STRUCTURAL LIGHTWEIGHT AGGREGATE CONCRETE

Edited by J. L. Clarke

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Structural Lightweight Aggregate Concrete

To the many people who, in the past, worked in the Research Departments of the British Cement Association and, previously, the Cement and Concrete Association.

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Preface

Concrete is the most widely used building and construction material in the world. Natural lightweight aggregates have been used since Roman times and artificial lightweight aggregates have been available for over 70 years. However, lightweight aggregate concrete has only a very small share of the market. A number of notable structures have been built in the UK, Europe and the USA and yet many designers appear to ignore the material. Some reject it on the grounds of the basic cost, taking no account of the benefits that can result from its use, such as reduced member sizes, longer spans, improved fire resistance, smaller foundations and better thermal properties.

Lightweight aggregate concrete is covered, briefly, in most structural design codes but reference is generally made to specialist documents for more detailed information. This book aims to bring together all aspects of the material, considering the manufacture of the aggregates, mix design and construction, design requirements and specific applications in buildings, bridges and other structures. Information has been included not only from the UK but also from the rest of Europe, the USA and Japan. The authors of the various chapters all have extensive experience of lightweight aggregate concrete and are drawn from all branches of the industry.

This book is intended for all those who may be concerned with lightweight aggregate concrete, be they specifiers, materials suppliers, designers, contractors or the eventual owners of the building or structure. It is hoped that, by dealing with all the aspects, this book will help lightweight aggregate concrete to achieve its rightful place in construction.

J. L. C.

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P. L. OWENS

1.1 Introduction, definitions and limitations

Structural lightweight concrete is defined as having an oven-dry density of less than 2000 kg/m^3 [1]. The aggregates used may be a combination of fractions of both lightweight coarse and fine materials or lightweight coarse material with an appropriate, natural fine aggregate. However, the general term lightweight concrete refers to any concrete produced to an oven-dry density of less than 2000 kg/m^3. This can be achieved with most natural aggregates if the concrete is made in such a way that excess air is incorporated for example, as no fines or foamed concrete. These types of concrete are outside the scope of this book and are not considered further.

Any aggregate with a particle density of less than 2000 kg/m^3 or a dry loose bulk density of less than 1200 kg/m^3 is defined as lightweight [2]. However, this necessary dual qualification in definition highlights a practical difference from most other aggregates used in structural concrete where particle densities greater than 2000 kg/m^3 are used. In the case of an appropriate lightweight aggregate the encapsulated pores within the structure of the particle have to be combined with both the interstitial voids and the surface vesicles. Nevertheless, these features in combination should not increase the density of the compacted concrete either by significant water permeation (absorption) or cement paste pervasion into the body of the aggregate particle when the aggregate is mixed into concrete.

The most appropriate method of assessing particle density in structural concrete is related to that of an aggregate with a 'reference' density of 2600 kg/m^3, in that this constitutes the major difference in what is a singular property of any lightweight aggregate. The minerals comprising the structure of most aggregates, whether lightweight or not, have densities close to 2600 kg/m^3, but it is the retention of **air** within the structure of an aggregate, when in use, that enables compacted structural concrete to be less than 2000 kg/m^3. Therefore producers of lightweight concretes, when requiring to compare the properties of one aggregate to another, should not only judge relativity, but also compare any differences in mass of the various concrete constituents, water, cement, etc., so that comparisons between aggregates are made strictly from the same base.

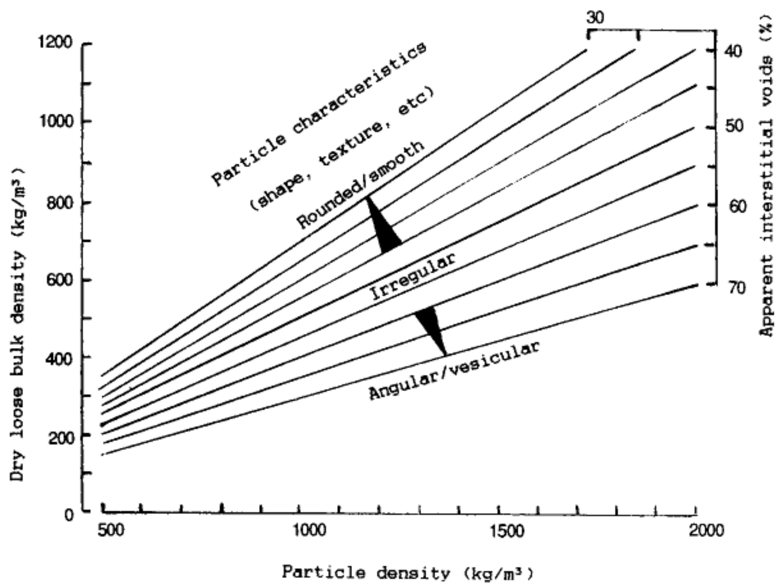

Figure 1.1 Effect of apparent interstitial voids on lightweight aggregates, as determined by particle characteristics on the relationship of particle density to dry loose bulk density.

