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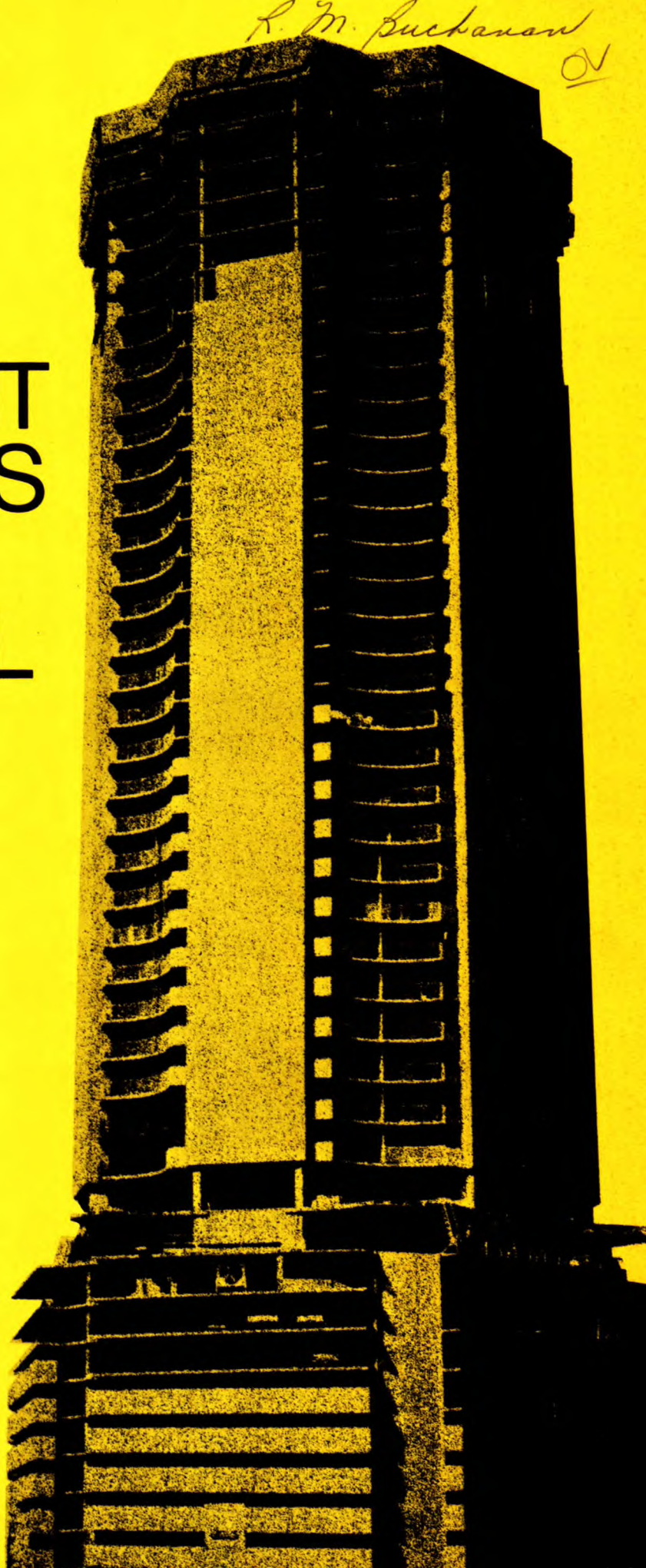
Centre canadien
de la technologie
des minéraux
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LIGHTWEIGHT AGGREGATES FOR STRUCTURAL CONCRETE

H.S. Wilson

Industrial Minerals Laboratory

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Cover Photograph

Edmonton House, Edmonton, Alberta, a 45-storey apartment building: the lower 11 providing parking for 357 cars; the upper 34 contain 344 apartments; the 12th is a mezzanine floor. All floors and partitions are of lightweight concrete.

