STRUCTURAL
LIGHTWEIGHT AGGREGATE CONCRETE

by

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ABSTRACT

The scope of this thesis is to discuss the use of structural lightweight aggregate concrete and examine its potentials of utilization in Türkiye. The methods of production, the types, and the characteristics of lightweight aggregates used for structural purposes are presented. Production and main properties of concrete made of these aggregates are surveyed. The unit price of this concrete is higher than that of normal weight concrete; however, the structures employing structural lightweight aggregate concrete may be economical if its advantages are fully utilized. Therefore, the economy of using this material is studied in detail. Types of structures which are likely to benefit most from using lightweight concrete are also reviewed. A general evaluation of investment is made. The availability of raw materials and the appropriate types of structural lightweight aggregates for Türkiye are discussed.

ÖZET

Bu tezin amacı, taşıyıcı hafif agrega betonu kullanımının değerlendirilmesi ve Türkiye'de uygulanma imkanlarının araştırılmasıdır. Yapısal amaçlarla kullanılan hafif agregaların üretim yöntemleri, çeşitleri ve özellikleri anlatılmıştır. Bu agregalarla yapılan betonun karışım hesapları ve genel özellikleri muhtelif kaynaklardan yararlanılarak incelenmiştir. Taşıyıcı hafif agrega betonunun birim fiyatı normal yoğunluklu betonunkinden daha yüksektir. Ancak avantajları iyi bir şekilde değerlendirildiği taktirde, çeşitli yapı türlerinde ekonomik olmaktadır. Dolayısıyla, kullanımının ekonomik yönü detaylı bir şekilde incelenmiş, avantaj sağladığı yapı türleri gözden geçirilmiştir. Yatırım değerlendirmesi yapılarak Türkiye'deki hammadde kaynakları ve uygun hafif agrega türleri sunulmuştur.

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1. INTRODUCTION

1.1. General

Concrete is the most widely used structural building material throughout the world. Its ingredients can usually be produced from native materials easily and cheaply. It can be readily adapted to local conditions. However, the structures made of it are heavy when compared with the live loads they are supposed to carry. Therefore, a small reduction in weight can lead to considerable savings. Deadweight can be reduced by several techniques such as prestressing, air entrainment, etc. In addition, the aggregates being used, which constitute the bulk of the weight, can be made lighter.

Most aggregates used in the construction industry are natural. Only a small proportion of these are lightweight since the maximum attainable compressive strength of concrete made of natural lightweight aggregates (LWA) is merely 20 MPa. Consequently, there has been some research in the manufacture of artificial LWAs of structural quality. Various methods of manufacturing have been developed to produce LWAs by giving a porous structure to the aggregate particles. The density of concrete produced with such aggregates can be as low as two thirds of that of concrete made with natural sand and gravel.

Structural LWAs have been commercially produced and used since the 1950s. Extensive research has been carried out to examine their properties. Most of this research was done in the USA, where structural lightweight aggregate concrete (LWAC) has its widest use. The economics of using this material has been particularly studied in the UK. In Türkiye, structural LWAs are not manufactured, and very little is known about them. To the best of the author's knowledge, this is the first comprehensive study of this topic.

This study covers the methods of production, the types, and the properties of structural LWAs. The differences between structural LWAC and normal weight concrete (NWC) in mix proportioning, mixing, and handling are discussed. A survey of the literature related to physical and mechanical properties of LWAC is presented. A key factor in the utilization of LWAs for structural purposes is the economic advantages they offer. Even though LWAC may cost more per unit volume than NWC, it is more economical in some types of structures. Therefore, a thorough economic study of employing this material in construction is made. It is elaborated by several cost comparison studies from foreign countries. A new case study is not carried out because structural LWAs are not manufactured in Türkiye and current price data is not available. General information about the types of structures which are likely to benefit most from using structural LWAC is given. Costs of initial investment and production are estimated in support of data obtained from several manufacturers. The availability and amount of raw materials, and the appropriate types of LWAs for Türkiye are discussed.

1.2. Historical Development

1.2.1. Production of structural lightweight aggregates

Building stones made of crushed volcanic rocks were the forerunners of lightweight concrete. Due to restricted sources of porous rocks, the use of LWAs made of these rocks is not widespread. Yet these aggregates are still used occasionally in some countries.

At the beginning of the Twentieth Century, there was a trend to find a process of artificial porosity in order to decrease the weight of building materials. One of the ideas to achieve this purpose was to produce artificial aggregates by expansion or sintering.

In the United States, prior to 1917, S. J. Hayde developed a rotary kiln process for heat expansion of shales and clays to form hard, lightweight structural concrete aggregates. At about the same time, F. J. Straub pioneered in the use of bituminous coal cinders as an aggregate for the manufacture of concrete masonry units which attained high production volumes following World War I. Commercial production of expanded slag began in 1928. The first sintered shale LWA was produced using a coal-bearing shale in 1948 [1].

It was not until 1935 that the first processed LWA, foamed blast-furnace slag, came into production in the UK. This was used for some of the precast panels in Mulberry Harbour in 1944. The early manufactured structural LWAs included Leca[1] and Lytag[2]. Over the past three decades, use of structural LWAC in the UK has progressively increased to a level which saw approximately 200,000 m^3 placed annually in 1988 and 1989 [2].

In the 1940s, Leca was also manufactured in Germany, Denmark, and Holland. Methods of manufacturing expanded clay aggregates were established in the former USSR before World War II and were followed later by Czechoslovakia, Poland, and Hungary [3]. Today LWAs of structural quality are available in most parts of the United States and Canada, and many other countries [1].

Industrial waste products, such as cinder, had already been turned into aggregates at the beginning of this century. However, these often contained high proportions of sulphur and unburnt elements of coal, which proved the unsuitability of these aggregates to be used in concrete. After World War II, different methods were used to eliminate the harmful impurities. The sintering of cinders by secondary burning led to a good structural LWA known as 'Agloporite.'

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[1] LWAs are frequently known by trade names, and a trade name may be linked to a particular process of manufacture or may be the brand name of the firm irrespective of the process.

In this sense, leca is a brand name which is used as an abbreviation for 'Lightweight expanded clay aggregate'.

[2] The brand name of a particular type of sintered pulverised-fuel ash lightweight aggregate.

1.2.2. Use of Structural Lightweight Aggregate Concrete

One of the earliest uses of structural LWAC in the USA was in the construction of ships during World War I. Concrete of the required compressive strength of 34 MPa was obtained with a unit weight of 1760 kg/m^3 or less, using expanded shale aggregate. The first reinforced LWAC buildings were constructed during the 1920s. In the early 1930s, the use of LWAC for the upper roadway of the San Francisco Oakland Bay Bridge was a key to the economical design of the bridge. Subsequently, some 104 ships were constructed employing structural LWAC during World War II.

Following World War II, studies focused attention on the structural potential of LWAC and initiated a renewed interest in lighter weight for building frames, bridge decks, and precast products. During the 1950s many multistory structures were designed to take advantage of reduced dead weight. Examples are the 42-story Prudential Life Building in Chicago, which incorporated LWAC floors, and the 18-story Statler Hilton Hotel in Dallas, designed with a LWAC frame and flat plate floors. Construction of major structures employing LWAC in nearly all metropolitan areas of the US and Canada continued since the 1960s at an increasing tempo [1].

The first building frame of reinforced LWAC in Great Britain was a 3-story office block constructed at Brentford in 1958 [4]. Since then many structures have been built of precast or in situ, prestressed or reinforced LWAC, thus indicating that it has the same adaptability as NWC.

There are many examples of bridges in Western Europe and the former USSR which have LWAC in their main spans [5], [6]. The longest LWAC bridge in Europe is the Arnhem Bridge in Holland with a main span of 136.5 m [7].

The use of LWAC in floating pontoons for marinas is also quite common [8]. This is because of its high durability against marine conditions.

Today structural LWAs of various types are manufactured and used all around the world; namely in the USA, Canada, Mexico, Great Britain, Germany, France, Italy, Spain, Holland, Belgium, Austria, Switzerland, Sweden, Denmark, Finland, Norway, Portugal, the former USSR, Poland, Czechoslovakia, Hungary, Bulgaria, and several other countries [9].

1.3. Classification of Lightweight Concrete

Lightweight concrete is produced mainly by three different methods: (a) by the use of LWAs; (b) by 'aerating' with gas bubbles; (c) by eliminating the fine aggregate from the mix to produce 'no-fines' concrete.

In this thesis lightweight concretes produced by the use of LWAs will be studied. There are many types of LWAs and their properties cover wide ranges. Depending on the required properties of concrete, such as density and strength, particular aggregates can be chosen. So first, the classification of lightweight concretes according to compressive strength and density is made. The classifications of ACI 213R [1] and RILEM[1] [9] are very common. These are given in Table 1.1 and Table 1.2.

TABLE 1.1. ACI classification of lightweight concretes [1].

Type of LWC	Low density concrete	Moderate strength conc.	Structural concrete
28-day air-dry unit weight (kg/m^3)	<800	800–1440	1440–1850
Compressive strength (MPa)	0.69–6.89	6.89–17.24	>17.24

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[1] The International Union of Testing and Research Laboratories for Materials and Structures.

TABLE 1.2. RILEM functional classification of lightweight concrete [9].

Type of LWC	Structural	Structural and insulating	Insulating
Oven-dry density (kg/m^3)	<2000	not specified	not specified
Compressive strength (MPa)	>15.0	>3.5	>0.5
Coefficient of thermal conductivity (W/mK)	not specified	<0.75	<0.30

As seen from the tables, lightweight concretes are subdivided into the following types:

(a) low density, insulating concretes;

(b) moderate strength concretes which are used for structural and insulating purposes. These are sometimes designated as "fill concretes;"

(c) structural concretes having a required minimum compressive strength and a maximum unit weight. Insulation efficiency of structural lightweight concrete is lower; however, it is still better than that of NWC.

<u>Lightweight concretes produced by the use of structural LWAs are in the scope of this thesis.</u>

1.4. Definition of Structural Lightweight Aggregate Concrete

There is no standard description for LWAC. Here the definition of ACI 213R [1] will be apprehended. (This is not a specification.) Accordingly, *"Structural lightweight concrete– Structural concrete made with lightweight aggregate; the air-dried unit weight at 28 days is usually in the range of 1440 to 1850 kg/m*^{3} *and compressive strength is more than 17,2 MPa."*

Some national standards specify the minimum value of compressive strength as low as 15 MPa [9]. In TS 2511 [10] structural lightweight concrete is defined as concrete having a density not exceeding 1900 kg/m^3 and a compressive strength of not less than 16 MPa.

1.5. Classification of Lightweight Aggregates

There are many types of aggregates which are considered to be lightweight. These aggregates may be subdivided mainly into three groups:

(A) Naturally occuring materials. Examples of these are pumice, scoria, volcanic tuff, etc. Since these materials are not found everywhere and are generally used to produce moderate strength concretes, such aggregates are not in the scope of this thesis. TS 3234 [11] specifies the production of pumice concrete.

(B) Naturally occuring materials which require further processing. Examples of these are perlite, vermiculate and expanded clay, shale, and slate. The former two are non-structural and used only for insulating purposes. Expanded clay, shale, and slate are widely used for structural purposes around the world.

(C) Processed industrial waste materials. Examples of these are sintered pulverised-fuel ash, expanded blast-furnace slag, sintered colliery waste, plastic particles, and clay-blended sludge ash. Some of these, e.g. plastic particles, are also non-structural.

Sufficient laboratory data and field experience for the groups (B) and (C) are available. There are criteria to be satisfied by these aggregates given in several specifications [12], [13], [14]. The full RILEM classification of LWAs is given in APPENDIX A.

2. STRUCTURAL LIGHTWEIGHT AGGREGATES

2.1 Definitions

Structural LWAs are defined mainly according to their dry, loose unit weight. The values may vary in the specifications of different countries. The following are the definitions:

ASTM C 330 [12]: Aggregate having a dry, loose unit weight of not more than 1120 kg/m^3 for fine aggregate, not more than 880 kg/m^3 for coarse aggregate, or not more than 1040 kg/m^3 for combined fine and coarse aggregate. (should also comply with all other requirements of ASTM C 330)

BS 3797 [14]: Aggregate having a loose, bulk density of not more than 1200 kg/m^3 for fine aggregate or not more than 1000 kg/m^3 for coarse aggregate.

TS 1114 [13]: Porous, inorganic aggregate used for the production of LWAC, having a loose unit weight of not more than 1200 kg/m^3.

2.2. Production

2.2.1. Processed Natural Materials

The processes by which structural LWAs are manufactured from natural materials may be divided into two main groups. In the first group, the idea is that certain clays, shales, and slates expand (or bloat) when heated to a semi-plastic stage. This is often termed "the point of incipient vitrification". In the second group, lightness is obtained primarily by sintering a granular material in such a manner that a solid structure is formed in which the interstitial spaces are preserved as voids or pores.

In addition to heating, all manufactured structural LWAs have to be graded to specified sizes. The size of an aggregate particle may be brought about by crushing before or after heating . Alternatively, this is done by the use of special pelletizing pans or drums during the production process. Grading is usually provided by screening.

2.2.1.1. Expansion Process. Raw materials used in the manufacture of expanded LWAs are suitable natural deposits of clays, shales, and slates. Deposits composed of inhomogeneous layers and those which are not large enough to meet the consumption of a production plant are not suitable. When these materials are heated, they expand to as much as seven times their original volume, owing to the formation of gas within the mass of the material at the fusion temperature (between 1100°C and 1300°C). The porous structure so formed is retained on cooling and the product may be used as LWA. The raw material should soften at a temperature which can be reached and maintained economically. At the same time it should contain mineral constituents which will produce gases at such temperature. If such mineral constituents are not naturally present, they may be incorporated during production [15].

Study of the chemical analysis has showed no obvious relationship between chemical composition and expanding properties. The basic clay minerals appeared to play no part in the expanding process. All the experiments [16] showed that it was the "impurities", such as compounds of iron, alkalies, alkaline earths, and carbon, which supplied the fluxes and gases for expanding. The mineral forms of the impurities were of importance. But since several mineral forms of each of the impurities were found present together, it was apparent that the possible phase relationships presented an extremely complex problem.

Most LWAs are expanded in rotary kilns. A rotary kiln for the manufacture of LWAs consists of a long, steel cylinder lined internally with refractory materials and is capable of rotating about its axis. It is installed with its axis inclined at an angle not exceeding 5° to the horizontal. The length of the kiln, usually thirty to sixty meters, depends in part upon the composition of the raw material to be processed [9]. The raw material is fed in a continuous stream at the higher end, and progresses to the lower, or burner, end. The heat causes formation of gases and onset of a pyroplastic condition in the material. The viscosity of the softened mass is sufficient to entrap the gases and to form an internal porous structure. This structure is retained on cooling. The material produced in a rotary kiln has a smooth, sometimes glassy surface and a rounded, often spherical shape.

The cooled material is crushed and screened to required gradations in one variation of the rotary kiln process. The resulting particles tend to be cubical and angular. In another variation, raw material is presized, by crushing and screening or by pelletizing, before being fed. The resulting particles tend to have a smooth shell over the cellular interior [1].

Another type of kiln used for this purpose is the vertical shaft kiln. A hot jet of flue gas entering at the centre of the base of combustion chamber lifts the material upwards. Then the material which falls down rolls to the foot of the combustion chamber, and the flue gas again forces it upwards. This process is repeated a number of times. This method is suitable for producing expanded clays and shales [17].