This aspect of apparent divergence between the various definitions of density, 'particle' versus 'dry loose bulk' is also concerned with the apparent percentage of interstitial voids and the way differently shaped particles of the same nominal size interact. The number of spherical particles, for a given volume, pack more naturally to a higher random density than do the same sized particles of either irregular or angular shape. To demonstrate this particular aspect of lightweight aggregate, Figure 1.1 illustrates the relationship between these two definitions of density, while incorporating the shape and texture of the particle, together with its apparent percentage void space. Thus those aggregates with the **lowest apparent percentage of void space** are those which give structural concrete densities significantly lower than 2000 kg/m^3.

1.2 Lightweight aggregates suitable for use in structural concrete

For structural concrete, the pragmatic requirements are generally that any lightweight aggregate is suitable that has a crushing strength sufficient to have reasonable resistance to fragmentation [3] while enabling concrete strengths in excess of 20 N/mm^2 to be developed and to produce a finished concrete in the dry density range 1500–2000 kg/m^3. Essentially, this means that where the concrete uses fine aggregates from natural sources, the particle density of the coarse aggregate in the 'compacted' concrete needs to be not greater than about 650 kg/m^3 at the lower end, nor more than about 1850 kg/m^3 at the higher end of the scale, because it is the degree of 'lightness' of the coarse aggregate that mostly influences the density of the finished oven-dry concrete.

Traditionally, producers and manufacturers of lightweight aggregates have been constrained by the following:

1. If from a natural source such as pumice, scoria, etc., the aggregate is what it is, so it has limited applications.
2. If manufactured, there are not only the limitations of the raw material and the method of processing, but also the main consideration, **the requirements of the market**. The market may be for an aggregate with good thermal insulation and not for structural applications. Added to this is the availability of the mineral resource, as the lower the finished aggregate particle density, the less will be the rate at which the resource will be depleted for the same volume of production. This creates an obvious conflict of interest: does a producer develop a lightweight aggregate for a market which depletes the resource at a greater rate, or for a speculative market with the possibilty of a smaller return on capital?

As a consequence of this dilemma, more lightweight aggregate producers have suffered failure than in any other segment of the aggregate industry because of conflicts in marketing strategy. However, it seems that most specifiers are limited in their appreciation of the advantages of lower density concrete in reinforced concrete construction, as the use of lightweight concrete has not been generally optimised. This is probably the result not only of inadequate design codes, which are more stringent than necessary as construction is a very 'conservative' and a traditional industry, but also of unfounded prejudice based on inadequate information at the design stage. Therefore, to overcome uncertainty requires demonstrable proof of long-term durability and stability of any concrete type, as well as the design information having to be presented in such a way that the advantages are immediately obvious.

1.3 Brief history of lightweight aggregate production

The history of lightweight aggregate production from natural sources dates back to pre-Roman times and continues today with volcanic porous rocks, but the sources are limited to regions of volcanic activity.

From around the end of the 19th century, with the development of reinforced concrete, and owing to the rarity of natural porous aggregate deposits and their non-existence in most developed countries, research for the manufacture of 'artificial' aggregates commenced. In Europe in the early part of the 20th century, development concentrated on foaming blastfurnace slags, as 'iron' production was basic to the industrial infrastructure. However, it was not until the early 1970s that significant developments in pelletising and expanding blastfurnace slags took place, so that today a slag-based aggregate with a smoother non-vesicular surface, more adaptable for structural concrete, is produced.