PREFACE

The Canada Centre for Mineral and Energy Technology (formerly the Mines Branch) has played the most prominent role in Canada, for over 25 years in research, development and processing of raw materials for lightweight aggregates. It has also become increasingly involved in research into properties of lightweight concrete.

The purpose of this monograph is to promote knowledge of and interest in the lightweight aggregates that can be used in structural concrete through a broad yet detailed description of their processing and utilization. It details raw materials, methods of production, properties, applications, specifications and economics of these lightweight aggregates. This publication should be of interest to a wide variety of people concerned with concrete as a construction material.

Lightweight aggregates could claim an increasing share in construction, partly due to the desirable properties given to concrete and also due to the decreasing availability of normal-weight aggregates in various areas of Canada.

D. F. Coates,
Director General

PREFACE

Le Centre canadien de la technologie des minéraux et de l'énergie (anciennement la Direction des Mines) a, depuis 25 ans, joué un important rôle, au Canada, dans la recherche, le développement et le traitement de matériaux bruts utilisés dans les aggrégats de poids léger. Il est devenu de plus en plus impliqué dans la recherche sur les propriétés du béton de poids léger, tout au long de ces années.

Ainsi, cette monographie a pour but de promouvoir une meilleure connaissance et un plus grand intérêt dans les aggrégats de poids léger pouvant servir à la fabrication du béton de construction. Elle le fait ici en donnant une description exhaustive de leur traitement et de leur usage. On y traite des matériaux bruts, des méthodes de production, des propriétés, des applications, des spécifications et de l'économie de ces aggrégats de poids léger. Ce document devrait, donc, intéresser un bon nombre de gens engagés dans l'utilisation du béton comme matériel de construction.

Etant donné les propriétés qu'ils confèrent au béton, ainsi que la pauvre disponibilité d'aggrégats de poids normal à travers le Canada, les aggrégats de poids léger pourraient bien prendre une plus grande place dans le monde de la construction.

MINERAL SCIENCES LABORATORIES
MRP/MSL 75-241(R)

LIGHTWEIGHT AGGREGATES FOR STRUCTURAL CONCRETE

by

H. S. Wilson*

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ABSTRACT

This monograph is concerned with lightweight aggregates that can be used in structural lightweight concrete; namely those produced from clay, shale, slate, blast furnace slag, and fly ash.

The clays, shales and slates are the most widespread of raw materials, although slate is not used in Canada. All the producers in Canada use the rotary kiln method, but sintering is also used in the United States. The production of expanded blast furnace slag is restricted to locations of steel plants producing pig iron in blast furnaces. There is only one plant in Canada producing expanded slag lightweight aggregate. Fly ash is not used in Canada but is to a limited extent in the United States.

A machine process was developed in Canada by which a pelletized expanded slag could be produced. This process almost completely eliminates the sulphurous fumes associated with the widely used pit process. Several of the machines have been installed in slag-expanding plants in various countries.

*Research Scientist, Construction Materials Section, Industrial Minerals Laboratory, Mineral Sciences Laboratories, Canada Centre for Mineral and Energy Technology, Department of Energy, Mines and Resources, Ottawa, Canada.

The lightweight aggregates being produced are all used in concrete masonry units, for both load-bearing and non-load-bearing applications. The lightweight aggregates produced from clays and shales and, to a limited extent, from expanded slag are used in structural cast-in-place and precast concrete in beams, columns, walls, roofs, and floors in low- and high-rise structures and in bridges.

Lightweight concrete is about 30 per cent lower in unit weight than normal weight concrete and is lower in thermal conductivity and sound transmission. Although the properties of the various lightweight concretes differ, they are similar in many respects to normal weight concrete. Each aggregate and the concrete made with it must be assessed on their own properties. ASTM standards have been adopted in Canada to limit the properties of the lightweight aggregates and the concretes made with them. Although the cost of lightweight aggregates is higher than that of normal weight aggregate, appreciable savings have resulted from their use in many applications, primarily because of the lower unit weight.

