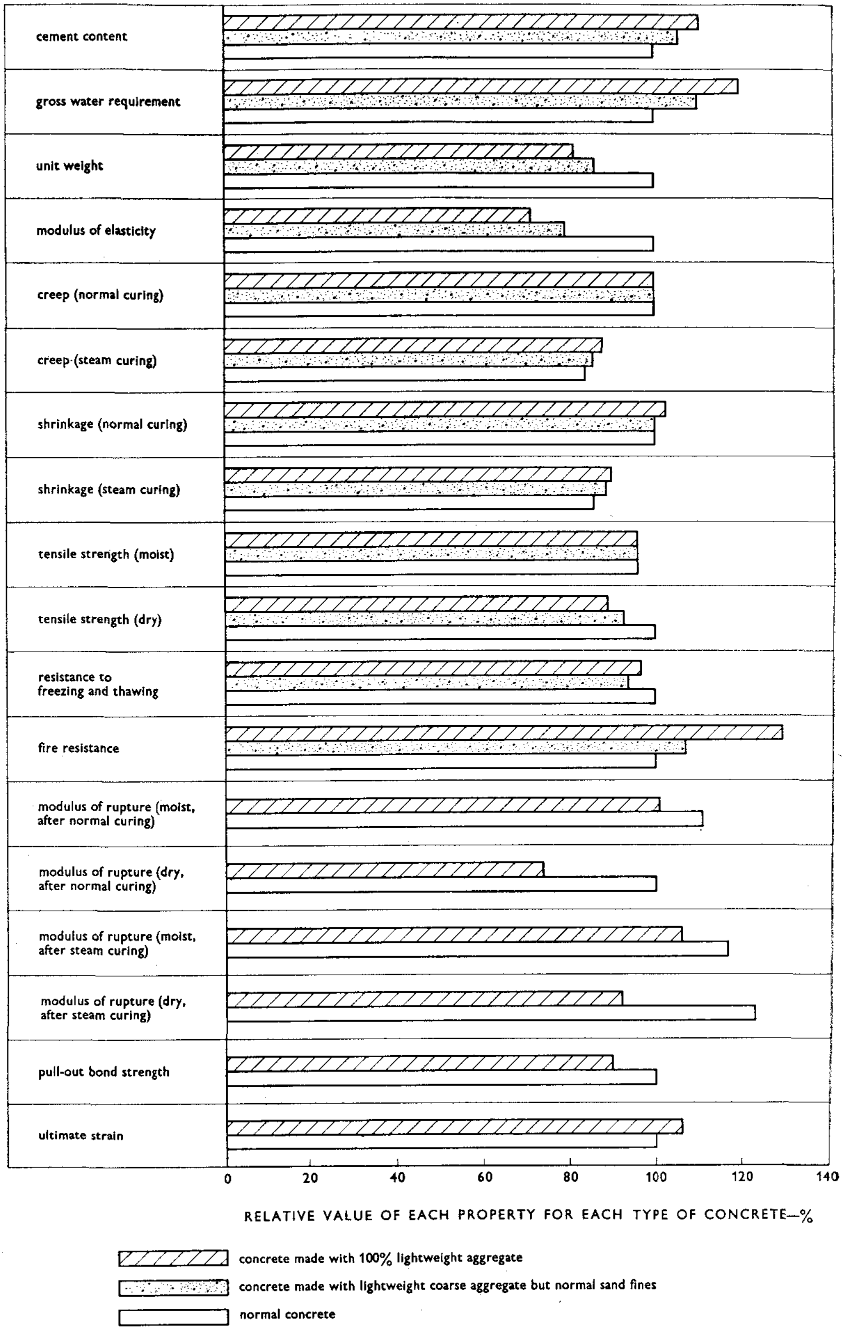

Fig. A18—A comparison of the principal properties of lightweight-aggregate concrete and normal concrete, both having an equivalent cube compressive strength at 28 days of 400 kg/cm^2 (5700 psi). Values plotted are relative only, but the plots are to scale. The data have been taken from Figs. A1 to A17 but have been modified to reflect data from other sources.