2.2.1.2. Sintering Process. For sintering, the raw materials must either contain carbonaceous matter which serves as fuel or must be mixed with fuel, such as finely ground coal or coke. Alternatively natural gas may be used.

The pre-treated raw material is deposited in an even layer on the sinter strand which is travelling under drying and ignition hoods. There are burners in such a manner that burning, initiated at the surface, continues through the full depth of the bed. Gases are formed causing expansive action, so that the material is sufficiently viscous to entrap the gas and thereby create the porous structure. The clinker formed is then cooled, crushed, and screened. The finished product tends to be generally sharp and angular with an open pored surface texture [9].

Clay and pulverised shale can be sintered by first mixing with moisture and fuel, and then pelletizing before burning. The finished product tends to be generally rounded or cylindrical in shape [1].

2.2.2. Processed Industrial Waste Materials

2.2.2.1. Expanded Slag. In the operation of a blast-furnace, the iron ore is reduced to metallic iron by means of coke, while the silica and alumina constituents combine with lime to form a molten slag at 1400°–1600°C [15]. This slag has a composition as follows :

Calcium oxide, CaO	30–50 %
Silicon oxide, SiO_2	28–38 %
Aluminium oxide, Al_2O_3	8–24 %
Magnesium oxide, MgO	1–18 %
Iron oxide, Fe_2O_3	0,5–1 %
Sulphur trioxide, SO_3	2–8 %

If the slag is cooled slowly, it solidifies to "air-cooled slag", which is used as a heavy aggregate. Cooling of the slag with large amounts of water produces "granulated slag", which is used for slag cement manufacture. The third type of cooling is with a controlled amount of water, applied in such a way that steam is trapped in the molten mass to give the slag a porous structure similar to that of natural pumice. This is called "expanded slag".

There are three main processes used in expanding molten slag:

(A) Static (non-mechanical) Process. In the static process, a large foaming pond or a large steel tray which has water sprays in the bottom and sides is employed. The molten slag at 1200° to 1400°C is poured into this pond. Following the treatment with pressurized water and steam the mass is discharged for the next operation. A different non-mechanical method –the Kinney-Osborne Process– employs a series of jets which direct compressed air, steam, and water against a falling stream of molten slag [15]. Expansive action occurs as entrapped water turns to steam and causes formation of the porous structure.

(B) Mechanical (machine) Process. In the mechanical process, the stream of slag is broken up by rotors, water being introduced at the same time. The aim is to mix the slag and water in a uniform manner before ejection from the machine [18]. This mechanical method gives better control of the product but the initial and the maintenance costs are higher than for the static methods [15], [18].

(C) Pelletizing Process. In the pelletizing process, the molten slag particles are bloated with water in a rotating drum and than rounded by being hurled through the air. Pelletized expanded slag is lighter than other expanded slags and the particles have smoother surfaces [4], [19]. The benefits of this process are decreased gaseous (hydrogen sulphade) emissions [20], immediate removal of pellets, minimized space requirements, low installation costs, and water conservation [19], [19].

2.2.2.2. Sintered Pulverised-Fuel Ash. Ash collected from the flue gases discharged from power stations burning pulverised-fuel is known as "pulverised-fuel ash (pfa)" or "fly ash". The composition of this ash [21] is as follows:

Silicon oxide, SiO_2	43–50 %
Aluminium oxide, Al_2O_3	24–28 %
Iron oxide, Fe_2O_3	6–12 %
Calcium oxide, CaO	2–4 %
Magnesium oxide, MgO	2–3 %
Alkalies	3–5 %
Loss-on-ignition	2–10 %

Pulverised-fuel ash consists mainly of minute spherical glassy particles which are as fine as cement. LWA is produced by dampening the ash with water and mixing it with coal slurry in screw mixers. The material is then fed onto rotating pans (known as pelletizers) to form spherical pellets. These pellets are sintered at a temperature of about 1200°C. This causes the ash particles to coalesce without fully melting [4], [7], [15].

The most widely used method of sintering pulverised-fuel ash is the employment of the sinter strand. The aim is to utilize the inevitable unburnt fuel of 2 to 15 per cent in the ash and to avoid the use of additional fuel. The vertical shaft kiln, because of its high thermal efficiency, is usually possible to sinter without supplementary fuel. The sinter strand, on the other hand, with low thermal efficiency, may often require additional fuel in the form of ground coke. However, the sinter strand can tolerate a wide variation in fuel content, while the vertical kiln will operate only within a range of about two per cent of fuel. Thus the sinter strand is much easier to operate, and the economical advantage of uninterrupted production has to be set against the extra fuel expenditure which it entails [15].

2.2.2.3. Sintered Colliery Waste. The raw material is blended with water and (if necessary) fuel; then it is sintered on the sinter strand to form a cellular structure. The clinker formed is then cooled, crushed, and screened to the required aggregate gradation. The aggregate particles are generally angular in shape and have open pored surface texture [9].

2.2.2.4. Heated Coal-mine Washery Tailings. Coal-mine washery tailings are the gangue and other refuse material resulting from the washing and concentration of ground ore [21]. Those which are not suitable for production of an expanded aggregate have been used in a new type of kiln of high thermal efficiency to produce LWA that satisfies BS 3797 [14]. Granules are formed from the tailings heated to 800°C to burn off combustible matter and then fired to 950°–1100°C. A major advantage of the process is that all of the energy required for drying and firing can be supplied by the tailings with the possibility of surplus heat being generated [7].

2.2.2.5. Clay-Blended Sludge. Sludge disposal is a nuisance for municipal wastewater treatment plants. The disposal problems have encouraged some recent studies [22], [23] which examined the potential of using dewatered sludge mixed with clay as LWA. In these studies, raw sludge has generally been mixed and blended with dry clay in various proportions. These clay-sludge mixtures were fired in kilns at temperatures about 1050°C and 1100°C. The ash produced was crushed, if not pelletized, and screened to required aggregate gradations. The laboratory results indicated a potential for the production of LWAs for structural concrete; however, further studies also need to be carried out to determine the effects on long-term properties prior to the material's acceptance as a suitable LWA.

2.3. Properties

To be able to produce structural LWAC satisfactorily, the properties of the aggregates and the effect on concrete should be well known. Important properties of different LWAs are summarized in Table 2.1 .

2.3.1. Particle Density (Bulk Specific Gravity)

Particle density is the mass of aggregates divided by the sum of the volumes of individual particles. Due to their porous structure, the specific gravity of LWAs is lower than that of normal weight aggregates (NWA). It also varies with particle size, being highest for the fine particles and lowest for the coarse particles, with the magnitude of the differences depending on the processing methods. The practical range of particle densities of coarse LWAs is about one-third to two-thirds of that for normal weight aggregates. Below this range the cement requirement may be uneconomically high to produce the required strength, and above this range the weight of concrete may be too high for LWAC.

Particle density is used in mix design to determine the absolute volume of the aggregate, and is helpful to know since it affects both the density and strength of concrete.

TABLE 2.1. Important Properties of Structural LWAs [9].

Aggregate	Type of Material	Method of manufacture	Shape and Surface Texture	Density (kg/ m3)		24-hour Water Absorption % by Volume	Typical Concretes	
				Particle	Bulk		Comp Str (MPa)	Density (kg/m3)
Sintered Pulverised-Fuel Ash	Processed Industrial Waste Material	Raw material, first pelleted, then sintered	Rounded or spherical grains, smooth or slightly rough surface.	1300 to 2100	600 to 1100	about 20	20 to 50	1500 to 1700
Expanded Blast-Furnace Slag	Processed Industrial Waste Material	expanded by spraying water to the molten slag, and crushed	Irregular angular grains with rough and open-pored surface	1000 to 2200	400 to 1100	10 to 35	10 to 45	1800 to 2000
Expanded Clay	Processed Natural Material	Preformed material, expanded in rotary kiln, or sintered	Rounded grains, smooth surface; more angular if sintered	600 to 1600	300 to 900	5 to 30	10 to 60	1000 to 1700
Expanded Shale and Slate	Processed Natural Material	Crushed material, expanded in rotary kiln, or sintered	Often angular and slightly rounded; mostly has smooth surface shell	800 to 1400	400 to 1200	5 to 15	20 to 60	1300 to 1600
Sintered Colliery Waste	Processed Industrial Waste	Crushed before or after sintering	Angular with open-pored surface	1000 to 1900	500 to 1000	about 15	10 to 40	1400 to 1600
Volcanic tuff (non-structural)	Natural	Crushed and screened	Irregular shape with surface pores	1300 to 2000	700 to 1100	5 to 30	5 to 20	1300 to 1800

2.3.2. Bulk Density (Unit Weight)

The bulk density of an aggregate is the mass of a given quantity of the aggregate divided by the total volume occupied by the material. Bulk density depends on the density, size, grading, and shape of the particles and on the mode of packing, i.e. loosely deposited, vibrated, or compacted. It also depends very much on the moisture content of the aggregate. If this may vary considerably it is proposed to proportion by volume rather than by weight. Procedures for the determination of bulk density are given in ASTM C 29 [24], in BS 3797 [14] [1] , and in TS 1114 [13]. In general the bulk density is roughly half the particle density [1], [4], [7], [9]. Unit weight requirements of LWAs for structural concrete according to ASTM C 330 [12] are given in APPENDIX B.

2.3.3. Particle Shape, Surface Texture, and Size

The shape and surface texture of LWAs depend mainly on the manufacturing process. LWAs processed on rotating pans, kilns, and drums tend to be rounded in shape and have a smooth and closed surface texture. Those which require crushing are irregular in shape and have a rough and open texture. The bond between aggregate surface and matrix is not normally a critical property. The relatively weak aggregate particles are generally split before their bond with the matrix can be overcome; thus, aggregates having rounded particles or a closed, smooth surface are often preferable. Particle shape, surface texture, and maximum size of aggregates influence proportioning of mixes in such factors as workability, fine-to-coarse aggregate ratio, cement content, optimum air content, potential strength ceiling, drying shrinkage, and water requirement.

There are nominal sizes for coarse aggregate particles (USA: 19 mm, 13mm, 10 mm; UK: 20 mm, 14 mm, 10 mm; etc.). Grading requirements of ASTM C 330 are given in APPENDIX C.

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[1] Previously the methods of sampling and testing LWAs were described in "BS 3681: Methods For Sampling and Testing of LWAs for Concrete, 1976 (1983)". In 1990, these methods were incorporated into BS 3797 [19].

2.3.4. Strength of Aggregate Particles

The strength of LWAs varies with type and source. In fact, there is no reliable correlation between aggregate strength and concrete strength [1], [9].

The concept of strength ceiling may be useful in indicating the maximum attainable strength in concrete. The strength ceiling is the point at which an increase in cement content brings no commensurate increase in concrete strength. This indicates that the strength threshold of the coarse aggregate is being exceeded, and that failure is being initiated by the aggregate rather than the cementitious matrix. It is influenced predominantly by the coarse aggregate and can be increased by reducing the maximum size of the coarse aggregate. This effect is more apparent for the weaker and more friable aggregates.

2.3.5. Water Absorption

LWAs have greater absorption capacity than NWAs because of their cellular structure. this affects the workability of the fresh concrete –effective water/cement ratio– as well as some important properties of the hardened concrete. The water absorbed by LWAs may vary between 5% and 25% by weight of dry aggregates, depending on the pore structure of the aggregate. This is figure about 2% for most NWAs.

As well as the total water absorption capacity, the rate of absorption, which depends on the aggregate particle surface pore characteristics plus other factors, greatly influences the mix design, workability, and placing of the fresh concrete. Absorbed water also affects the properties such as strength, creep, shrinkage, and thermal response of the hardened concrete. It should also be noted that the water which is internally absorbed in the LWA is not immediately available to the cement as mixing water. Nearly all moisture in the natural sand, on the other hand, may be surface moisture which is available to the cement [1], [9].

2.3.6. Resistance To Freezing and Thawing

LWAs should have an adequate frost-resistance when wet, if they are to be used in concrete which is subject to frequent freezing and thawing cycles. If the aggregates are completely saturated, freezing of the pore water would damage the aggregate structure. Therefore, the total moisture content of the LWA used in fresh concrete will have to be less than a certain per cent if the concrete is to resist rapid freezing [25]. However, even after a long period of storage in water, LWAs are only partly saturated. Thus, the air filled pores provide a compensating cushion for the ice formed in the other pores.

Aggregate particles will be safer inside a concrete mass than when stored in open air. The resistance of these aggregates against freezing and thawing are evidenced by satisfactory results of frost-resistance tests on concrete [9].

2.3.7. Chemical Properties (Harmful Substances)

There are some substances which can be harmful if they exceed a certain amount and concentration in natural sand and gravel. These are mainly organic materials, some sulphur compounds, chlorides, and swelling materials. On the contrary, manufactured LWAs are usually free of harmful substances and do not show deleterious chemical reactions [7], [9] since they are produced by artificial means under permanent control.

British (BS 3797) and American (ASTM C 330) standards limit the amounts of organic impurities, clay lumps, staining, sulphate content, and loss-on-ignition. APPENDIX D gives these limitations.

3. PRODUCTION OF STRUCTURAL LIGHTWEIGHT AGGREGATE CONCRETE

3.1. General

The processes used in the production and the utilization of LWAC –proportioning, mixing, handling, compacting, curing, etc.– are not very different from those of NWC. In all these processes the familiar rules of good concrete.practice apply. Yet there are two basic differences [7]:

(a) LWAs have much higher water absorption capability; this is the most important difference.
(b) the coarse aggregates are lighter than the mix.

Absorption behavior is specific to each aggregate, and since it influences the concrete quality it should be taken into consideration.

The particle density affect the density/strength relation of the concrete and should also be considered. Practical techniques are modified to overcome the problems caused by these differences.

3.2. Mix Design

Generally the principles and procedures used for designing ordinary concrete apply to LWAC with several extra factors to be considered. Proportioning of structural LWAC mixes is the determination of economical combinations of mix constituents in a way that the optimum combination of the desired properties is developed.

3.2.1. Influence of Mix Constituents

The first factor to be considered in mix design is the choice of aggregate as the properties of the aggregate have utmost importance on concrete properties. Aggregates should be light enough to make concrete that is below the specified maximum density and strong enough to make concrete that conforms with the specified strength. Not all LWAs are suitable for producing concretes having the desired properties. Various types of LWAs will not always produce similar compressive strengths for concretes of a given cement content and slump. Unit weight of the mix is also significant. It depends primarily on the unit weight of the aggregates. It is also influenced by the cement, water, and air contents and the proportions of fine-to-coarse aggregate. The use of natural sand as fine aggregate in LWAC will increase the strength while increasing the unit weight of concrete. Hanson [26] did some experiments on the effects of this replacement.

LWACs of the same strength but made with aggregates of varying strength should be compared. Aggregates with low strength and density are expected to have higher cement requirement, lower concrete density, higher early strength and little subsequent hardening, better bond between concrete and reinforcement, low modulus of deformation. Aggregate with high strength and density will generally have properties slightly different from those of NWC [9].

Slump should be the lowest satisfactory value. Air entrainment in LWAC, as in NWC, improves durability. Moreover in some types, it is a particularly effective means of improving workability of otherwise harsh mixtures. Recommended ranges of total air contents for LWACs in American [1], British [27], and Turkish [10] standards are given in APPENDIX E. Workability, the most important property of fresh LWAC, is also increased with air-entrainment; however, staying in the recommended ranges will be the safest and most economical even in cases of sand replacement [1].

The specification of water/cement ratio is generally avoided because the short term water absorbency of LWACs makes its measurement difficult in the field [1], [7].