The lightweight aggregates have other, non-structural, applications such as back fill, floor fill, and soil conditioning. In the case of expanded slag, it is finding a use in the manufacture of portland-blast furnace slag cement.

LABORATOIRES DES SCIENCES MINÉRALES

MRP/MSL 75-241(R)

DES AGREGATS DE POIDS LEGER POUR
DU BETON DE CONSTRUCTION

par

H.S. Wilson*

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RESUME

Cette monographie s'intéresse aux agrégats de poids léger qui peuvent être utilisés dans du béton de construction de poids léger, comme ceux produits à partir d'argile, de schistes argileux, d'ardoise, de scories de haut-fourneau et de cendre volante.

Les argiles, schistes et ardoises sont les matériaux bruts les plus répandus, bien que l'ardoise ne soit pas utilisée au Canada. Tous les producteurs canadiens utilisent la méthode du four rotatif, mais le frittage est aussi utilisé aux Etats-Unis. La production de scories dilatées de haut-fourneau est restreinte aux usines d'acier produisant de la fonte brute dans des haut-fourneaux. Il n'y a qu'une usine au Canada qui produit des agrégats de poids léger de scories dilatées. La cendre volante n'est pas utilisée au Canada, mais elle l'est, jusqu'à un certain point, aux Etats-Unis.

Un processus mécanique a été développé au Canada, par lequel une scorie dilatée et réduite en boulettes pourrait être produite. Ce procédé élimine presque complètement les fumées de sulfure associées à la méthode du bassin qui est très courante. Plusieurs de ces machines ont été installées dans des usines de fabrication de scories dilatées de plusieurs pays.

Tous les agrégats de poids léger produits sont utilisés dans des unités de maçonnerie de béton pour le soutènement de charge et le non-soutènement de charge. Les agrégats de poids léger produits à partir d'argiles et de

*Chercheur scientifique, Section des matériaux de construction, Laboratoire des minéraux industriels, Laboratoires des sciences minérales, Centre canadien de la technologie des minéraux et de l'énergie, Ministère de l'Énergie, des Mines et des Ressources, Ottawa, Canada.

schistes argileux et jusqu'à un certain point de scories dilatées sont utilisés dans du béton de construction coulé-sur-place et pré-coulé pour des poutres, des colonnes, des murs, des toits et pour des planchers de hautes et basses structures ainsi que pour des ponts.

Du béton de poids léger est à peu près 30% moins pesant par unité que du béton de poids normal et possède un taux inférieur de conductivité thermique et de transmission sonore. Bien que les propriétés des différentes sortes de béton de poids léger varient, elles ressemblent en bien des points à celles des bétons de poids normal. Chaque agrégat ainsi que le béton fait à partir de celui-ci doivent être jugés selon leurs propriétés particulières. Les normes de l'ASTM ont été adoptées au Canada afin de contrôler les propriétés des agrégats de poids léger et les bétons faits à partir de ces agrégats. Même si le coût des agrégats de poids léger est plus élevé que celui des agrégats de poids normal, on a beaucoup économisé à les employer pour différentes applications, principalement à cause de leur poids inférieur à l'unité.

Il y a d'autres façons non-structurales d'utiliser ces agrégats de poids léger: dans la terre de remblai, le remblayage de plancher et le conditionnement du sol. Dans le cas de la scorie dilatée, elle semble pouvoir être utilisée dans la fabrication de ciment de scorie de haut-fourneau Portland.

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INTRODUCTION

The term 'lightweight aggregate' is a 20th century expression, but the concept of incorporating low density material in concrete is anything but new. The Roman Emperor Hadrian took considerable interest in structures built during his reign (117-138 AD). The dome of the Pantheon in Rome, 142 feet (43.3 m) in diameter, contains pumice and pozzolan. Because the concrete, using lime cement, was of excellent quality, the Pantheon and other masses of Roman concrete on the coast between Naples and Gaeta are still in good condition.