In comparison to slag, it was not until about 1913 that research in the USA revealed that certain clays and shales expanded when fired. This developed about 1917 in Kansas City, Missouri, to the production in a rotary kiln of a patented expanded aggregate known as Haydite which was used in the construction of the USS *Selma*, an ocean-going ship launched in 1919 [4]. There followed in the USA the development of a series of aggregates known as Gravelite, Terlite, Rocklite, etc. In Europe, however, it was not until 1931 that the manufacture of LECA (lightweight expanded clay aggregate) commenced in Denmark. Therafter developments quickly spread to Germany, Holland and the UK [5]. Variations to the principles of expanding suitable argillaceous materials, such as the geologically older forms of clay – e.g. shale and slate – have all been undertaken in the UK since the 1950s and have been variously known as Aglite, Brag, Russlite and Solite. All these companies have failed for one reason or another, mainly because of inaccessibility of the market, non-homogeneity of the feed stock, emissions and high cost of production, **but never on the technical performance of the aggregate in concrete**.

In the 1950s the Building Research Establishment (BRE) developed the technology for the production of a high-quality lightweight aggregate based on pelletised pulverised-fuel ash (PFA), an ash resulting from burning, generally in power stations, pulverised bituminous or hard coals [6]. PFA is the residue of contaminants in hard coals that are present as the result of erosion of natural minerals which sedimented into the coal measures as they formed. Thus there is a connection between PFA and other argillaceous minerals, except that most of the PFA has already been subjected to temperatures in excess of 1250°C, which vitrifies and bloats some of the larger particles, known as cenospheres. Two construction companies became involved in the exploitation of PFA and the BRE know-how. Cementation Ltd worked at Battersea Power Station, with two shaft kilns which failed operationally. John Laing & Co. Ltd set up at Northfleet, with a sinter strand which has evolved in the UK as the most successful method of producing structural grades of lightweight aggregate from PFA under the trade name of Lytag. Lytag has limited ability to reduce the density of fresh concrete much below 1750 kg/m^3 (when using Lytag fines) and can, with natural fine aggregate, produce a density of fresh concrete at about 1950 kg/m^3.

Where there is a requirement to produce high-strength concrete at densities lower than, say, 1850 kg/m^3, the manufacturers of Germany's expanded shale aggregate Liapor have, from about the early 1970s, been able to produce aggregates to within a desired particle density between 800 and 1700 kg/m^3. This highlights one of the most significant advances in lightweight aggregate manufacture as the **particle can be designed to suit the concrete density requirements**, thereby giving greater versatility to the application of this particular aggregate.

There are a number of other developments taking place in lightweight aggregate manufacture, such as the production of hybrids using pulverised-fuel ash and suitable argillaceous materials (clay, shales and slate) There are also what are euphemistically called 'cold' bonded aggregates which are mixtures of PFA with lime or Portland cement. These latter aggregates, although manufacture is now becoming more successful, have applications more appropriate to the production of masonry than to reinforced concrete.

1.4 Manufacturing considerations for structural grades of lightweight aggregate

1.4.1 The investment

For any lightweight aggregate the investment in manufacturing plant is considerable, for not only does there have to be sufficient and appropriate resource material available, but also there has to be a market. In the USA, most cities are based on the principle of high-rise development, with the inevitable use of lightweight aggregate. Meanwhile Europe, with its more historic traditions and older infrastructure, has lagged behind. Now more consideration is being given to the conservation of land-based resources such that the developers and promoters of various schemes find it more difficult to obtain permission, not only for mineral extraction, but also to acquire new sites for high-rise structures.

1.4.2 The resource materials

The most important asset for any lightweight aggregate manufacturer is to have sufficient raw material in a form and state ready for immediate use, which means that manufacturers using either PFA or molten slag have immediate advantages over other resource minerals. The limitations, however, are that the process of sintering PFA fuses the PFA particles in such a way that it densifies the aggregate, while to 'entrain' air into molten slag ultimately means that the particle density is limited to about 1750 kg/m^3.

Alternatively, an aggregate based on argillaceous materials such as clay, shale or slate can have its density varied by the manufacturing technique. In the case of the lighter aggregates they use less raw material, so for the stronger and denser aggregates the resource is depleted at a greater rate. One solution [7] is to make an aggregate based on PFA mixed with a minor proportion of clay, say in this case between 15 and 30%, which can be heat expanded to make an aggregate of the required particle density, say $1350 \pm 50\,kg/m^3$.

1.4.3 The various processes of lightweight aggregate manufacture

Most manufacturing processes for lightweight aggregates, with the exception of processes using blastfurnace slag, have been limited to the use of either a sinter strand or a rotary kiln. In instances where the fresh pellets before firing are in a suitable form, the sinter strand is preferred. Where the form of the fresh pellet is cohesive and its shape can be retained, the rotary kiln produces the most rounded particle with the most impermeable surface.