Appropriate admixtures may be used in LWAC but they should not be added to the mixer until absorption capacity of the aggregates has been largely satisfied [7]. Otherwise, the admixtures cannot be utilized totally because part of it will be absorbed by the aggregates.

3.2.2. Proportioning Mixes

In order to make the most economical use of materials to produce concrete of the required properties, mix proportions should be selected carefully. There are some differences between the proportioning of NWC and LWAC:

- Absorption of LWAs are much higher.
- Although NWAs are somewhat similar to each other, LWAs have a larger range of strength and density.
- The relative density of LWA particles varies with their size; the coarser being lighter than the finer particles.
- Time-dependent water absorption of aggregate particles may lead to a loss of workability.
- LWA particles are generally harsher than NWA particles, thus require air-entrainment and/or admixtures to improve cohesiveness of the mix.

The principles and procedures for proportioning NWC may be applied in many cases to LWAC [1]. With some aggregates these procedures are difficult to use, therefore other methods have been modified for such cases.

There are several methods of proportioning the mixes; the explanations of these methods are out of the scope of this study. These methods are fully described in ACI 211.2 [28], FIP Manual on LWAC [29], CEB/FIP Manual of LWAC [9], ACI 211.1 [30], namely:

- absolute volume method
- volumetric method
- specific gravity factor method–trial mix basis
- specific gravity factor method–pycnometer basis
- weight method
- effective water/cement ratio method

3.3. Mixing and Handling

3.3.1. Mixing and Delivery

All LWAs are capable of absorbing more water than NWAs. In the 24-hour absorption tests their absorption was found to be between 5% and 25% of the dry weight of the material. This, of course, depends on the type of aggregate and particle size. However, in open-air storage, actual moisture content of LWAs does not usually exceed 70% of 24-hour absorption depending on the weather conditions [9].

If the aggregates have relatively low absorption capacity, no special prewetting is required. In cases where the absorption capacity is high (greater than 10%) and the moisture content rather low (less than 8–10%), prewetting to a uniform moisture content or premixing with some of the water before the addition of other ingredients is recommended [1], [9]. This will minimize the slump loss during transportation.

Drum mixers are widely used but their drawback is that the mortar fraction tends to build up on the blades; therefore the pan mixers are preferable [7], [9]. Truck mixers, because of their low efficiency, require a longer mix time. However, mixing should not continue for a very long period for some very friable aggregates tend to break down if overmixed [7], [9].

In ready-mixed concrete, loss of workability may be expected during transport because of the absorption rate and initial moisture content. This may be significant if the delivery time is long.

Admixtures should not be added until the absorption capacity of the aggregate has been substantially satisfied otherwise the effective dose will reduce.

3.3.2. Pumping

LWAC is more difficult to pump than ordinary concrete. The problems are again caused from the capacity of coarse aggregate particles to absorb large quantities of water with a corresponding decrease in workability [1], [9], [31]. Pumping involves high pressure which forces water into aggregates. This reduces plasticity and causes increased friction which finally makes pumping impossible.

Several techniques are developed to overcome this problem. The first one is to presaturate LWA before mixing concrete. (ACI 213R [1] advises three methods for presaturation: atmospheric, thermal, and vacuum.) This minimizes the absorption of aggregate, therefore minimizing the slump loss during pumping [1]. Another method is to use additives, permitting extra water to be added without risk of segregation and inhibiting the rapid absorption under pressure. It is also usual to employ natural sand fines when pumping is being considered.

ACI 213R [1] gives general recommendations about the proportioning of lightweight coarse and normal weight fine aggregate pump mixes: presaturation, maintaining 335 kg/m^3 minimum cement content, using admixtures, a slight reduction in the volume of coarse aggregate and corresponding increase in fines, use of well graded natural sand, and proper gradation. It also gives advice about pumping and the pump system; use of the largest size, clean lines "buttered" with grout at the start, avoiding rapid size reductions from the pump to line, and reduction in the operating pressure.

3.3.3. Placing, Compacting, and Finishing

The methods used for placing, compacting, and finishing NWC are also used for LWAC with little modification. In general, it is easier to move and consolidate LWAC [1], [7], [9].

The most important point in placing and compacting LWAC is to avoid the separation of coarse aggregates. Coarse aggregates will tend to rise in the case of overvibration mainly because of their lower density than the mortar fraction of the mixture [1], [7]. On the other hand, LWAC must be thoroughly vibrated as LWAs tend to release entrapped air more slowly than NWC does [9]. The problem can be avoided by a well proportioned, workable mix with a minimum water content, proper equipment for handling and placing, proper consolidation, skilled supervision, and good workmanship. A slump value of 75 mm (maximum 100 mm) will be sufficient [1].

Finishing techniques for LWAC are described in ACI 302.1R [32]. For a good finish, prevention of segregation, timing the finishing operations properly, and using appropriate finishing tools are recommended.

All LWACs bleed to some extent [9]. This will not cause any problems as the bleeding water disappears in half an hour. Finishing operations should be performed after this water disappears [1].

3.3.4. Curing

The water absorbed into the aggregate particles, which up to now has been regarded as a cause of problem, is now available for curing as an advantage. In temperate climates this is sufficient to ensure proper hydration without any other precautions [9]. However, as this may sometimes mislead, it is better to apply the same curing methods to LWAC which are applied to NWC [7]. Moreover, in rather hot climates this will certainly be necessary.

Just after finishing, curing would start as soon as possible [1]. ACI 302.1R [32] contains information on proper curing of LWAC floor slabs. The methods of curing are:

- water curing (wet coverings, panding, and sprinkling)
- moisture retention cure (water-proof paper and spray-applied curing compound membranes)
- hot air curing
- steam curing
- infra-red curing

In all these methods, there are some important points to be considered: free water in concrete should be prevented from boiling in heat curing; optimum temperature gradient should be 15 to 25°C/hr; concrete temperature should not exceed 50°C; and pre-steaming time should be sufficient in steam curing. Steam curing can be used more effectively with LWAC than with NWC because of the lower heat capacity and greater thermal insulation of LWAC. Tests showed that the evolution of heat due to cement hydration produces a rise in the temperature of the concrete, which is about twice as high for LWAC as for NWC [9].

In general 7 days of curing is considered adequate with a temperature in excess of 10°C [1]. ACI 308 [33] should be referred in this respect.

In cold weather concreting, tests have shown that LWAC provides better frost-resistance during the critical first 48 hours and higher compressive strength in a structure [9].

4. PROPERTIES OF STRUCTURAL LIGHTWEIGHT AGGREGATE CONCRETE

4.1. General

Physical and mechanical properties of LWAC should be well known in order to employ it efficiently and economically in construction because some properties of LWAC are superior to those of NWC while some others are slightly unfavourable.

Today there are numerous types of structural LWAs produced and used in many countries all around the world. For this reason, the properties of concretes produced with these aggregates vary to an extent. However, reasonable values are present thanks to many laboratory studies and field experience. In fact we have a great deal of knowledge about the physical and mechanical properties of structural LWAC.

In this chapter, information about these properties obtained from various papers, reports, specifications, manuals, guides, and standards will be presented.

4.2. Density

The low density of structural LWAC is the primary reason of its utilization. Density of concrete contributes significantly to the loads that structural members can carry. These obviously affect the design and economics of a structure. Depending on the mix constituents used, LWACs are produced with densities from 1440 to 1850 kg/m^3 [1].

There are several factors affecting the density of LWAC. Approximately 70% of the total volume of concrete is taken up by the aggregates [9]; therefore, the density of concrete is mainly governed by the aggregate particle density. For structural concrete ASTM C 330 [12] limits the dry loose weight of coarse aggregates to 880 kg/m^3 and the fine aggregates to 1120 kg/m^3. Replacement of the fine LWA particles by natural sand also increases the concrete density by about 80 to 160 kg/m^3 [1], [26] (see Figure 4.1.) This effect will be less for foamed slag concrete [15]. As the density of concrete is dependent upon the mix proportions, an increase in cement content of 100 kg/m^3 can increase density by about 50 kg/m^3 [7]. The inclusion of entrained air usually allows reduction in fine aggregate and free water contents but requires some increase in cement content. These changes result in a decrease in density equivalent to the volume of entrained air (i.e. about 90 kg/m^3) [7]. The effects of admixtures are marginal.

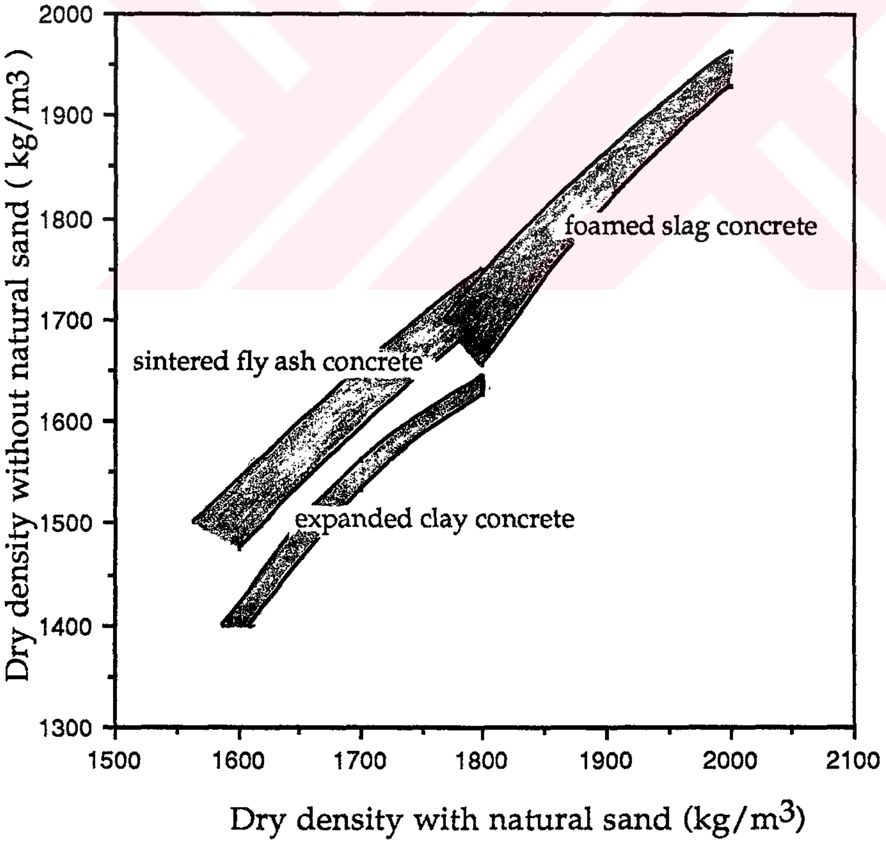

FIGURE 4.1. Dry density of LWACs of equal compressive strength with and without natural sand [15].

4.3. Compressive Strength

Compressive strength is another significant parameter of structural LWAC. Today satisfactory levels of compressive strength can be obtained with manufactured LWACs [4], [31], [34], [35], [36], [37], [38]. Even high strength concretes of 100 MPa [39] with a corresponding density of 1865 kg/m^3 were achieved. Design strengths of 20 to 35 MPa are common in the USA and in Europe [1], [4], [9], [37].

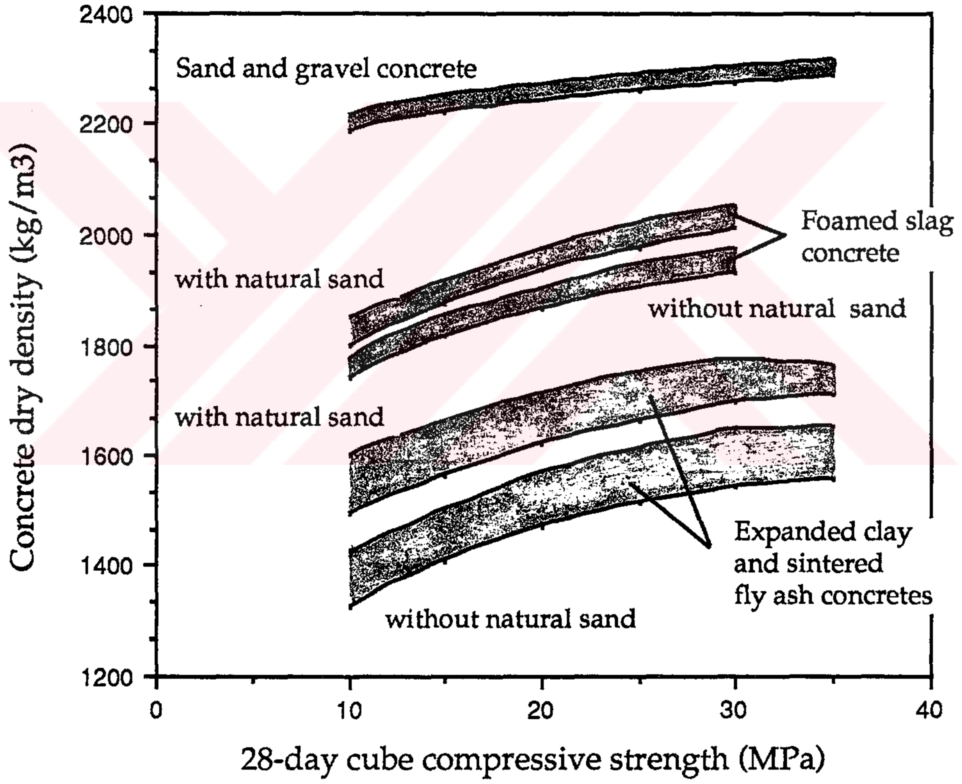

FIGURE 4.2. Relationship between compressive strength and dry density of LWACs [15].

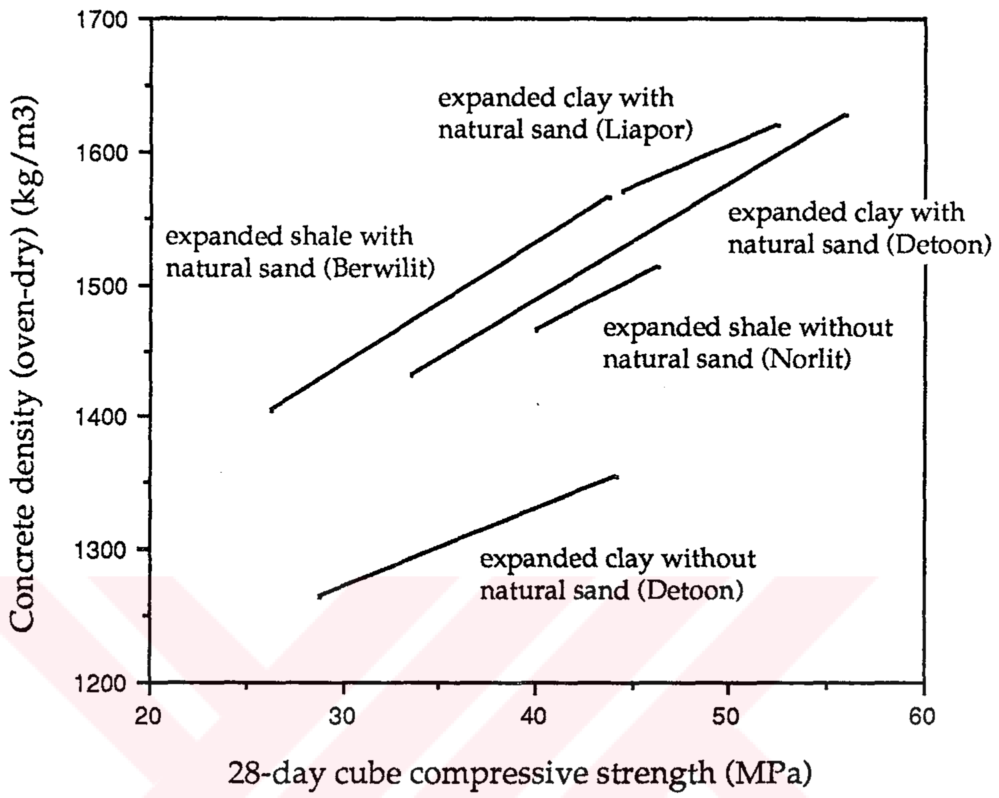

FIGURE 4.3. Relationship between the compressive strength and dry density of LWAC containing expanded clay and expanded shale aggregates [9].