The concrete used during the Middle Ages was generally inferior to that of the Romans, and it was not until the early 19th Century that it began to be of better quality. The invention of portland cement in 1824 was a boon to the industry, and gradually, since then, the use of concrete has tended to become more of a science than an art. The first standards association was formed in 1877 in Germany.

A method of producing lightweight aggregate from shale was patented in the United States in 1917. The first plant in Canada to produce a lightweight aggregate was built in 1927, but the industry did not grow until after World War II. It is still not a large industry; in 1974 Canadian production had a total value of \$ 5,273,000. The sources of normal weight aggregates are moving further from the market areas because of depletion of existing deposits. Also, insulation of buildings is becoming more important with the increasing cost and decreasing availability

of fuel. Because of these trends, lightweight aggregates should play greater roles in construction in the future.

'Lightweight aggregates' refers to aggregates produced from clay, shale, slate, blast furnace slag, fly ash, pumice, vermiculite, perlite and diatomite. This publication is concerned only with those aggregates that can be incorporated into structural concrete, namely, expanded clay, shale, slate, and blast furnace slag, and sintered fly ash.

Clay, shale, slate and fly ash require heat treatments to develop their lightweight characteristics. Blast furnace slag is a by-product of the process for making pig iron from iron ore; the slag being expanded into a lightweight aggregate using a controlled amount of water.

The lightweight aggregates possess such characteristics as: low unit weight, low thermal and acoustic conductivity, fire resistance, medium to low absorption, and inertness in their field of application, which is principally in construction. They are used alone and also in combination with portland and refractory cements, and asphaltic compounds. As aggregates, combined with a bonding agent, they are formed into slabs, beams, bricks and blocks of many shapes and sizes. They are also used in the monolithic formation of beams, columns, walls, roofs and floors. They are used alone as: insulation, soil conditioners, fertilizer and herbicide carriers, etc.

EXPANDED CLAY, SHALE AND SLATE

Geology

The most widespread occurring materials that can be used to produce lightweight aggregates are the surface clays, shales and slates. These are materials that have been derived from the decomposition of pre-existing rocks by weathering. This transformation is promoted by the gases and moisture in the atmosphere, by water and its contents, and by organic matter. These agents, acting on the various components of the rock, cause oxidation, carbonation, hydration, hydrolysis, and solution. The components of the rock react in various ways to the action of the decomposition agents; quartz, the major constituent of granite, is not readily altered, but feldspars change to carbonates, clay minerals and silica. The ferro-magnesian minerals such as biotite, hornblende and pyroxene form carbonates, iron oxides and silica, while micas are altered to carbonates, clay minerals, silica and iron oxides. Decomposition of some minerals promotes the decomposition of other minerals. For example, the oxidation of sulphides such as pyrite, marcasite and galena forms sulphuric acid which affects adjacent minerals.

Decomposition can extend to a considerable depth below the surface, depending on the elevation of the water table. It is primarily limited to the depth of the water table because of the lack of oxygen and carbon dioxide below this depth. Humid regions have a much greater depth of decomposition. In Brazil, some shales have decomposed to a depth of 118 metres (387 feet).

Decomposition may be accompanied by disintegration, the mechanical fracturing of rock masses, resulting from frost action, changes in temperature, wedging by plant roots, growth of minerals, and abrasion (1,2). Decomposition products may remain in place or be moved by air, water, ice, or a combination of these agents. Transportation may be for only a short distance or for many miles to a completely different environment, and the resulting deposits may be shallow or of great depth.

There are several particle size definitions of the general term "clay". According to Krumbein and Pettijohn (3), a true clay will be composed of grains of material at least 50 per cent of which are less than $1/235$ mm ($39\text{ }\mu\text{m}$) in size. The majority of these grains are clay minerals. These authors differentiate a silt from a clay in that more than 50 per cent of the grains of silt are between $1/16$ and $1/256$ mm (625 and $39\text{ }\mu\text{m}$). Claystones and siltstones are indurated clays and silts. If they are bedded or fissile parallel to the bedding, they are classed as shales. Weakly metamorphosed claystones are referred to as argillites, and slates are any predominantly argillaceous rock in which slaty cleavage has been developed by metamorphism.