1.4.4 The techniques of production

The various production techniques rely either on agglomeration or expansion (bloating). Agglomeration takes place when some of the materials melt at temperatures above 1100°C and the particles that make up the finished aggregate are bonded together by fusion. Alternatively, expansion develops when either steam is generated, as in the case of molten slag, or a suitable mineral (clay, shale or slate) is heated to fusion temperature, at which point pyroplasticity occurs simultaneously with the formation of gas which bloats the aggregate.

When argillaceous materials are heated by firing to achieve appropriate expansion, the resource mineral should contain sufficient gas-producing constituents and reach pyroplasticity at the point of incipient gas formation. Gas can be developed by a number of different reactions, either singularly or in combination, from the following:

(a) volatilisation of sulphides from about 400°C
(b) decomposition of the water of crystallisation from clay minerals at approximately 600°C
(c) combustion of carbon-based compounds from approximately 700°C
(d) decarbonation of carbonates from approximately 850°C
(e) reaction of Fe_2O_3, causing the liberation of oxygen from about 1100°C.

Most argillaceous materials that are suitable become pyroplastic at between 1100 and 1300°C. However , depending on the actual source of the material and its chemical composition, the temperature at which bloating for each material becomes effective is within a relatively small range, usually about ±25°C. At this point the bloated material has to be removed immediately from the firing zone and cooled quickly to freeze the particle at that degree of bloat, otherwise it will continue to expand. When ultimately the thickness of the pore wall becomes too thin, there is insufficient resistance to fragmentation and the particle will not be sufficiently strong to resist fragmentation for structural concrete.

A principle of success with all lightweight aggregate manufacture is homogeneity of the raw material source, as variability inevitably causes fluctuations in manufacture and the finished product. To emphasise this, it can be demonstrated how present-day manufacturers have had to go to considerable lengths to ensure that homogeneity of the raw material is obtained.

1.5 Lightweight aggregates available in the UK

The lightweight aggregates available in the UK, and currently listed in 1993, are given in Table 1.1.

Table 1.1 Lightweight aggregates available in the UK (1993)

Aggregate proprietary name	Type	Manufacturing process	Shape/texture	Dry loose bulk density (kg/m^3) (typical)	Concrete strength (N/mm^2) (typical)
Foamed slag	Foamed slag	Foaming bed	Angular/ vesicular	750	<40
Leca/Fibo	Expanded clay	Rotary kiln	Rounded/ smooth	425	<30
Lytag	Sintered PFA	Sinter strand	Rounded/fine	825	>40
Pellite	Blastfurnace slag	Pelletisation	Irregular/ smooth	900	>40
Granulex	Expanded slate	Rotary kiln	Irregular/ rough	700	>40
Liapor	Expanded shale	Rotary kiln	Rounded/ smooth: fine	650	>40

1.6 Production methods used for the various lightweight aggregates

1.6.1 Foamed slag

In this process, produced in the UK, molten blastfurnace slag at more than 1350°C is poured onto a foaming bed consisting of a large number of water jets set in a concrete base. The water immediately converts to steam on contact with the molten slag and penetrates into the body of the material, at which point the steam becomes superheated. Owing to the rapid expansion that then takes place, the slag foams to form a cellular structure. Alternative methods of expansion include spraying water onto the molten material when it is being tapped from the blastfurnace so that the material is cooled rapidly, with steam becoming entrapped within the structure of the particle. At the completion of foaming the slag is removed and stockpiled, from where it is subsequently crushed and graded to size (Figure 1.2). The aggregate produced is very angular with an open vesicular texture.

1.6.2 Leca and Fibo

Leca (produced in the UK) and Fibo (produced in Scandinavia) are expanded clay aggregates manufactured in a rotary kiln which consists of a long, large-diameter steel cylinder inclined at an angle of about 5° to the horizontal. The kiln is lined internally in the firing zone with refractory bricks which, as the kiln rotates, become heated to the required temperature and 'roast' the clay pellets for the required degree of expansion to occur. The length and configuration of the kiln depends in part on the composition of the clay and length of time it takes to 'condition' the clay pellet in the pre-heater to reach a temperature of about 650°C to avoid it shattering before becoming pyroplastic.