It is the coarse aggregate that is of prime importance in concrete strength. Weaker particles require stronger mortars, and thus higher cement contents are required. The strength ceiling can also be increased at the same cement content and slump by reducing the maximum size of the coarse aggregate. The compressive strength of LWAC is usually related to cement content at a given slump rather than water/cement ratio [1]. The actual free water/cement ratio is similar to those experienced by ordinary concrete; however, the extra water absorbed by the aggregates may sometimes be confusing. In any case the adoption of water/cement ratio while helpful in laboratory is not practicable in construction. The strength is therefore related to cement content and workability [7].

The sand replacement of fine aggregates, while increasing the density, has a beneficiary effect on compressive strength [26], [40]. In general it is observed that increasing density also increases the compressive strength of LWAC for any particular type of LWA. (See Figure 4.2 and 4.3.) The curing regimes for LWACs also have a significant effect on the strength development and these effects are similar to what occurs in NWC [38].

4.4. Cement Content

As mentioned before, cement and water content required for a particular strength and slump has a very important effect on LWAC properties. However, because of the high water absorptivity of LWAs, the mix proportions are not expressed in the usual water/cement ratio but in terms of cement content at a particular slump. Table 4.1 gives the relationship between compressive strength and cement content. When the strength ceiling is reached, an increase in cement content would bring no commensurate increase in concrete strength.

TABLE 4.1. Approximate relationship between average compressive strength and cement content [1].

Compressive strength (MPa)	Cement content (kg/m^3)	
	All-lightweight	Sand-lightweight
17.24	237–303	237–303
20.68	261–332	249–332
27.58	314–392	291–392
34.47	374–445	356–445
41.37	439–498	415–498

4.5. Tensile Strength

Tensile strength of concrete is another important parameter as some structural properties of reinforced concrete such as shear resistance, anchorage and bond strength, and resistance against cracking depend mainly on the tensile strength. But it is difficult to determine it directly so that splitting tensile strength and flexural tensile strength (modulus of rupture) are used to estimate tensile strength on the knowledge [9], [40] that there is a relationship in between. When considering tensile strength main differences between LWAC and NWC arise from [7]:

- the fracture path in LWAC going through rather than around the aggregate particles;
- the higher total water content of LWAC. For drying concrete greater moisture gradients occur which can cause marked reduction in tensile strength.

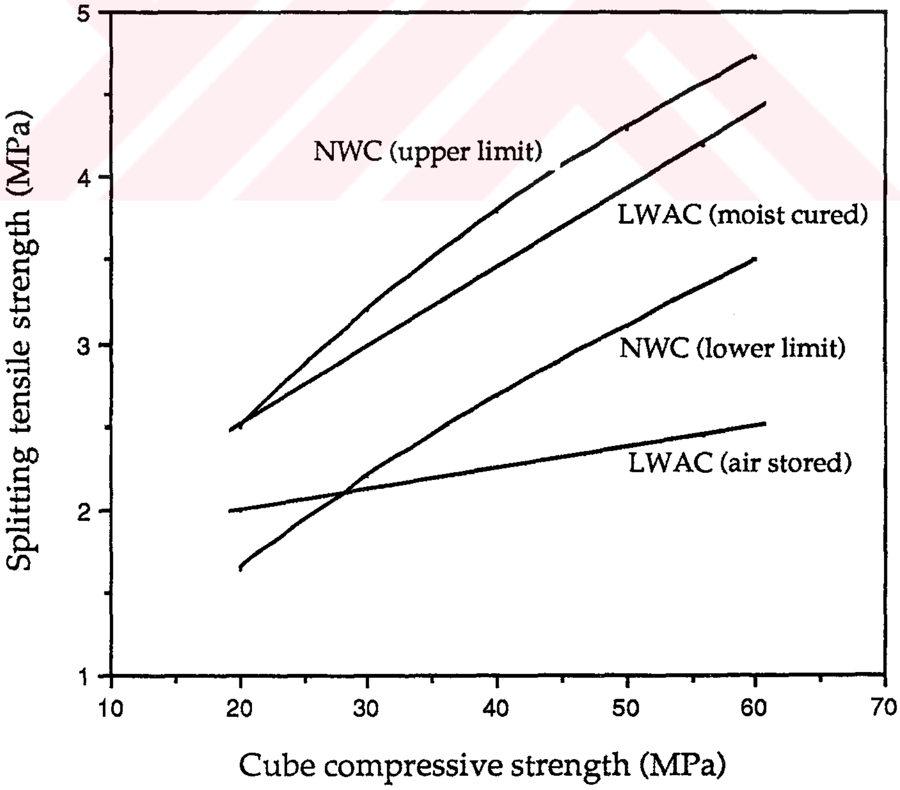

FIGURE 4.4. Relationship between tensile strength and cube compressive strength [1], [9], [46].

The tensile strength of moist cured LWACs is related mainly with compressive strength [41]. It is indicated [15], [34], [41] that in general the modulus of rupture and the splitting tensile strength of LWACs tend to be of the same order as that obtained with NWC having the same compressive strength. For a given compressive strength the splitting strength depends mainly on the aggregate type used and then on the curing method [9]. For air-dried LWAC, tensile strength is lower than that of moist cured [41], [42], [38].

Test results [43], [44] have shown that replacement of lightweight fines by natural sand has no effect if the specimens are moist cured but increases splitting strength if the specimens are air-dried. Test specimens [45] with higher moisture content had higher modulus of rupture than those with lower moisture content.

4.6. Modulus of Elasticity

The moduli of elasticity of LWA particles are lower than those of most gravels and crushed rocks [7]. This fact, together with the need for higher cement contents, results in greater overall deformation [7], [39]. Thus, for the same compressive strength, the modulus of elasticity of structural LWAC is considerably lower than that of NWC [15], [34], [39], [47]. Generally the modulus of elasticity for LWAC is considered to vary between 1/2 and 3/4 of that for NWC [1].

Modulus of elasticity of structural LWAC increases with compressive strength and density of concrete [15]. It was also suggested that the basic difference between LWAC and NWC was in the form of the stress/strain relation; this is best represented for LWAC by a parabola limited to the maximum strain value without the additional rectangle as is usual in NWC [47].

Although some expressions are given in several specifications, for more precise values tests on concrete will need to be conducted.

4.7. Poisson's Ratio

Poisson's ratio changes only slightly with age, strength or aggregate used [1]. Tests by Schideler [34] indicated that static values of Poisson's ratio for LWAC and NWC were approximately equal while values determined by the dynamic method were greater for NWC than for LWAC. Average values are given in Table 4.2.

TABLE 4.2. Average values of Poisson's ratio for LWAC and NWC [34].

Concrete	Condition	Static	Dynamic
Lightweight	wet	0.20	0.22
	dry	0.19	0.18
Sand and gravel	wet	0.20	0.23
	dry	0.20	0.21

4.8. Creep and Drying Shrinkage

Creep and shrinkage are two related phenomena of concrete. Both are affected by many factors [1] such as : type and gradation of aggregate, type of cement, total and free water contents of the mix, amount of entrained air, magnitude of stress, method of curing, size of specimen, and environmental conditions.

Laboratory tests almost invariably show that LWAC has significantly greater creep and shrinkage than NWC [7] in similar conditions. However, further research [47], [48] has shown that full-scale structural elements should have much reduced creep and shrinkage in an external environment.

As the density and strength of LWAC increases, it has been shown [1], [15], [34], [47], [49] that both creep and drying shrinkage decrease considerably. Creep may also be significantly reduced by low-pressure curing and very greatly reduced by high-pressure steam curing. Replacement of lightweight fines by natural sand usually reduces shrinkage of LWAC [26], [43], [49]. The reinforcement prestressing loss due to creep and shrinkage in LWAC structural design is somewhat greater than those in NWC [49].

4.9. Durability

Durability expresses the property of concrete to remain intact during its effective life without significant change in its characteristics.

Resistance of LWAC against freezing and thawing, and salt scaling is not less than that of NWC [1], [37], [49]. Tests on LWAC [47], [50] have shown that air entrainment provides a higher degree of durability. Yet many LWACs were found to be durable even without air entrainment, if dry aggregate was used [9], [47], [38]. This can be attributed to the porosity of the aggregate particles, which has a similar effect to entrained air voids. This effect depends on the absorption properties of the aggregates and can not be relied if the aggregate contains much water. The durability of LWAC is improved at higher strengths (lower water/cement ratio) and many LWACs can perform equivalent to or better than NWCs [1]. The duration of freezing appears to have no significant effect on the concrete durability [38]. The following cases are the real evidence for the durability of LWAC against freezing, thawing, and salt environments:

- LWAC has shown satisfactory performance in Arctic conditions [38].
- The reinforcement of the LWAC tanker "Selma", the biggest concrete ship ever built, showed no signs of corrosion when examined 34 years after casting in the USA at the end of World War I. The concrete was also in excellent condition [37].
- The more than 100 m long LWAC cantilever arm of the ski-flying platform in the Bavarian Alps in an altitude of higher than 1000 m did not show any changes after eight winters [5].

For alkali-aggregate reaction, as most LWAs are manufactured at very high temperatures, they do not react detrimentally with water nor with alkalis from the cement. The chemical stability of all types of concrete are governed mainly by the nature and quality of the cement. Although the LWA particles are porous, thereby less resistant against penetration of harmful materials, the cement paste in LWAC is usually stronger and denser than that in NWC. Therefore, in general, LWAC is as resistant to chemical attack as ordinary concrete [7], [9], [34].

The abrasion resistance of LWAC is poorer than that of NWC, after the surface layer has been abraded [7], [9]. It also varies with compressive strength in a manner similar to NWC. In practice, sintered pulverised-fuel ash concrete has been used in multistory car park construction, and there were no signs of wear even after 11 years service. However, if surfaces are likely to be subjected to heavy wear, an abrasion-resistant top layer may be required.

4.10. Bond Between Concrete and Reinforcement

The nature of bond between LWAC and steel is likely to be similar to that of NWC [7]. In fact, field experience in the USA has indicated satisfactory behavior of LWAC with respect to bond [1].

Yet there is some doubt on reliability of bond between steel and LWAC [7], [9], [15], [47] which is mainly because of the fact that test results cannot be directly applied in practice. Higher water content and weaker aggregate particles are supposed to [7] have a reduced effect on the bond in LWAC. The bond strength for deformed bars can therefore be lower; however, when the strength of the matrix exceeds that of the concrete, the bond strength of deformed bars in LWAC is often higher than in NWC [9], [15]. For round bars, on the other hand, bond strength should mainly depend on the strength of the mortar mix [9].

With lower cement content mixes and especially with weaker coarse aggregates the bond strength is reduced with respect to NWC, but it may well be that bond behavior is similar when higher cement contents and stronger LWAs are used [47]. Schideler [51] also considers that the bond strength of

LWAC is very good and that at equal compressive strengths, comparable bond strengths should be expected.

In any case, to resist splitting due to local anchorage forces, adequate transverse reinforcement must be provided in the anchorage zone [1], [7], [9].

4.11. Water Absorption and Permeability

Water absorption of LWACs are generally higher than that of typical NWC [1], [9]; the amount depending [7], [47] on the quality of the cement paste, the porosity of the aggregate, the head of water and the duration of contact. Comparison between concretes of different densities should be made on a volume basis [7], [47].

It has been proved by research [26], [47] that there is no relation between water absorption and durability of concrete.

LWAC is not necessarily more permeable than NWC [7], [9]. The rate of movement of liquid through concrete is very largely related to the paste and to the presence of microcracking and fissures [7]. The test carried out at the US Naval Construction Center on a LWAC sphere proved that LWAC has the same performance as that of NWC. It also showed that although the aggregates were quite permeable under pressure, the concrete was not; the surrounding paste minimized the permeability [47]. Another test result [52] indicated that the coefficient of permeability of both NWC and LWAC were insensitive to the concrete stress level up to the point where extensive interconnection of microcracks occurs. Rapid increases in permeability occured at approximately 54 to 62% of the ultimate strength for NWC and 72 to 83% of the ultimate strength for structural LWAC. Above these load levels the flow rates increased rapidly.

Resistance of LWACs against water vapour diffusion is generally lower than that of NWC [9].

4.12. Thermal Properties

In general, LWACs have better thermal properties than NWC.

The thermal conductivity k (or λ) is the rate of heat flow through unit thickness of material. It is obvious that LWACs have lower k-values. The primary reason is the lower density because decreasing density (increasing amount of pores) also decreases thermal conductivity (Figure 4.5). The moisture content is also effective; increased moisture content of hardened concrete will increase its conductivity. The lower thermal conductivity of LWAC may cause bigger differences between exposed and internal surfaces but this do not cause any significant problems as the differential strains do not exceed permissible limits [7].

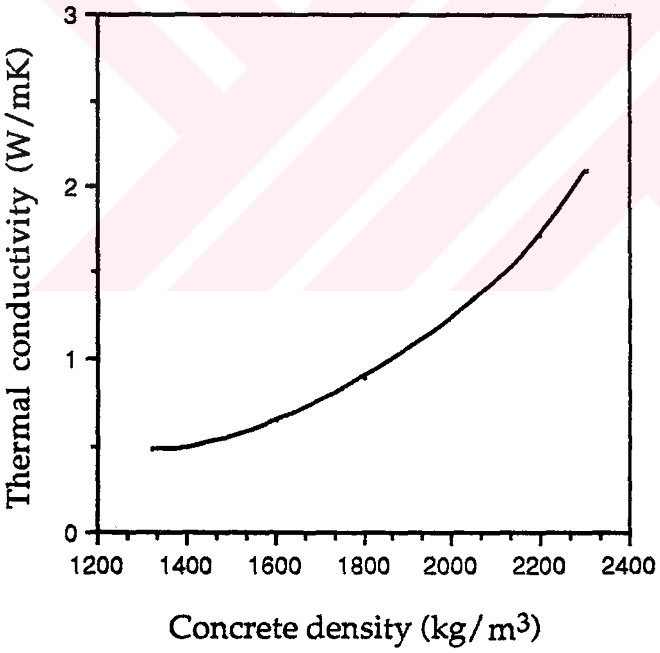

FIGURE 4.5. Relationship between the density of concrete and its thermal conductivity [1].

Coefficients of thermal expansion for LWACs are 7 to 11×10^{-6} mm/mm/C while those of sand-gravel concrete are 9 to 13×10^{-6} mm/mm/C [1], generally.

The specific heat of oven-dry LWACs does not vary greatly, nor does it differ much from that of ordinary concrete [9].

With the usual higher cement content, the LWAC will exhibit a higher temperature rise. Yet the effects of this rise are compensated for by the lower E-value, the higher tensile strain capacity, and the lower coefficient of thermal expansion. The net result has been found to be a significant reduction in the risk of cracking [7].

At cryogenic temperatures LWAC has an additional advantage over ordinary concrete associated with its better thermal performance, its lower modulus of elasticity, and higher water content [7].