The argillaceous materials differ widely in composition, consisting of a variety of minerals. Silica is the predominant chemical component. It is present as part of the clay minerals and undecomposed silicates, and as free silica, usually quartz. Alumina is present in the clay minerals and other silicates such as feldspar. Iron occurs as oxides, in chlorites and micas and other iron silicates, and as pyrite, marcasite and siderite. Lime

and magnesia are present in carbonates, silicates, or in gypsum. The alkalies occur in feldspars or in clay minerals. Minor constituents include titania, manganese, phosphorus and organic matter. In Canada, the clay minerals, in order of decreasing general abundance, are illite, chlorite, montmorillonite and kaolin.

It is the common clays and shales that are generally used in the manufacture of lightweight aggregate. Some slates are used in the United States but generally they are too thinly bedded to develop satisfactory bloating. A clay or shale that is used to manufacture brick or tile will frequently be a suitable raw material. To be suitable, it must bloat when heated to incipient fusion.

Mechanism of Expansion of Clay and Shale

A clay, shale or slate which will bloat or expand must possess two qualities:

- (a) when it is heated to the point of incipient fusion, a gas or gases must be formed;
- (b) the glass formed on heating the material must be of such a viscosity as to entrap the gases formed.

This bloating phenomenon has been of interest for many years. To the manufacturers of brick it is an undesirable property and must be prevented. Bricks are heated at a rate such that the gases will be evolved before the glass begins to form. Many researchers have advanced theories on the phenomenon of bloating. A review of some of the more recent investigations follows.

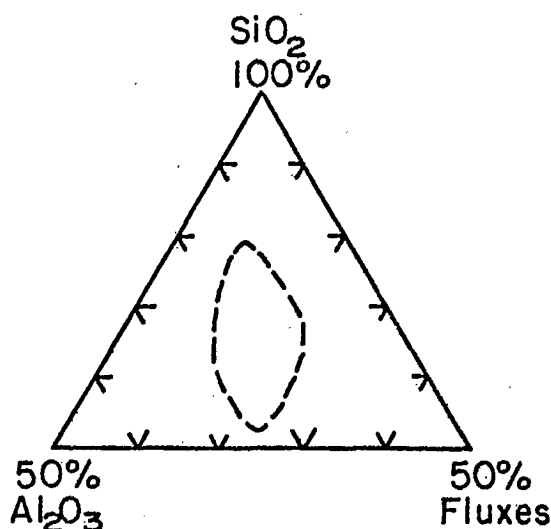


Figure 1. Composition Limits of Bloating Clays

Riley (4) plotted the chemical compositions of a large number of clays on a triaxial diagram (Figure 1) and found a limited area within which bloating clays fell. He considered that this area bounded the composition limits from which a sufficiently viscous glass would be formed on heating. Some non-bloating clays within these limits did not contain gas-producing compounds, although the optimum glassy phase was formed. He adjusted the compositions of some non-bloating clays which fell outside the "bloating area" to bring them within the limits, by additions of silica and alumina, and found they bloated. He also produced artificial clays from kaolinite, silicic acid and microcline feldspar so that their compositions fell just outside the limits. He adjusted the compositions with additions of various gas-producing compounds (pyrite, hematite, calcite, dolomite, siderite, magnesite, pyrite plus calcite, and hematite plus calcite),

and brought the compositions within the bloating limits. Only 14 of 52 compositions bloated well, the remainder bloated poorly or not at all. The gas-producing compounds that were added also acted as fluxes; it is evident that the combination of fluxes is important because not all are of equal activity.

Blyumen (5) studied surface tension and viscosity and showed that; silica and alumina increase the viscosity of the glass, soda and potash widen the vitrification range (temperature range between the start of vitrification and fusion), and calcium, magnesium and ferrous oxide decrease the viscosity and shorten the vitrification range.