The clay is dug and, to eliminate natural variability, is usually deposited by layering into a covered stockpile with a spreader before it is removed from the stockpile by scalping with a bucket conveyor. In the process, a high degree of blending is achieved. The clay is prepared by mixing thoroughly to a suitable consistency before pelletisation. The prepared raw material – and that obviously means producing smaller sized pellets than are required for the finished product (as their volume can be increased three to six times) – is fed into the kiln. This can be in three segments, the higher end for drying and pre-heating, while at the lower end firing and then cooling takes place. During the progress of the prepared material through the kiln, the temperature of the clay pellets gradually rises until expansion actually occurs. The expanded product is discharged from the firing zone as soon as possible for cooling to freeze the particles at the required degree of expansion. Cooling takes place either in a rotary cooler or fluidised bed heat-exchanger. The finished product is graded and, if necessary, crushed to particle sizes less than 16 mm. While the particle density can be varied depending on the range of temperatures at which expansion takes place, the mean expansion temperature is about 1200 ± 50°C. This varies for different clays but most manufacturers are limited to expandable clays which have a confined range of bloating

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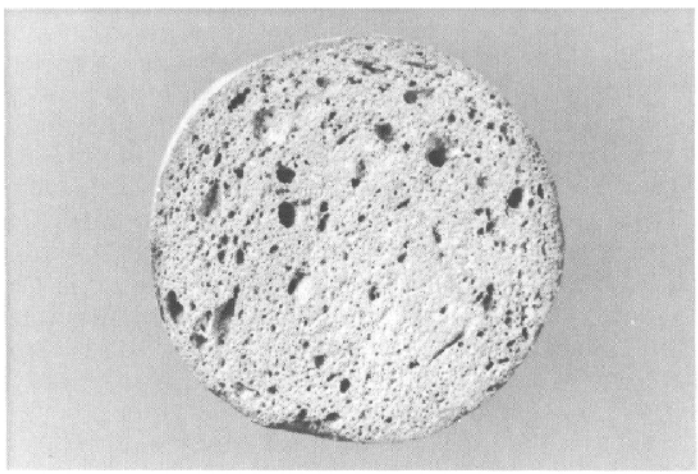


Figure 1.2 (a) Typical Leca particles, 12 mm size. (b) Sectioned Leca particle about 30× enlarged.

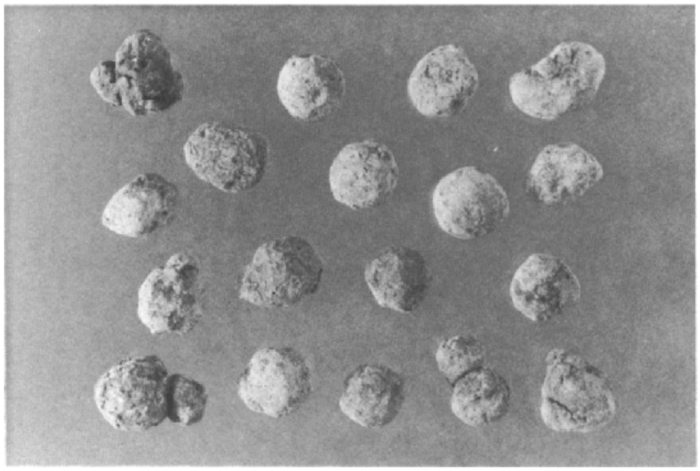
temperatures. In some cases, the range is less than 25°C between non- and full expansion. In instances such as this, the scope is limited for the manufacture of intermediate density grades. However, manufacturers of such aggregates, by requiring to optimise their production, usually have preferences for lower particle density aggregates, in the range 400–800 kg/m^3, as this tends to conserve the resource which gets depleted at a greater rate at higher particle densities. Thus there is a greater attraction to produce aggregates for thermal insulation than for structural applications. However, for the lower density structural concrete, i.e. 1300–1600 kg/m^3, these aggregates are the most suitable. As shown in Figure 1.2, the surface texture is closed and smooth with a 'honeycombed' or foamed internal structure, where the pores are not interconnected.