4.13. Fire Resistance

LWAC is inherently more resistant to fires and is a very suitable material for construction where high fire rating is required. It provides a better fire performance than NWC in general [1], [2], [7], [53]. This is evidenced by the reduced cover requirements in American [54] and British [27] standards. This superiority results mainly from the following factors:

- Physical and chemical stability of the aggregates at high temperatures as they have undergone various heating processes during manufacture.
- Lower coefficient of thermal expansion and lower elastic modulus of the aggregates reducing the tendency to form internal cracks.
- Lower thermal conductivity and diffusivity reducing the rate of heat penetration.

For LWAC there is no appreciable reduction in compressive strength up to a temperature of about 500°C. For NWC the corresponding temperature is 300°C. With higher temperatures the strength decreases, and at 800°C it retains about 40% of its original strength, the corresponding value for NWC is about 20% [7].

4.14. Others

(A) Resistance to fatigue loading. There is evidence [55], [45] to show that, in compression, LWAC and NWC test specimens behave similarly under cyclic stressing, down to a density of about 1500 kg/m^3. However, the strength of LWAC under sustained loading of indefinite duration varies between 70 and 75% of the short term strength, whereas for NWC it is about 80% [9]. The moisture content has a considerable influence on the fatigue strength and endurance limit of LWAC. The lower the moisture content, the lower is the maximum flexural fatigue strength and the higher is the fatigue endurance limit [45].

(B) Ultimate strain. The ultimate compressive strain of most LWACs may be somewhat greater than the value of 0,003 which is assumed for design purposes [1].

(C) Protection against corrosion of the reinforcement. Experience shows that under normal conditions well compacted concrete can effectively protect embedded reinforcement against corrosion, provided that the concrete cover exceeds a certain minimum thickness [9]. There is little difference between LWAC and NWC for comparable conditions [7].

(D) Acoustic properties. Insulation of airborne sound transmission in dense, solid, homogeneous walls and floors is primarily governed by their mass. On this basis the thickness of a LWAC wall would have to be greater than one made with ordinary concrete. However, there are exceptions where experimental evidence has shown better insulation for LWAC than would be expected [7], [9].

5. ECONOMICS

5.1. Introduction

Although structural LWAC has been used throughout the world for about 60 years, the economics of using this material is still disputable. In order to judge the economy of a construction material it must be compared with alternative materials. However, cost comparisons of different forms of construction are obviously difficult to evaluate on a reliable basis. Besides, the conclusions will be open to criticism as there are many factors affecting the cost. Aggregate prices vary from place to place. The cost of concrete depends on cement content, type of aggregate, and the required density. Furthermore making two separate designs for comparison is time consuming and expensive.

These factors have resulted in limited inquiry into the economics of LWAC. While the advantages of using LWAs in construction are many and the disadvantages few, the cost effectiveness of many of these points remained unnoticed to both the building investor and the consultant engineer [56]. The lack of reliable information resulted in the low usage of LWAs. Even though the economical advantages of structural LWAC have been presented in some literature [8], [9], [31], [57], [53] the proportion of output used in construction is still lower than expected [2], [57]. Fortunately, relatively high values of time-honoured usage in the USA [1], [6], [18] and Germany [37] gives clues about the economy of this material.

Manufactured LWAs are almost always more expensive than natural aggregates. This has inevitably induced the widespread belief that structural LWAC must be more expensive in any kind of construction [56], [58]. Little [31], Bombard [37], Skoyles [56], Bender [59] and some others insist that although the unit price of LWAC is higher than NWC, the total cost of the concrete structure may be justifiable, if not lower. Bender [59] notes that the engineers in the USA hesitate to use LWAC in structures not because of the economy which is evident, but because of their suspicion of its durability.

The most important economical advantage of structural LWAC is the reduced weight when compared with ordinary concrete. For intermediate concrete strengths it is possible to make a LWAC having the same strength as NWC of similar mix proportions. The "specific strength" is increased since the density is lower. This is important in structural members with large spans and great heights; e.g. bridges, industrial buildings, and aircraft hangars.

The case for LWAC being cheaper than NWC lies [58] not only in the costs of materials but also in those of time and labour. This is because the production cycle for LWAC, given good site management, can be significantly shorter.

Generally the advantages other than reduced weight, such as thermal insulation and fire-resistance, are not considered because they are not so easily quantifiable [37], [56], [57].

The ease of adaptability when compared with any other construction material would be in favour of structural LWAC. The reason is that the production and handling are similar to those of ordinary concrete. Some extra care, and experience over time, will be adequate to produce and handle it with the existing workmen and the equipment currently being employed in concrete construction. Specially trained teams, as in steel construction, are not required.

The major cost element for all types of aggregates is the cost of transportation from the point of extraction or production to the point of use. This is particularly important for LWAs because their points of production are not so widespread as the points of extraction of natural aggregates.

5.2. Advantages Due to Reduced Weight

5.2.1. General

The reduced weight of structural LWAC is said to ensure, in an average case, a total saving of the order of 5 to 7% of the price of the concrete structure and often about 2% of the total cost of the building [9]. The savings may reach values of 10 to 15% where the high specific strength of LWAC is fully employed [56].

In highly seismic zones reduction of dead load becomes more significant. The lateral and horizontal forces acting upon a structure during earthquake motions are directly proportional to the weight of that structure. These forces will be reduced by the lower dead weight. From the point of seismic behavior, properly detailed columns made with structural LWAC performed as well as columns made with NWC when subjected to moment reversals [60]. A large number of multistory buildings as well as bridge structures effectively utilized structural LWAC in areas subject to earthquakes principally along the West Coast of the USA and in those countries bordering the Pacific Ocean Rim [1].

A case study[1] [58] made in 1983 in the UK proved the falsity of the view that LWAC is necessarily more costly than NWC construction. It showed that LWAC represents "value for money" with a saving of 0,2% in the total cost of the building only by the advantages provided by the reduced weight. Another cost model based on a 13-story block using sintered pulverised-fuel ash aggregate demonstrated that although the aggregate was more expensive (costing 15% more per m^3), a saving of 6% was made on the total costs for labour and material [56].

In two old buildings in London, not only were the existing floors replaced by new lightweight ones but by changing the floor heights, two additional floors were obtained. This solution was possible because the lighter

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[1] Refer to APPENDIX F for a brief summary and results.

superstructure did not impose any additional weight on the existing foundations [56].

Structural LWAC can be a favourable alternative when it is essential to produce a fairly light structure because of the complication of the architectural design [61].

5.2.2. Saving in Dimensions and Reinforcement

One of the essential advantages of reduced weight is the saving on member dimensions and reinforcement in the superstructure. For practical purposes we can make a simple evaluation in order to have an idea about the order of reduction in the dead load of the structure. Let,

γ_{NWC} = density of NWC

γ_{LWAC} = density of LWAC

D = dead load
L = live load
T = D + L = total load

then the per cent saving in dead load by LWAC is

$$\frac{\gamma_{NWC} - \gamma_{LWAC}}{\gamma_{NWC}} \cdot 100 \qquad (5.1)$$

Considering the proportion of the dead load to the total load, [D/(D+L)], the reduction in total load is

$$\frac{\gamma_{NWC}-\gamma_{LWAC}}{\gamma_{NWC}}\cdot\frac{D}{D+L}\cdot 100=(1-a)\left(\frac{1}{1+b}\right)\cdot 100=\frac{1-a}{1+b}\cdot 100 \qquad (5.2)$$

where $a=\frac{\gamma_{LWAC}}{\gamma_{NWC}}$ and $b=\frac{L}{D}$

The per cent savings in total load are plotted against the ratios "a" and "b" in Figure 5.1 and Figure 5.2 respectively. It is seen that the saving increases with decreasing ratios of both "density of LWAC to density of NWC" and "live load to dead load".

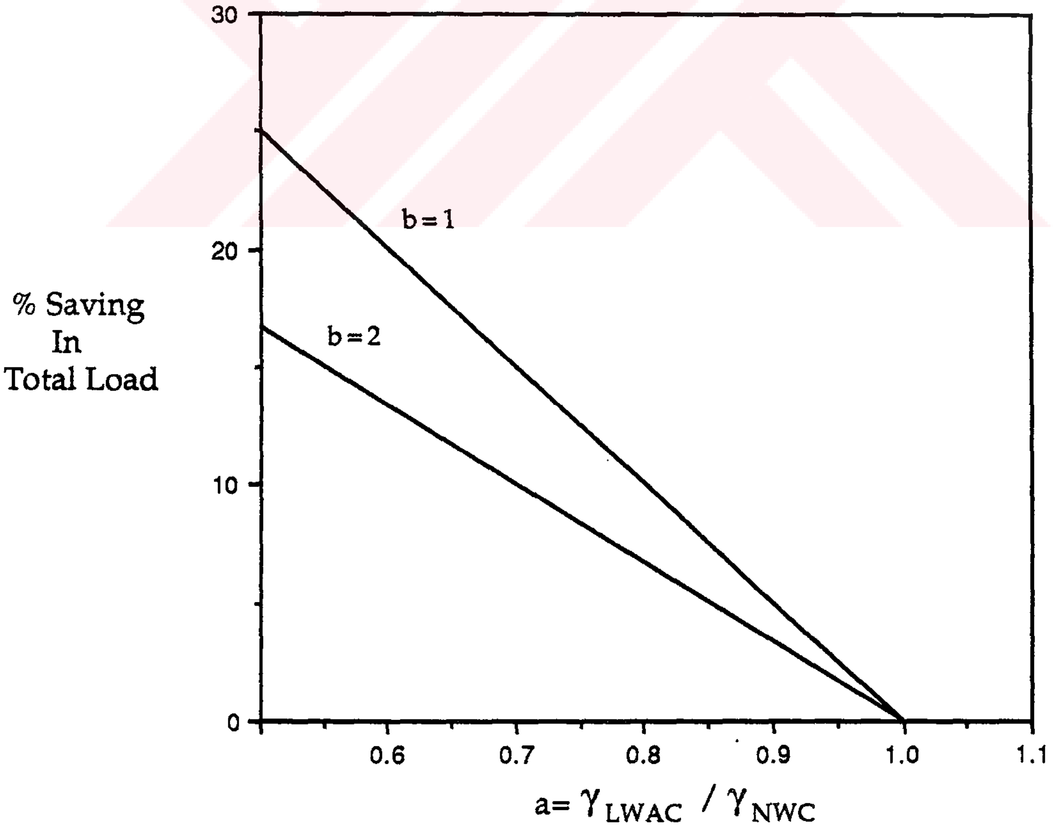

FIGURE 5.1. Relationship between density ratio (a) and per cent saving in total load.

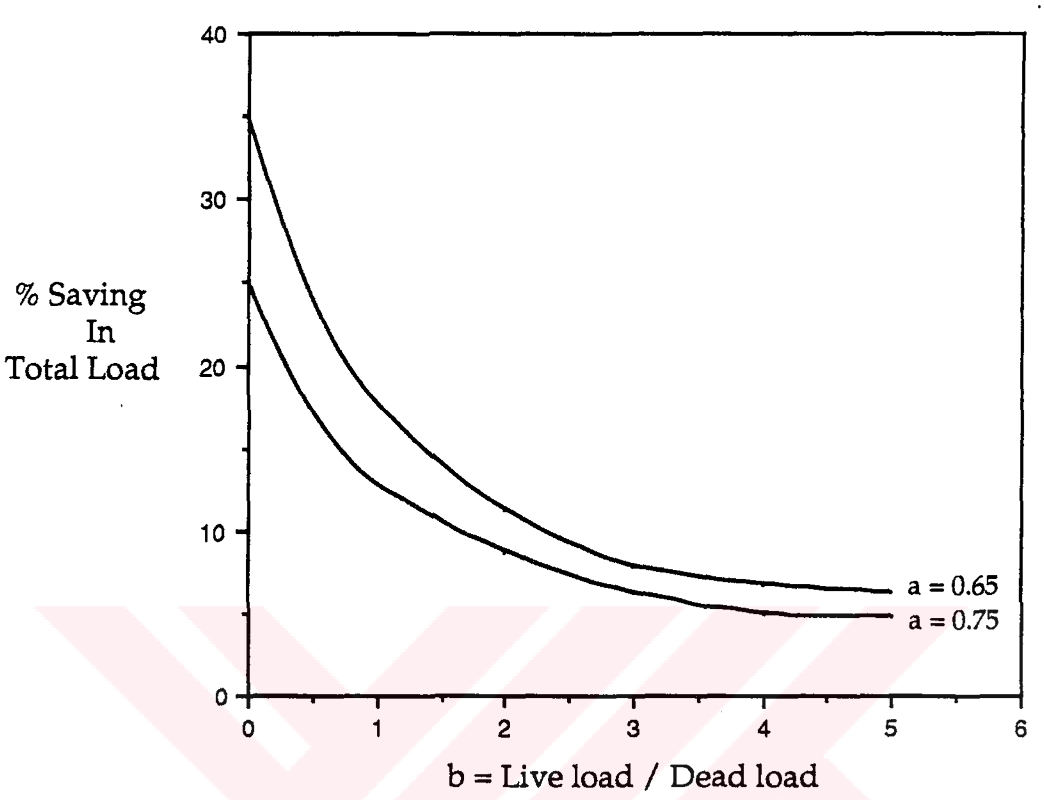

FIGURE 5.2. Relationship between load ratio (b) and per cent saving in total load .

Since the slabs constitute about 70% of the total concrete volume of a building, the use of LWAC in slabs can give significant load savings. The results of a comparative cost study[1] [57] showed that, when compared with NWC, the cost of LWAC in floor slabs could be as much as 14% cheaper, and at worst 5% dearer than NWC when a tower crane is used. When using a mechanical hoist, the figures would be from 1% cheaper to 5% dearer. These values give a general idea about the economics of the two materials.

Another comparative study [53] indicated that LWAC slabs were more cost effective and different floor systems allowed savings of about 4%.

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[1] Refer to APPENDIX G for a brief summary and results.

A simpler inspection can be made after the member dimensions and reinforcement of a NWC structure are determined. Bending moment is directly proportional to the load and reinforcement can be assumed to be proportional to bending moments (provided that the dimensions are fixed.) Thereupon, the savings in Figure 5.1 and Figure 5.2 would reflect the saving in reinforcement. Otherwise, if the amount of reinforcement is kept constant, the reduced load will decrease the effective depth. It is obvious that the simultaneous saving in both the dimensions and reinforcement will exceed any one of the values.

As the volume of columns generally do not exceed 10% of the total concrete volume in a structure [9], it is recommended to use NWC in columns. This is more economical because the weight saving is small and LWAC is more expensive. Sometimes, the columns are designed with NWC in order to minimize long term creep and shortening [53]. There are many examples [37], [57], [61] of buildings having LWAC floor slabs with NWC or even steel frames. In some cases where the building is relatively large and the ground conditions are poor, the marginal weight saving of the frame is taken into consideration; so the full frame is constructed of LWAC. "One Shell Plaza Tower" in Houston, USA is a typical example.

The lighter weight and reduced dimensions would give another saving in formwork and scaffolding. This saving would be up to 20–25% [9].

5.2.3. Saving on Foundation Costs

Another essential advantage of reduced weight is the saving on foundation costs. This is because of the 20 to 30% lighter dead load of the superstructure imposed on foundations [59], [53]. The real savings would be more than this because the dead load of the substructure will be reduced at the same time.