Pavlov (6) found that to achieve optimum viscosity the following two conditions must be met:

- (a) the ratio $\frac{\text{free silica}}{\text{total fluxes}}$ equals 4 or less - the lower the ratio, the greater the bloating;
- (b) the ratio $\frac{\text{Fe}_2\text{O}_3 + \text{Mgo} + \text{Na}_2\text{O} + \text{K}_2\text{O}}{\text{CaO}}$ is greater than 4.

Studies by Vrublevsky (7) and Kromer (8) show how some of the clay minerals contribute to bloating through the formation of the glass phase. Vrublevsky studied the mineralogical composition and the crystallochemical changes in some Russian clays during firing. The basic crystal structure of most clay minerals is made up of two components, a tetrahedral layer of (Si, Al)-O and an octahedral layer of (Al, Mg, Fe)-(O, OH). The fundamental structural unit of the kaolins is composed of one tetrahedral and one octahedral layer. The micas, illite, montmorillonite, and vermiculite consist of single octahedral layers sandwiched between two oppositely-facing tetrahedral layers. The sheets thus formed

are separated by cations which may be readily exchangeable (montmorillonite) or entirely non-exchangeable (mica). In chlorites, these interlayer cations are replaced by an octahedrally-coordinated layer having the composition $(\text{Mg}, \text{Fe}, \text{Al}) (\text{OH})_2$.

The alumina-rich kaolin minerals do not bloat because a glassy phase is not formed until they are heated to 1400°C (2550°F). Illites, montmorillonites and chlorites bloat because their high content of alkali or alkaline earth elements promotes the formation of a glassy phase at 950° to 1050°C (1740° to 1920°F). These minerals also retain a percentage of water up to the temperatures at which bloating normally occurs.

Kromer used a hot-stage microscope in his study. He found that clays containing illite, montmorillonite, and illite interlayered with chlorite bloated, whereas clays containing kaolinite did not. He considered that the iron minerals were important fluxes.

These authors show that it is not sufficient to say that the composition shown on a ^{triangular} ~~tri~~axial diagram, as in Figure 1, will determine the viscosity of a glass. It depends on the clay minerals and on the combinations and ratios of the fluxes.

Everhart et al (9) studied the bloating gases and the sources of the gases in a large number of clays from Ohio. They were bloated, crushed in a vacuum, and the gases thus released were analyzed. In over 50 per cent of the bloated clays, carbon dioxide was the sole bloating gas. Others contained carbon dioxide and sulphur dioxide, but never sulphur dioxide alone. They found that calcite was the predominant source of carbon

dioxide, with dolomite and ankerite less common sources. In a few cases, coal was the only source of the gas. Pyrite and, in some cases, marcasite were the sources of the sulphur dioxide.

Hill and Crook (10) used chemical and mineralogical analyses in their study of a number of Australian clays and shales. They found that a high proportion of the iron in the materials fired to the bloating temperature was in the ferrous (reduced) state. They also found that the proportion of ferrous iron increased as the materials were heated through the bloating range. They believed that the reduction of ferric iron to the ferrous state with accompanying release of oxygen was the principal source of the bloating gas.

Wilson (11) improved the bloating of a poor-bloating clay through additions of lignosulphonates (calcium-ammomium, calcium, and sodium), flour, and sodium carbonates. Additions of 2 per cent were adequate with all additives.

Chopra et al (12) made a thorough study of the Pulta Silt from Calcutta, India. They found that both organic matter and calcium carbonates produced carbon dioxide, which caused bloating. Either by removing the organic matter or by destroying the calcium carbonate, the bloating of the silt was reduced; when both operations were performed, the silt did not bloat.