1.6.3 Lytag

Lytag is produced in the UK from pulverised-fuel ash (PFA). Large quantities of suitable PFA are produced in the UK as a powdered by-product of pulverised-fuel (bituminous coal) operated furnaces of power stations. Suitable PFA, usually of less than 8% loss on ignition, which is mostly unburnt carbon in the form of coke, is first homogenised in bulk in its powder form. Once homogenised, it is then conditioned through a continuous mixer with about 12–15% water and, as necessary, an amount of fine coal is added to make up the fuel content to between 8 and 12% of the dry mass of the pellet to enable it to be fired. This conditioned mixture of PFA is then fed at a controlled rate onto inclined and revolving nodulising dishes. The inclination, the revolving speed, together with the rate at which the conditioned PFA is fed onto the dish, as well as some additional water added as a fine spray, controls the size and degree of compaction of the green pellets, which self-discharge from the pelletiser, when they become generally about 12–14 mm in size. Without any further treatment these green pellets are conveyed to the sinter strand where they are fed by spreading to form an open-textured and permeable bed to the width and depth of the continuously moving grate. This is in the form of a continuously moving conveyor belt, comprising a series of segmented and jointed grates through which combustion air can be drawn to fire the bed of nodules, as well as permitting exhaust for the gases of combustion. Once prepared on the bed, the strand immediately carries the pellets under the ignition hood that fires the intermixed 'fuel'. The chemical composition of PFA resembles that of clay, but unlike clay, as the PFA has already been fired, no pre-drying or pre-heating of the pellets is necessary, as the pellet is able to expire the water as vapour and combustion gases without incurring damage. Once ignited at about 1100°C, and as the bed moves forward, air for combustion is drawn by suction fans beneath the grate, and without the PFA particles becoming fully molten, bonding or coagulation of the PFA particles within the pellet is achieved. Controls for producing the correct amount of coagulation within the pellets are obtained by being able to vary both the speed of the strand and the amount of air drawn through the bed.

The finished product is formed into a block of hard brick-like spherical nodules, lightly bonded by fusion at their points of contact. As the sinter strand reaches the end of its travel and commences its return to the feeding station, a large segment of the finished product forming the bed is

(a)



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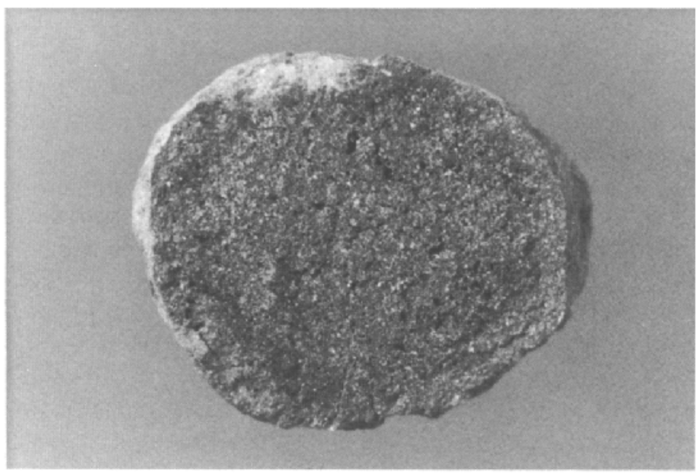

Figure 1.3 (a) Typical Lytag particles, 12 mm size. (b) Sectioned Lytag particle about 30× enlarged.

discharged into a breaker. This has the ability to part pellets that are inevitably only lightly bonded together before the finished aggregate is graded.

The surface and internal structure of the finished pellet (Figure 1.3), while closed, is nevertheless sufficiently open textured to have encapsulated interstices between the coagulated PFA particles. While these interstices, although minute, are water permeable, they do eventually 'breathe' sufficiently, by emission, to allow any moisture to evaporate, even when encased in concrete.

1.6.4 Pellite

Pellite (produced in the UK) is a pelletised expanded blastfurnace slag. The process of slag pelletisation was developed in the early 1970s in order to overcome environmental problems associated with the production of foamed blastfurnace slag on open foaming beds or pits. Not only does the slag pelletisation process overcome these problems but it also produces an aggregate with a closed surface.

To manufacture this pelletised aggregate, liquid blastfurnace slag at a temperature of about 1400°C passes through a refractory orifice 'block' to control the rate of flow. It is then allowed to flow onto an inclined vibrating plate with water running down its surface. The vibration of the plate breaks up the slag flow and the trapped water immediately vaporises and expands the slag.