These savings can be observed quantitatively in pile and strip foundations. In pile foundations, either the number of piles required would decrease, or pile dimensions would be smaller. This is shown in Figure 5.3 for Dutch conditions [9]. In strip foundations, the width and depth of members would decrease. With the reduced material costs, further savings are guaranteed in formwork.

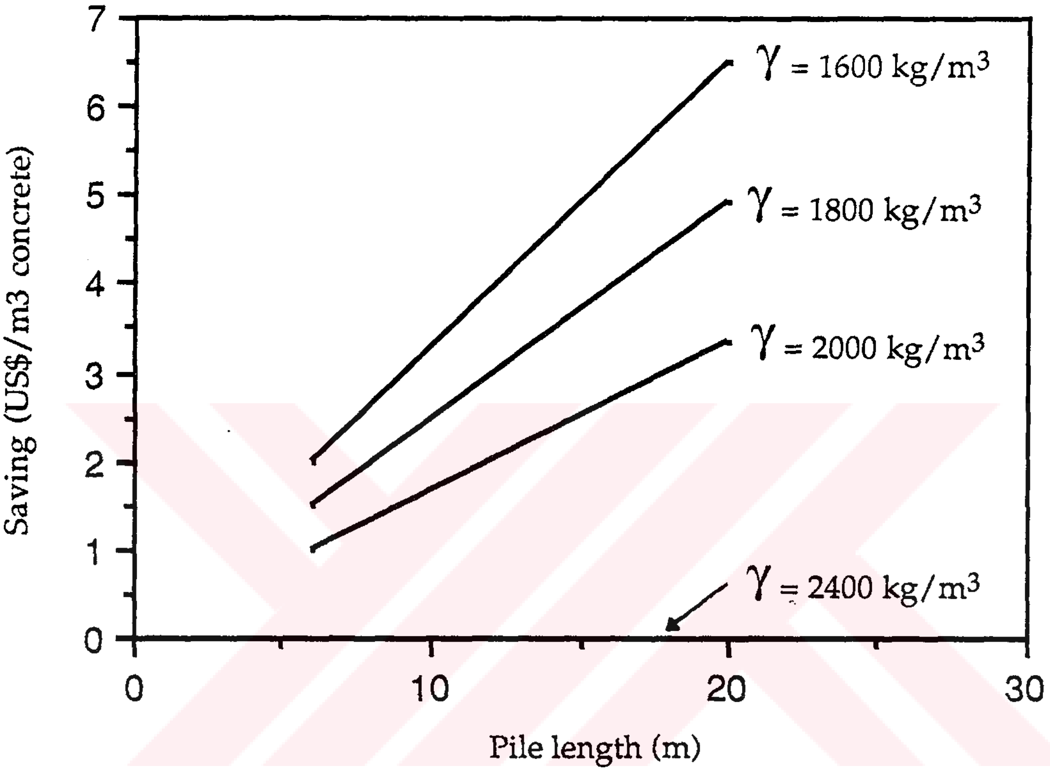

FIGURE 5.3. Saving in pile cost versus the pile length and the density of the concrete used for the superstructure [9].

The degree of savings varies with the site conditions. With low permissible soil stresses the savings are significant, while with high values (about more than 3 kg/cm^2) they become negligible [9].

Two specific examples are:

(A) A case study [58] made by the Concrete Society (UK) concluded that the reduced dead load required shorter piles with savings of 5.8% for solid slab construction and 9.8% for waffle slab construction. Overall, the substructure for the LWAC alternative was 2.4% cheaper than that for NWC in solid slabs, and 3.8% cheaper for waffle slab construction.

(B) A comparison of the calculated costs for a 12-story building designed both in NWC (2400 kg/m^3) and LWAC (1750 kg/m^3) concluded a saving of 24% for LWAC in its pile foundations. Costs in DM per m^2 floor surfaces were 15.92 for NWC and 12.04 for LWAC.

5.2.4. Saving in Costs of Transportation and Erection

One of the factors affecting the cost of concrete is the price of the aggregates which is governed mainly by the cost of transportation. The reduced unit weight of LWAs will give an advantage here. The theoretical saving will be in the order of the ratio of unit weights of LWAs and dense aggregates; however, in practice, this is limited by the volume capacity of the trucks. In the case of cheaper sea transportation, the saving would be relatively higher. The density of fresh NWC is 1.25 to 1.50 times that of structural LWAC [9]. Depending on this ratio, a further saving may be gained.

In precast concrete structures, there is economy in being able to cast, transport, and erect larger pieces, thereby saving on the total number of pieces. Bender [65] made a detailed analysis of a bridge comparing estimates using lightweight and normal weight concrete. The estimate was overwhelming in favour of LWAC. The structure was a precast segmental post-tensioned box girder bridge with several spans of 90.5 m and 46.6 m, and a constant depth of 4 m. Although the aggregates were more expensive and the cost of production equipment was higher due to larger forms for larger segments, all other items were less for LWAC because the larger pieces resulted in a significant reduction in the number of pieces: from 558 to 398. Erection of 558 NWC pieces required 260 days while the larger 398 pieces required 199 days. The overall cost of the superstructure was reduced by 18% and that of the substructure by 6%, giving a total saving of nearly 2million US$. A strong advantage was evident in the project[1].

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[1] Refer to APPENDIX H for details.

5.3. Other Economical Advantages

The economical advantages of LWAC other than its reduced weight can be summarized as follows:

- superior fire-resistance [7], [62] provided by the aggregate particles;
- faster reinstatement in the event of fire [58];
- better thermal insulation than NWC;

TABLE 5.1. Typical thermal insulation values for LWAC and NWC [63].

	Density (kg/m^3)	Thermal conductivity (W/m°C)
LWAC	1600	0.81
NWC	2300	1.75

- water impermeability; this allowed structural LWAC to be used in marine structures and ships [8].
- greater ease of operation on site [56];
- absence of expansion joints, which enables large areas to be poured at one time [56], [57];
- convenience for making fixings due to the ease of cutting and drilling [56];
- savings in the application of plaster and other finishes [57];
- labour saving potential compared with other methods of lightweight floor construction; this is illustrated by the higher proportion of use in the USA [57].

5.4. The Environmental Factor

There are large amounts of waste materials such as pulverized-fuel ash, blast-furnace slag and colliery shale in almost all industrialized countries. The waste stocks are increasing rapidly while at the same time the deposits of natural aggregates are decreasing. Much of these waste materials are potentially recyclable for use as raw material to make LWA and other products. Unfortunately in practice a very small proportion of these materials are utilized. The recycling of such wastes into LWAs would reduce the costs of disposal and decrease our reliance on natural materials. This would not cause any other environmental problem. In this way the industries producing wastes would be able to earn money, instead of what they are doing currently, paying for the disposal of waste materials.

In addition to industrial wastes, naturally occuring clays and shales are also used for the manufacture of LWAs. It is unlikely [64], however, that the use of these clays and shales will increase significantly due to the increasing interest in recycling waste products.

5.5. Disadvantages

- The most important drawback of LWAC is the higher unit price compared to NWC. The price of LWAs is generally twice as much as that of natural sand and gravel.
- Production requires a high capital cost.
- Increased cover to improve abrasion resistance in externally exposed concrete may be required [57].
- Thicker floor slabs may be required where heavy live load has to be carried [57].
- Shear strength is lower [57].
- Larger areas and an extra silo for LWAs is needed in ready mixed concrete plants [9], [56].
- Longer mixing times are required [9].
- Possible prestress losses are greater than NWC [9], [49].
- Lower tensile strength may require increased shear reinforcement [7].

- Lack of adequate experience may cause problems at the beginning.
- Since LWAs are quite irregular in shape, they generally require admixtures, and sometimes more cement to have a desirable workability [56].
- Greater care and supervision during production is required [9].

5.6. Specific Applications

Up to here, the economy of using LWAC in construction has been considered. In the following sections (5.6.1–5.6.9) the types of structures which are likely to benefit most from using LWAC, i.e. showing its feasibility, will be reviewed.

5.6.1 Bridges and Bridge Decks

Structural LWAC has been used widely and successfully for bridge construction for over 60 years. There are now about 200 concrete and composite bridges containing LWAs in the USA and Canada, about 100 in the former USSR, and many in Western Europe [6]. The types range from simple reinforced concrete foot bridges to long-span post-tensioned segmental box girder bridges. Weight reduction of 25 to 30% on the superstructure can be achieved with consequent savings of reinforcing and prestressing steel, and on piers and foundations. Overall cost savings of 10% or more are possible even though the cost of LWAs are higher [6].

LWAC has economical advantages for concrete bridges having T–beam or box sections with spans exceeding 30 m, where dead load plays a dominant role in design [9]. For slab bridges, spans of 15 to 20 m would be economical. Typical savings in weight are shown in Figure 5.4.

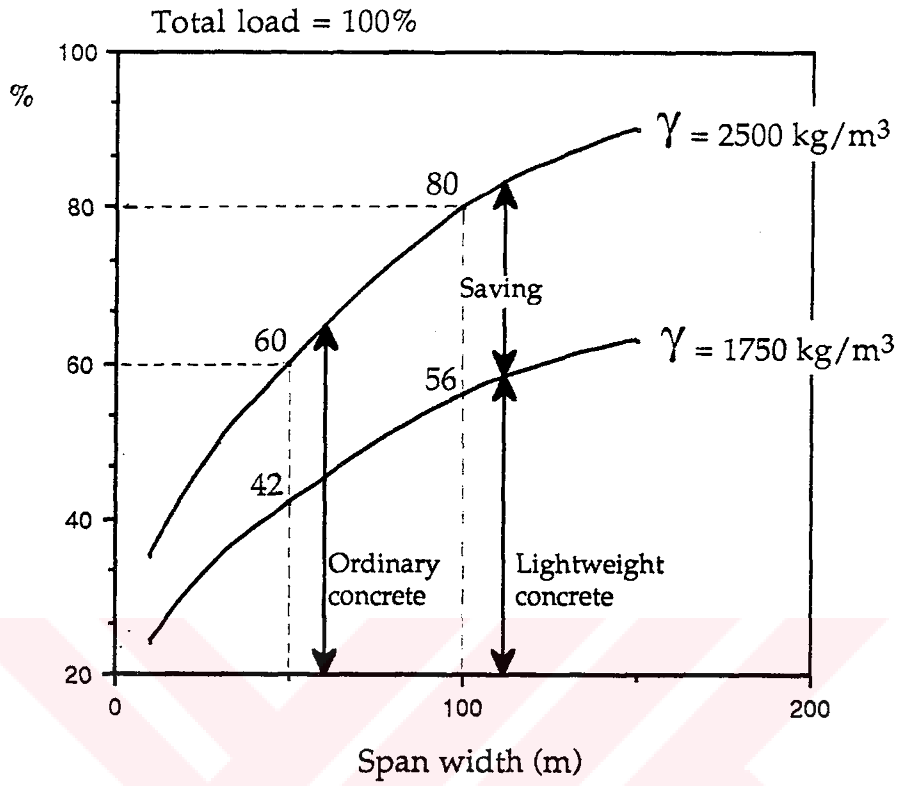

FIGURE 5.4. Dead load to live load ratios for bridges constructed with NWC and LWAC [9].

American experience, accumulated in more than 60 years, is summarized [6] as follows;

- Reduced density has been advantageous where foundations have been difficult, where space has been congested, or for special bridges (lift span and floating spans).
- Existing bridge support systems have been retained when decks have been replaced with wider LWAC ones.
- By combining LWAC deck slabs with structural steel support members, significant savings have been achieved.
- Long haulage distances favour precast prestressed LWAC beams.
- LWAC is best competitive in post-tensioned segmental cantilever box sections.

TABLE 5.2. Typical LWAC bridges in the world [6], [47].

Cons Date	NAME AND LOCATION	TYPE OF BRIDGE	SPAN (m)	USAGE OF LWAC	REMARKS
1976	Napa River US	post–tensioned box girder	max.76 min.50	beams & slab	sand–lightweight, 31 MPa at high seismic zone aesthetic award winner
1979	Parrots Ferry US	winged box girder	200	beams & slab	longest LWAC bridge, 42 MPa weight red.20%, cost 10% saved
	Oakland Bay, San Francisco	suspension bridge		upper deck	sand–lightweight, 21 MPa $3M saving
1950	Narrows, US			deck	$320000 saved by LWAC deck
1977	River Rhine, Cologne, D	post–tensioned segmental	184	beams & deck slab	40 MPa, 1900 kg/m^3 longest Lwac bridge in Germany
1970	Fühlingen, Cologne, D	post–tensioned segmental, beam and slab	136 (lw 84)	beams & deck slab	25 MPa, 1800 kg/m^3 50% smaller moment in midspan 12% smaller moment at supports
1971	Removable Road bridges Münich, D	simple support precast beam element	40 & 25	beams & deck slab	25 MPa, 1900 kg/m^3
1967	Wiesbaden,D	arch bridge	93	whole	39 MPa
1968	Osnabrück,D	post-ten.,segm	85		cantilever
1972	Bickensteg, D	cable–stayed	69.5	girders	drop–in–girder bridge
1972	Dukenburgse Nijmegen, NL	continuous box girder	37.4 & 112.2		sand–lightweight 38.5 MPa, 1750 kg/m^3
1968	Europoort, Rotterdam,NL	3span,prestres portal frame	30.8	beams & slab	LWAC to used reduce horizontal forces on piled foundations
70's	Zutphen, NL	prestressed	125-81	whole	built by cantilever method
70's	Arnhem, NL	2-cell, boxgirder	136.5	beams & slab	one of the longest LWAC bridges in Europe
1972	Ettelgem, Belgium	four–span cont. beam & slab	21	whole structure	first all–lw bridge in Belgium beams 47MPa, slabs 45MPa
	Belgium	preflex girders cast–in–place	26.4	deck slab	40 MPa
	Belgium	two–span cont. cast–in–place	34.2	slabs	45 MPa
60's 70's	USSR	prestressed girder	max. 33	mainly girders & slabs	25–30% weight reduction 15–18% reinforcement reduction
70's	Poland	composite prestressed	ave. 20	mainly girders & slabs	40 MPa for precast beams 25 MPa for slabs

D: Germany NL: Netherlands
B: Belgium

- Durability of well designed and produced LWAC is satisfactory; ready-mixed LWAC for in-situ work appears to be quite common.

A brief summary of the use of structural LWAC in bridges in various countries is given in Table 5.2.

5.6.2. Marine and Off-shore Structures

Structural LWAC has frequently served a role in marine construction such as in the concrete ship building programme during the two world wars. Perhaps the best known ship was the USS Selma [7], a 7500 tonne tanker with a length of 132 m and a beam of 13 m, launched in 1919 in the USA. At the end of its seagoing service life the Selma was purposely sunk. The principal findings of the inspection made were that the average compressive strength of the expanded shale concrete at 34 years was more than twice the measured 28-day value and that the reinforcement showed little deterioration even for covers as low as 16 mm [8].

During World War II, LWAC ships were again built [8]. They were up to 12,750 tonne displacement with cargo, 110 m length and 17 m in beam. Some of the floating structures (pontoons) used in Mulberry Harbour during World War II were made of LWAC [61]. Barges of various shapes and sizes were also built.

The 1970s have witnessed the arrival of the first notable LWAC floating dock in Genoa's Harbour (Italy) with overall dimensions of 342.8 m by 79 m and a lifting capacity of 100,000 tons. The concrete was made of expanded clay and natural sand yielding a density of 1870 kg/m^3 and a compressive strength at 28-days of 54 MPa [65].

The use of LWAC in marine and off-shore structures presents the designer with a much larger range of concrete properties than is possible with NWC:

- Additional buoyancy can be achieved by the lower density.
- The ratio of the dead load to the superimposed load is more advantageous.