At the lower end of the vibrating plate, water is sprayed onto the surface of the slag. This enables gas bubbles to form in the body of the slag, creating further expansion while also chilling its surface. At the bottom of the vibrating plate the expanded globules of semi-molten slag are discharged onto a horizontally rotating drum fitted with fins which project the material through a water mist. The trajectory of material is such that the slag forms rounded pellets which are sufficiently chilled to avoid agglomeration when they come to rest. After pelletisation is complete the material is removed, allowed to drain and, finally, screened into the requisite size.

As Figure 1.4 shows, the nature of the manufacturing process produces a finished product that comprises semi-rounded pellets with a smooth surface encasing a glassy matrix and a discrete cellular structure, which is essentially non-absorbent.

1.6.5 Granulex and Liapor

Two other sources of European lightweight aggregate, besides Fibo, are available: Granulex and Liapor. They are not made in the UK but are, however, suitable for the production of high-strength or prestressed concrete. Both aggregates are produced by bloating argillaceous minerals in a rotary kiln.

Granulex is produced from slate in north-western France, just north of Le Mans. The product is very similar to the now defunct Solite, produced in north Wales. The slate is first reduced to about 12–15 mm, and is then fed into a three-stage kiln consisting of a pre-heater, followed by a firing or expanding section before being discharged into a cooler. The firing or

(a)

(b)

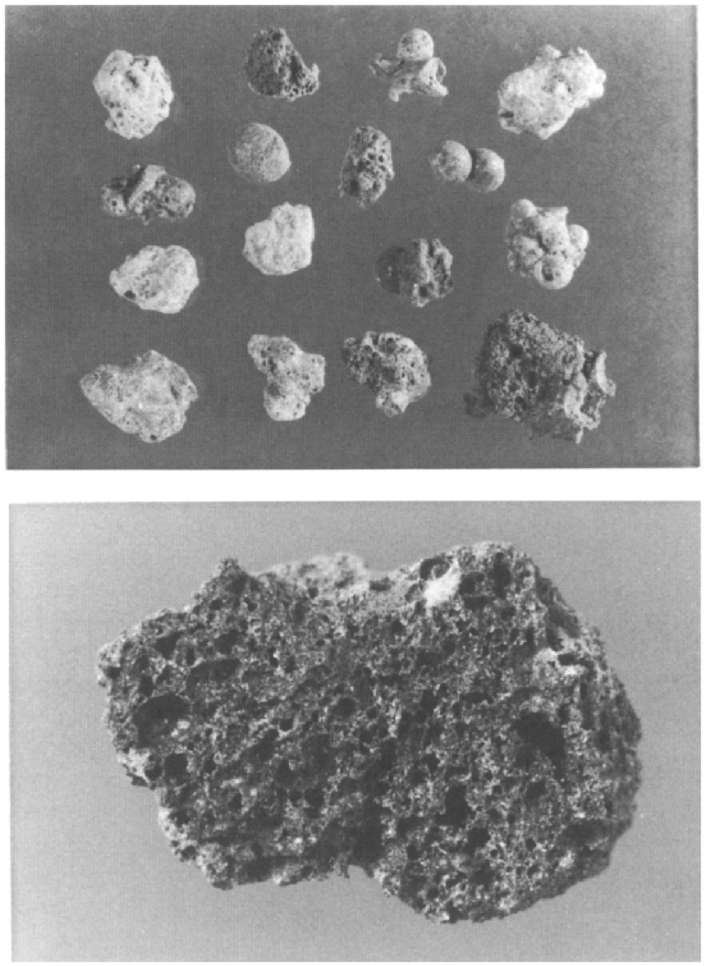

Figure 1.4 (a) Typical Pellite particles, 12 mm size. (b) Sectioned Pellite particle about 30× enlarged.

bloating temperature is about 1150°C when the laminated platelets of slate become pyroplastic and the gases released cause the particles of aggregate to expand to form an almost cubic particle shape, taking the original particle density of the slate from about 2700 kg/m^3 to a pre-determined density anywhere between 650 and 1250 kg/m^3 depending on the required amount of bloating, although this has to be very carefully controlled. The finished product is crushed and graded up to 25 mm maximum size (Figure 1.5) and the surface texture of the finished particle is coarse and rough. However, the surface is sufficiently closed, owing to its vitrified nature, such that internally it has an extremely low water absorption.