- LWAC exhibits better crack resistance from shrinkage, creep, and thermal expansion movements [47].
- LWAC has better energy absorption characteristics from impact and cyclic loading [55].
- LWAC is easier to drill, fix into, or cut [56].

5.6.3. Industrial Buildings

Another application of LWAC is in the widespan industrial buildings. A study [66] comparing structural systems indicated that in industrial buildings use of LWAC is economical if thin shell or prestressed elements are to be used. As the area of unobstructed floor space increases, the cost differential becomes less and concrete may be less costly.

Several typical examples are:

- Factory building in Augsburg, Germany [37]. An area of 6000 m^2 is sheltered with simply supported pretensioned LWAC beams. Concrete of 1850kg/m^3 density and 40 MPa compressive strength was used.

- Aircraft Hangar in Nordholz, Germany [37]. An area of 8100 m^2 is roofed with simply supported extremely wide spanned (90 m) post-tensioned LWAC beams. Concrete of 1800 kg/m^3 density and 40 MPa compressive strength was used.

- Jumbo Aircraft Hangar for Frankfurt Airport, Germany [5], [37]. A two span (130 m each) post-tensioned LWAC suspension roof anchored at ballasted framework supports the shelter free of columns, with a service area of about 30,000 m^2. Concrete of 1800 kg/m^3 density and 25 MPa compressive strength was used.

5.6.4. Thin Shell Structures

The lower density of LWAC again proves to be economical in thin shell structures. A cost comparative study [66] determined that in almost all designs investigated, LWAC was more economical than ordinary concrete. As the spans increased and the thicknesses decreased, the savings of LWAC became more significant. For short spans, where the thickness and the amount of reinforcement were governed by the minimum requirements, costs of LWAC and NWC were approximately equal.

Several typical examples are:

- BMW Museum building in Munich, Germany [37]. This is an automobile museum with a post-tensioned LWAC shell in the form of a surface of revolution. Concrete of 1800 kg/m^3 density and 25 MPa compressive strength was used.

- Assembly Hall in the University of Illinois, USA [65]. The roof of the building comprises 24 folded plate segments in LWAC and is tied by a prestressed concrete ring beam. Its diameter is 122 m and covers an area of 11,600 m^2. Expanded shale coarse and sand aggregates were used to make a concrete of 1680 kg/m^3 density and 28 MPa cylinder compressive strength.

- St Albert's Church at Freiburg, Germany [65]. This is a space structure, circular in plan, comprising eight three-hinged portal frames in an axially symmetrical arrangement. It encloses a volume of 9800 m^3, has a diameter of 28.6 m and a height of 20 m. Sand-lightweight concrete of 1495 kg/m^3 density and 35.5 MPa cube compressive strength was used.

- Race-course Grandstand at Doncaster, UK [65]. Pretensioned vaulted roof units, 6 cm thick and cantilevering 15.24 m were cast in LWAC. Sand-lightweight concrete of 1870 kg/m^3 density and 54 MPa compressive strength was used.

5.6.5. High Rise Buildings

During the 1950s in the USA many multistory buildings were designed from the foundations up to take advantage of reduced deadweight with LWAC [1]. Examples are the 42-story Prudential Life Building in Chicago, with LWAC floors, and the 18-story Statler Hilton Hotel in Dallas, with a LWAC frame and flat plate floors.

Today the tallest LWAC building in the world is again in the USA, One Shell Plaza Tower in Houston [65]. The complete structure was executed in LWAC, and the building became commercially viable. The height of the tower is 218 m and the total covered floor area is 130,000 m^2 ; the typical floor span is 11 m. The concrete was sand-lightweight with a density of 1840 kg/m^3 and a 28-day cylinder strength of 42 MPa. Another example in the USA is the Marina City Towers [65] of Chicago with 180 m height and 39 m outside diameter. The sand-lightweight concrete had a density of 1680 kg/m^3 and a cylinder strength of 25 MPa.

Europe started challenging America in tall buildings with the construction of the BMW Administrative Building in Munich [37] completed in 1972. The four circular bays of the building are suspended from the top on a central tie. The building has a height of 100 m with LWAC floors. Sand-lightweight concrete of 1660 kg/m^3 density and 41 MPa compressive strength was used.

The most well-known buildings of the UK with LWAC floors are the National Westminster Bank Tower (183 m), the P&O Building, and the Commercial Union Building, all in London [4], [31], [65]. The whole frame of Guy's Hospital Tower (London) is also made of structural LWAC and it has a height of 134 m [2], [7].

The last example is from Australia. The Barclay's Bank Building has 23 LWAC floors. Because of time limitations, speed of construction and a flat-surface rather than a coffered one were wanted; both demands were put into reality by the use of LWAC [61].

5.6.6. Precast Construction

The use of LWAC in precast construction demands the same considerations as NWC. Larger units can be lifted for a given crane capacity and transported for a given carrying adequacy. Alternatively, lighter units allow the use smaller cranes. Larger panel sizes may reduce the number of joints required. This speeds up construction rates and reduces the cost of jointing. Drilling for fixing is quicker, easier and cheaper. External LWAC wall panels possess improved thermal insulation. LWAC wall and floor panels are more resistant to accidental loading as they are generally more resilient and absorb more energy [65] in the elastic range than NWC.

Several typical examples are:

- In many of the external wall panels for the students' residences at the University of East Anglia, Norwich [2] in the UK LWAC was used due to restricted cranage capacity.

- The C&A store at Swansea, UK consists of some 400 precast concrete elements [31] manufactured in Norwich and transported by train to Swansea. Concrete of 1800 kg/m^3 density and 30 MPa compressive strength for floor units, and 1600 kg/m^3 density and 15MPa compressive strength (air entrained) for wall panels were used.

- The temporary road bridges in Munich, Germany [6],[37] were designed as demountable structures capable of being erected by mobile cranes. Precast concrete components were used for the superstructure and supporting columns.

5.6.7 Prestressed Structures

The actual application of LWAC in prestressed construction has generally been limited to the extent of cases in which LWAC proved to be the undisputable alternative. Bardhan-Roy [67] claims that if the limitations of

LWAC are viewed in the overall context of a project and if all the beneficial properties are properly exploited, there appears to be plenty of scope to make the design perfectly satisfactory and serviceable without sacrificing economy.

A number of examples of prestressed LWAC exist, most of them being used in bridges [6]; these were discussed before. There are also many examples of pretensioned or post-tensioned LWAC beams in industrial buildings and aircraft hangars [37], [65]. Prestressed LWAC is also used in garage structure members [68], [53], LNG-containers [37], ski-flying platforms [37], [65], cantilever roofs of grandstands [2], [65], and many other constructions.

6. A GENERAL EVALUATION

6.1. Introduction

Presently no structural LWA is manufactured in Türkiye. Possibilities on its production and use have not been investigated either. Only, eight years ago a construction firm named Gök İnşaat considered of producing structural LWAs under the licence of a German company named Liapor but to no avail.

Natural LWAs, such as pumice and scoria, are extracted and used occasionally in some parts of Central and Eastern Anatolia [69]. Erciyas [70], Sükan et. al. [71], Atasu [69], Bizden [72], Taşdemir [73], and some others have conducted research on concretes made with natural LWAs.

There is a brief Turkish standard –TS 1114 [13]– specifying both natural and manufactured LWAs for concrete .

6.2. Available Raw Materials in Türkiye

(A) Natural raw materials. These include clays, shales, and slates. The late Prof. Kemal Erguvanlı investigated the deposits of these materials in Türkiye [74]. He found that there are many clay deposits in a wide band extending between the Western Black Sea and Western Mediterranean regions. However these were either not large enough to build up a local expanded clay production plant or were composed of inhomogeneous layers and contained an excess amount of impurities. This proved the unsuitability of the clay for most occasions. Further research should be conducted if the construction of a new LWA plant is planned.

(B) Industrial waste materials. These include mainly fly ash and blast-furnace slag. Colliery and other wastes are not encountered frequently.

In Türkiye large amounts of fly ash are being generated from power stations burning pulverised-fuel. Only a very small proportion of this fly ash is being utilized either in cement production or as an admixture in concrete; the rest is disposed of [75]. There is no periodically published data about the annual quantities of manufacture and use. However, Tokyay et. al. [75] give information about the production capacities of power stations (both existing and under construction at that time) in 1989. Some unofficial data have been also obtained from Türkiye Elektrik Kurumu (TEK). These are presented in Table 6.1 and Table 6.2.

TABLE 6.1. Amount of fly ash production in Türkiye.

Name of Power station	Location	Production in 1989* (tons)	Production in 1992**(tons)
Çayırhan	Ankara	420 000	§§ 438 000
Tunçbilek	Kütahya	607 200	§§ 540 000
Yatağan	Muğla	1 075 200	§§ 1 522 280
Afşin–Elbistan	K. maraş	2 434 400	2 628 288
Yeniköy	Muğla	1 135 200	750 000
Soma A-B(1-4)	Manisa	1 396 000	1 396 000
Soma B(5-6)	Manisa	§ 1 248 000	1 248 000
Çatalağzı	Zonguldak	§ 834 000	§§ 526 466
Seyitömer I-IV	Kütahya	§ 1 420 000	§§ 1 600 000
Orhaneli	Bursa	§ 430 920	229 142
Kangal	Sivas	§ 576 000	630 000
TOTAL		11 576 920	11 508 176

* From reference [75]

** Data obtained from Türkiye Elektrik Kurumu

§ power station under construction, values estimated

§§ fly ash + ash

TABLE 6.2. Amount of fly ash sold by power stations.

	1989		1992		1993
Name of power station	Amount sold (tons)	Per cent of total prod.	Amount sold (tons)	Per cent of total prod.	until May (tons)
Soma A	14 040	16,7	320	0,4	—
Çayırhan	—	—	86	0,02	—
Tunçbilek	1 362	0,2	1 448	0,3	60
Yatağan	17 932	1,3	—	—	—
Yeniköy	—	—	67	0,01	16 621
Seyitömer	—	—	50	0,003	—
Orhaneli	—	—	182	0,08	944
Kangal	—	—	11 921	1,9	—
TOTAL	33 334		14 074		17 625

A report prepared by Elektrik İşleri Etüd İdaresi [76] states that all the fly ash produced by Çatalağzı, Tunçbilek, Soma, and Seyitömer power stations are completely suitable for use in LWA manufacture. The chemical and mineralogical compositions, and the physical properties of most Turkish fly ash are given by Tokyay et. al. [75], indicating that they are similar to the fly ash produced in most other countries. This figure normally proves the suitability for use in structural LWA production.

The iron and steel industry in Türkiye consists of three large steel plants –Ereğli, Karabük, İskenderun– and other smaller private producers. The former three utilize iron ore as the raw material. The slag produced in these plants is suitable for use in LWA manufacture. Since scrap iron is used in other smaller plants, the slag is not appropriate and the amount is very low. The amounts of production per year are given in Table 6.3. The data –unofficial and rounded– is obtained from Türkiye Demir Çelik İşletmeleri and Ereğli Demir Çelik İşletmeleri through personal communication. The amount of slag production depends on the total amount of pig iron produced and on the technology of the particular plant. Currently, part of the slag is exploited by several cement manufacturers and by some other industries.

TABLE 6.3. Amount of blast-furnace slag production in Türkiye (tons per year).

	1990	1991	1992
İskenderun	—	670 533	706 856
Karabük	220 000	—	231 414
Ereğli	—	—	490 000
TOTAL			1 428 270

6.3. Cost of Initial Investment

The cost of initial investment is a key factor in the consideration of a new LWA plant. In the USA and several European countries significant investments of LWA manufacture were made some 30 years ago; most of these are still working. In those times because energy was relatively cheaper, the energy input was considered less than it is today. However, since the energy crisis of the 1970s, energy efficient methods have been preferred by necessity.

Today the old LWA manufacturing plants may still make a profit because they had already amortized themselves long before and they have a definite market share. Yet a new plant (e.g. in Türkiye) must be energy efficient in order to be feasible.

No manufactured LWA can be produced without a high capital cost. To give two specific examples:

- D.B. Horler [64] of Lytag (UK) Ltd. stated in 1980 that a new sinter plant producing LWA at about 250,000 m^3/year would entail a capital cost of over £4,5million. Considering the inflation rate in the UK this would approximately make £ 11 million (171 billion TL) today.

- Another rough estimation of cost of investment is made by B. M. Tvete, technical director of the Danish company *Aker Exclay* . He states that an expanded clay LWA plant having a production capacity between 200,000 and 300.000 m^3/year would cost 25 to 35 million US$ (253 to 355 billion TL). This is for a complete plant including clay treatment, rotary kiln, sieving plant, buildings, etc.

The capital cost of a blast-furnace slag processing plant may be expected to be relatively low since this need not include any heat treatment. Neither a rotary kiln nor a sinter strand is required, and this would save money.

6.4. Cost of Production

During the manufacture of LWAs there are two main operational costs:

(A) The cost of raw material. For natural raw materials, this consists of the price of the material itself, and the cost of extraction and that of transportation to the LWA plant. This is unavoidable even for sand and gravel but would not be so high if the plant is located near the deposit.

For waste materials, this consists of the costs charged by the producer of waste material and that of transportation to the processing plant. The prices of fly ash and blast-furnace slag in Türkiye are given in Table 6.4. In general these increase in relation to the inflation rate.

TABLE 6.4. Prices of fly ash and blast-furnace slag (TL/ton)

	1989–90–91	1992	1993
Fly ash	850	2000	3500
Granulated bfs	—	—	85000

(B) The cost of energy input. An important factor in LWA manufacture is the process energy required. Different processes require various levels of energy input.

As discussed in Chapter Two, there are two basic processes involved in manufacture of LWAs : rotary kiln process and sinter strand process.

The choice of process depends on the material and the process temperature. Different raw materials require different process temperatures. This naturally has a direct effect on the cost of production. In terms of specific fuel consumption, flexibility of operation, and ease of maintenance, the sinter strand is advantageous. But when higher process temperatures and relative particle movement are necessary, then the rotary kiln is required.

In his paper presented at Concrete International 1980, Horler [64] stated that the total energy utilization is $2{,}66\times10^{6}$ Btu/ton of LWA produced in the rotary kiln process and that it is $1{,}04\times10^{6}$ Btu/ton in the sinter strand method. Besides the large difference between the energy inputs, the finished products from the two processes are different. The rotary kiln process usually produces lighter aggregates, while the sinter strand produces relatively heavier aggregates which have better structural properties.

Expansion of blast-furnace slag does not require any energy input since it comes in a molten form from the blast-furnace. The slag is carried by railcars from the blast-furnace to the place where it is cooled. Equipment (static or mechanical) to expand it during cooling would be sufficient for the whole process.

The required processing energy is a significant factor in the consideration of manufacturing LWAs because the market price of the aggregates will be affected by the cost of energy. It should be remembered that coal is the cheapest fuel in Türkiye as there are many coal mines. Utilization of low quality coal, colliery wastes, and unburnt proportions of fly ash will increase the economy of LWAs. Other fuels, such as oil, are more expensive as they are imported.

The cost of transportation from the plant to the place where the aggregate will be used should also be considered. As for any construction material, this has an effect on the market price. If the plant is near a center of population, this cost would be fairly low. Alternatively if marine transportation is possible, then longer distances would become economical.