Liapor is produced from shale in Bavarian Germany between Nurenberg and Munich. The shale, a low moisture content soft rock, is quarried and transferred by open tipper truck some 6 km to the processing plant, where it is reduced by primary crushers before being dried and milled into a powder, generally of less than 250 μm. It is then homogenised and stored ready for pelletisation. This process is similar to that used for making Lytag except that no fuel is added. However, after the pellets have been produced to the appropriate size, depending on the expansion required, they are compacted and coated with finely powdered limestone. The resultant pellets are spherical with a very high 'green' strength. They are then conveyed to a three-stage rotary kiln, a pre-heater, an expander, followed by a cooler. They are unlike any other aggregate produced by the use of natural argillaceous material, in that the feed stock is reduced to a powder and is then reconstituted into a pellet of predetermined size, and the amount of expansion can be controlled to give a particle of the required density. The technique used for producing the different particle densities is the control of firing temperature and the rotating speed of the firing kiln. The coating of limestone given at the time of finishing the green pellet increases the amount of surface vitrification to the finished product, which is very impermeable. Of all the aggregates currently available, Liapor gives the greatest versatility to the designer for pre-selecting an appropriate concrete density to suit the requirement. As Figure 1.5 shows, while the particle shape and surface texture of Liapor remain essentially the same, internally the porosity can be varied according to the amount of bloat required for the specified density.

1.7 The future

Research on structural concrete has established that appropriate lightweight aggregates **do not have the deficiencies in performance compared to concrete made with natural aggregates**. As the need increases for alternatives to aggregates from natural sources, there are opportunities for capitalising on the resources that exist, for which there is currently no accepted use in their present form. For instance, it is estimated that there are some 150 million tonnes of 'stockpiled' PFA in the UK. On the Continent and in other EC countries such a practice is now being penalised by environmental protection legislation by taxation of the power companies. Although Lytag has provided a basis for the exploitation of PFA,

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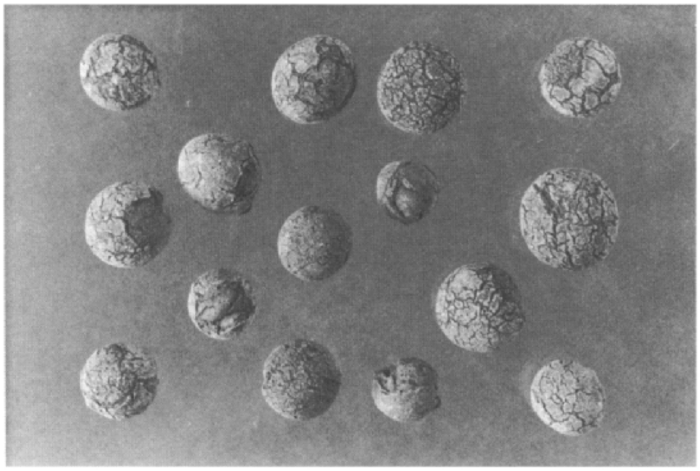

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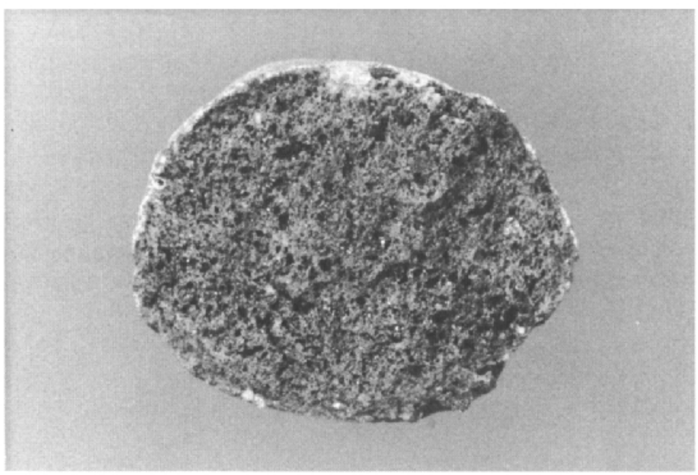

Figure 1.5 (a) Typical Liapor particles, 12 mm size. (b) Sectioned Liapor particle about 30× enlarged.

the finished aggregate has a single density and, as such, has been limited in its ability for wider applications in structural concrete.

This, together with the limitations on the amount of excessive residual fuel that the PFA sometimes contains, restricts full capitalisation of the technology of PFA conversion to a structural aggregate. Alternatively, expanded clays have their own limitations, mainly because of restrictions placed on the availability of suitable material. In 1992 the one source of expanded clay aggregate produced in the UK has been threatened