6.5. Recommendation on Appropriate Type of Aggregate

In order to consider the production of structural LWAs in Türkiye, the appropriate type of aggregate should be determined. There is evident superiority in aggregates made of industrial waste materials (pulverised-fuel ash, blast-furnace slag) for several reasons. First of all, although there are not large well-known deposits of natural raw materials –clay, shale, and slate– vast quantities of fly ash and blast-furnace slag are being disposed of every year as they can not be utilized. Even the disposal from the plant costs money. It consists of several fractions: the cost of transportation from the plant to the ash park by various means (conveyor belt, trucks, etc.), the cost of labour for this job, the cost of expropriation for the park area, etc.

Secondly, the energy requirement to convert the industrial waste materials into LWAs is relatively low. As the blast-furnace slag comes at about 1400°C from the blast-furnace no extra energy is required to heat it. For pulverised-fuel ash, as it almost always contains a few percentages of unburnt fuel, the energy requirement to sinter it is very low. The total energy requirement in the sintering process is lower than that in the rotary kiln process. Natural raw materials are processed either in the rotary kiln or the sinter strand, and they require much more energy.

Environmental consideration certainly favours utilization of industrial waste materials in the manufacture of LWAs. In this way large amounts of waste materials would be used while natural aggregates would be less exploited. Therefore the most appropriate types of structural LWAs for Türkiye are expanded blast-furnace slag and sintered pulverised-fuel ash.The capital cost of the former is less while the raw material of the latter is cheaper.

7. CONCLUSION

Structural lightweight aggregate concrete has satisfactory performance and is no less durable than concrete made with natural sand and gravel. It can be employed anywhere instead of normal weight concrete if the necessary precautions are taken. Concretes of considerable strength can be readily produced with proper structural lightweight aggregates.

Structural lightweight aggregate concrete is most economical when the dead weight is large compared with the total load. By employing it in the superstructure, the bulk of the foundations can be reduced. The saving of foundation costs is most pronounced with tall buildings and with bad soil conditions. In any structure, when the spans get larger, lightweight aggregate concrete becomes more economical. Time and cost for erection and handling of prefabricated components can be saved. The increased heat, frost, and fire resistance have favorable effect on the indirect building and maintenance costs.

Reduced weight can be availed in highly seismic zones. Here column behavior which is critical during earthquakes should not be a problem since tests show that properly detailed columns made of structural lightweight aggregate concrete perform as well as those made of normal weight concrete under seismic loading.

The most appropriate types of structural lightweight aggregates for Türkiye are those produced from industrial waste materials, especially pulverised-fuel ash. Use of clay, shale, and slate should only be considered as a later measure.

The capital cost of a structural lightweight aggregate manufacturing plant having a production capacity of approximately 250,000 m^3/year varies between 20 to 35 million US$.

Feasibility studies for lightweight aggregate manufacturing plants should be carried out in Türkiye without further loss of time. Legislation and specifications related to construction should be modified to force and encourage the production and use of structural lightweight aggregates manufactured through the recycling of industrial wastes.

APPENDIX A: RILEM Recommendations on Terminology of Lightweight Concrete

A) Classification of types of lightweight concrete

1– Fully compacted concrete
2– Partially compacted concrete
3– No-fines concrete
4– Aerated concrete, produced by chemical processes (gas concrete)
5– Aerated concrete, produced by physical processes (foam concrete)
6– Microcellular conrete

B) Classification of types of binder

1– Cement
2– Limes
3– Mixture of cement and lime
4– Gypsum plaster
5– Organic

C) Classification of types of aggregate for lightweight concrete

1– Natural materials (unprocessed)
    1.1– Coral
    1.2– Tufa
    1.3– Pumice
    1.4– Vocanic ejecta
    1.5– Scoria
    1.6– Tuff
    1.7– Crushed stone*
    1.8– Gravel*
    1.9– Natural sand
    1.10– Silica powder (finely divided silica)
    1.11– Crushed sea shells
    1.12– Diatomite
    1.13– Lava

2– Processed natural materials
    - 2.1– Exfoliated vermiculate
    - 2.2– Expanded clay
    - 2.3– Expanded diatomite
    - 2.4– Expanded obsidian
    - 2.5– Expanded perlite
    - 2.6– Expanded shale
    - 2.7– Expanded slate
    - 2.8– Expanded mixture of sand and limestone
    - 2.9– Agglomerated clay
    - 2.10– Sintered clay
    - 2.11– Sintered desert rock-debris
    - 2.12– Sintered fire clay
    - 2.13– Sintered under-clay (lower clay)
    - 2.14– Sintered shale
    - 2.15– Hollow ceramic particles
    - 2.16– Ground burnt shale**
    - 2.17– Coated pumice

3– Unprocessed by-products
    - 3.1– Air-cooled blast-furnace slag*
    - 3.2– Ground blast-furnace slag**
    - 3.3– Furnace clinker
    - 3.4– Winkle clinker
    - 3.5– Pulverised-fuel ash (fly ash)
    - 3.6– Furnace bottom ash
    - 3.7– Crushed bricks
    - 3.8– Crushed aerated concrete

4– Processed by-products
    - 4.1– Expanded blast-furnace slag
    - 4.2– Expanded pulverised-fuel ash (fly ash)
    - 4.3– Foamed blast-furnace slag
    - 4.4– Granulated blast-furnace slag
    - 4.5– Sintered colliery waste
    - 4.6– Sintered pulverised-fuel ash (fly ash)
    - 4.7– Sintered household refuse
    - 4.8– Agglomerated coal-shale

    - 4.9– Agglomerated furnace clinker
    - 4.10– Expanded glass waste

- 5– Organic Materials
    - 5.1– Plastic particles
    - 5.2– Chaff (grain husks or chopped straw)
    - 5.3– Wood particles
    - 5.4– Wood fibres

* To be used only for concrete types of 2 and 3.

**To be used only for concrete types of 4 and 5.

D) Classification of types of curing

- 1– Curing at normal temperature and normal pressure
- 2– Curing at elevated temperature and normal pressure
- 3– Curing at elevated temperature and elevated pressure (autoclaving)
- 4– Combined methods of curing

E) Determination

Lightweight concrete is characterised by four numbers following the order of the preceding classification chapters.

Examples:

Structural LWC with foamed blast-furnace slag aggregate	1/1/4.3/1
Aerated concrete	4/3/1.10/3
Concrete for building block using clinker aggregate	2/1/3.3/2

APPENDIX B: Unit Weight Requirements of Lightweight Aggregates for Structural Concrete According to ASTM C 330-85 [17]

TABLE B.1. Unit Weight Requirements of Lightweight Aggregates for Structural Concrete.

Size Designation	Dry,Loose Weight, max, (kg/m^3)
Fine aggregate	1120
Coarse aggregate	880
Combined fine and coarse aggregate	1040

APPENDIX C: Grading Requirements of Lightweight Aggregates for Structural Concrete According to ASTM C 330-85 [17]

TABLE C.1. Grading Requirements of Lightweight Aggregates for Structural Concrete.

	Percentages (by Weight) Passing Sieves Having Square Openings								
Size designation	1in.	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8	No.16	No.50	No.100
Fine aggregate									
No. 4 to 0	...	...	...	100	85–100	...	40–80	10–35	5–25
Coarse aggregate									
1 in. to No. 4	95–100	...	25–60	...	0–10	...	...	...	...
3/4 in. to No. 4	100	90–100	...	10–50	0–15	...	...	...	...
1/2 in. to No. 4	...	100	90-100	40–80	0–20	0–10	...	...	...
3/8 in. to No. 8	...	...	100	80–100	5–40	0–20	0–10	...	...
Combined fine & coarse aggregate									
1/2 in. to 0	...	100	95–100	...	50–80	...	...	5–20	2–15
3/8 in. to 0	...	...	100	90–100	65–90	35–65	...	10–25	5–15

APPENDIX D: Limitations for Harmful Substances

ASTM C 330-85 [17]

Organic Impurities. Darker LWAs when subjected to the test shall be rejected unless it is proved that this is not dangerous.

Staining. LWAs containing 1.5 mg or more ferric oxide (Fe_2O_3) shall be rejected for structural use.

Clay lumps. The amount will not exceed 2% by dry weight.

Loss-on-ignition. This will not exceed 5%.

BS 3797: 1990 [19]

Sulphate content. The amount will not exceed 1% when it is expressed as sulphur trioxide.

Loss-on-ignition. The values are given below.

TABLE D.1. Loss-on-ignition values according to BS 3797: 1990 [36].

Aggregate	Maximum loss-on-ignition
Blast-furnace slag	not applicable
Expanded clay, shale, and slate	4%
Pyroprocessed pfa	4%
Pfa stabilized by other means	8%

APPENDIX E: Recommended Ranges of Total Air Contents for Lightweight Concrete

TABLE E.1. Air content according to ACI 213R [1].

Maximum size of aggregate	Air content percent by volume
19 mm	4 to 8
10 mm	5 to 9

TABLE E.2. Air content according to BS 8110 [36].

Maximum size of aggregate	Air content percent by volume
20 mm	5
14 mm	6
10 mm	7

TABLE E.3. Air content according to TS 2511 [37].

Maximum size of aggregate	Minimum air content
16 mm	6.0 ± 1.5
8 mm	7.5 ± 1.5
For workability only	4.0 – 8.0

APPENDIX F: Brief summary and results of Concrete Society (UK) Technical Paper No.106 "A case study of the comparative costs of a building constructed using lightweight aggregate and dense aggregate concrete [64]"

This report compares the cost of a multi-story office block designed in both lightweight and dense structural concrete. It was designed from first principles for a site in Central London. Various alternatives are included: the comparison of flat slab with waffle floor construction, and the alternative of a building being wholly constructed in LWAC.

The report deals with the complete cost analysis of a building excluding costs of purchasing the site and demolition of the previous building. Both the capital and quantifiable parts of running costs are compared between the two principal structural solutions for the design.

Broadly the conclusions drawn from his study are that, in terms of measurable direct costs of the total construction, the use of LWAC is no more expensive than NWC, and in fact is marginally cheaper. When the costs in use are considered, and other benefits such as increased floor area, greater fire resistance and improved energy conservation are properly quantified, still greater cost advantages could accrue.

The cost of concrete materials per m^3 were (June, 1981) :

1. Lightweight granular/natural sand concrete

OPC	370 kg	x	£45.08/tonne	=	£16.67
Sand (Zone 2)	590 kg	x	£6.30/tonne	=	£3.72
Lytag granular	670 kg	x	£13.63/tonne	=	£9.13
	1630 kg				£29.52

2. Dense aggregate concrete

OPC	330 kg	x	£45.08/tonne	=	£14.87
Washed sand	687 kg	x	£6.30/tonne	=	£4.26
20 mm gravel	1195 kg	x	£7.48/tonne	=	£8.94
	2212 kg				£28.07

3. Range of quoted costs of 39 MPa skip ready-mixed concrete

Gravel	£30.00 – £33.00
Lytag	£38.50 – £43.50

These are first quotes and are open to discounts.
OPC: Ordinary Portland Cement

TABLE F.1. Capital costs of the flat slab construction.

	LWAC		NWC	
	£	£/m^2	£	£/m^2
Substructure	100,282	19.7	102,660	20.2
RC frame	133,838	26.5	129,967	25.7
External walls	73,880	14.6	73,880	14.6
Roof covering & RWG	12,204	2.4	12,204	2.4
Windows & ext. doors	97,153	19.2	97,153	19.2
Internal waals	25,382	5.0	25,382	5.0
Internal doors	7,389	1.5	7,389	1.5
Wall finishes	11,569	2.3	13,705	2.7
Floor finishes	72,822	14.4	72,822	14.4
Ceiling finishes	27,633	5.4	28,845	5.7
Fittings	1,058	0.2	1,058	0.2
Services	1,009,850	199.4	1,009,850	199.4
Building works	77,125	15.2	78,691	15.5
External works	28,899	5.7	28,899	5.7
Drainage	14,145	2.8	14,145	2.8
Penthouse	68,722	13.6	68,722	13.6
Preliminaries	237,167	46.8	237,284	46.9
TOTAL	1,999,118	394.7	2,002,656	395.5
Saving using LWAC = 0.2%				

TABLE F.2. Capital costs of the waffle slab construction.

	LWAC		NWC	
	£	£/m^2	£	£/m^2
Substructure	97,848	19.4	101,585	20.1
RC frame	146,770	29.0	142,799	28.3
External walls	73,880	14.6	73,880	14.6
Roof covering & RWG	12,204	2.4	12,204	2.4
Windows & ext. doors	97,153	19.2	97,153	19.2
Internal waals	25,382	5.0	25,382	5.0
Internal doors	7,389	1.5	7,389	1.5
Wall finishes	11,507	2.3	13,547	2.8
Floor finishes	72,758	14.5	72,758	14.5
Ceiling finishes	27,380	5.4	28,754	5.8
Fittings	1,058	0.2	1,058	0.2
Services	1,009,850	199.4	1,009,850	199.4
Building works	77,125	15.2	78,691	15.5
External works	28,899	5.7	28,899	5.7
Drainage	14,145	2.8	14,145	2.8
Penthouse	68,722	13.6	68,722	13.5
Preliminaries	237,485	46.9	237,632	46.9
TOTAL	2,009,553	396.8	2,014,448	397.8
Saving using LWAC = 0.2%				

APPENDIX G: Brief Summary and Results of the Concrete Society Draft Technical Report: "A Comparative Study of the Economics of Lightweight Structural Concrete [63]"

This report demonstrates a comparison between various types of lightweight floors each having the same specification of foundations and shows the ranking of lightweight structural concrete with its equivalent structural elements to be between 20% cheaper and 9% dearer when examination is made as the worst possible case. Moreover, in the case of solid slabs (which are not strictly comparable because of the stronger foundations required) lightweight concrete is about 7% cheaper than hollow tiles and 14% cheaper than dense concrete floors considering the best case.

When the many other capital and cost in use savings are considered, lightweight structural aggregate concrete can be seen as value for money in many more cases than the present limited number of design cost planning decisions indicate. These advantages can be more clearly demonstrated by the use of the forms appraising a project recommended in the appendices of the report.

TABLE G.1. Summary of per cent savings.

Range			%			
			Mech. Hoist		Tower Crane	
Case	Type of floor	Span(m)	Lower	Higher	Lower	Higher
1	Simply supported	4.5	2.1	2.8	2.2	2.9
2	Simply supported	6.0	2.4	2.6	3.3	2.0
3	Simply supported	7.5	3.1	8.5	2.3	7.9
4	Continuous	4.8	1.5	6.3	1.4	6.5
5	Continuous	6.0	1.2	6.0	0.7	5.8
6	Continuous	7.5	0.0	4.6	0.9	3.9
7a	Flat slab-Hollow block		6.0	1.3	7.0	2.0
7b	Flat slab-Dense concrete		0.1	4.5	14.7	4.8

APPENDIX H: Result of an Analysis of a Bridge Comparing Estimates Using LWAC and NWC [65]

TABLE H.1. Summary of cost estimates. (values in $)

ITEMS	Alternate I NWC	Alternate II LWAC
Cost of materials	2,493,394	2,500,246
Production equipment	406,000	451,000
Production labor	1,453,603	1,032,259
Manufacturers overhead	1,453,603	1,032,259
Manufacturers profit	290,720	206,451
Freight	203,220	150,000
Cost of segments of site	6,300,540	5,372,215
Erection equipment	1,100,157	862,200
Erection labor	653,152	463,326
Contractors overhead	522,521	370,661
Contractors profit	857,637	706,840
Total superstructure	9,434,007	7,775,242
1979 Substructure cost	2,521,368	2,363,095
21% Cost escalation of substructure	529,487	496,250
TOTAL	12,484,862	10,634,587
Saving using LWAC = 15%		

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