From the foregoing discussions it is evident that there is a diversity of opinion on the actual causes of bloating. From the works of Riley, Blyumen, Pavlov and Vrublevsky, it is evident that the chemical composition of a clay determines the viscosity of the glass formed on heating. If the fluxes are present in

sufficient quantity and the alkaline earth content is relatively low, the viscosity of the glass formed will be adequate to entrap the bloating gases. Also, the clay minerals should be montmorillonite, illite or chlorite. The work of Everhart et al (9), Hill and Crook (10), Chopra et al (12), and others not reported here shows that the bloating gases may be one, or a combination, of carbon dioxide, sulphur dioxide, oxygen and water. These gases can be formed from carbonates, organic matter, sulphates, sulphides, clay minerals and ferric oxide.

Methods of Production

The rotary kiln method is most commonly used to produce lightweight aggregate from clay, shale, or slate. All plants producing this material in Canada and most of those in the United States use rotary kilns, the exceptions being 8 plants in the United States using the sintering method. Both methods can be divided into 4 stages: quarrying, preparation of raw material, heat treatment, and preparation of aggregate.

Rotary Kiln Process

Quarrying

The method used in quarrying, which is common to both processes, depends on the nature of the deposit and the size of the operation. The topography of the area is important in planning the quarry operation; a land surface which is flat can result in problems that are not as evident in a sloping land surface. In areas where rainfall is appreciable, drainage can be a problem.

Water which collects in a quarry may have to be pumped out. The quarry could be worked in such a way that water would drain to a lower unused section while the higher, drained section was being worked. In sloping land, advantage might be taken of the natural drainage courses. A clay would be much more susceptible to the effect of water than would a shale.

Invariably, the material to be processed is overlain by undesirable material that will have to be removed. In sloping land surfaces, this can be less of a problem than in flat-lying land. If the surface drops away sharply at the edge of a deposit, such as at the side of a valley, the overburden frequently can be pushed over the edge of the embankment. In flat country, the overburden must be collected and transported a sufficient distance so that it will not have to be moved a second time to uncover the desired material. The amount of overburden that can be removed economically depends on such factors as the topography and geography of the deposit and the distances the overburden and raw material have to be transported. It could vary from $\frac{1}{2}$ to 2 feet (0.2 to 0.6 metres) per foot of recoverable raw material. The dip of the deposit, the angle at which the bed is inclined from the horizontal, should be considered. Clays are usually horizontal, but shale beds frequently dip at appreciable angles. It may be uneconomic to strip overburden from a deposit of shale over the desired area if the dip is appreciable. The overburden may be slight in one area, but excessive a short distance away.

Clays, being relatively soft, can be recovered for processing by some type of a tractor-drawn scraper, a tractor with

a front-end loader attachment, a power shovel, a drag line, or a back-hoe. All of these machines are available in various capacities to suit the size of the operation. A scraper or front-end loader would be better suited to relatively shallow deposits; whereas the shovel, drag line or back-hoe would be of more use in deeper deposits. The clay may not be uniform, but may vary in composition and properties at different levels. Frequently a clay deposit will weather at the surface with consequent leaching out of some components because of the action of rain; the depth of weathering depending on exposure to water and air. Deposits may vary at different levels, having been deposited at different times and under different conditions. It might be desirable to blend the various clays in a deposit, in which case a shovel, drag line, back-hoe or clay planer would be the most appropriate type of recovery equipment. It may be desirable to use only certain levels in the deposit, in which case the undesirable material would have to be removed.

Shales are of various hardnesses. Some can be dug from the deposit by the machines mentioned, without prior treatment, whereas if too hard to be dug, a tractor with a ripper attachment might be adequate to break them up. The depth loosened, depending on the hardness of the shale, varies from a few inches to 3 to 4 ft (0.9 or 1.2 m). Harder shales and slates would have to be drilled and blasted to break them up. A shovel is the most suitable recovery equipment for shale that has been broken by blasting.

In preparation for blasting, a hand-held drill, (Figure 2), could be used to drill shallow holes in a shale, whereas a

ram track drill of the type shown in Figure 3 could be used for deep holes in a hard shale. The crawler-mounted tractor with a bull-dozer blade and ripper tooth as shown in Figure 4 is typical of the equipment used to break up shales of intermediate hardness.

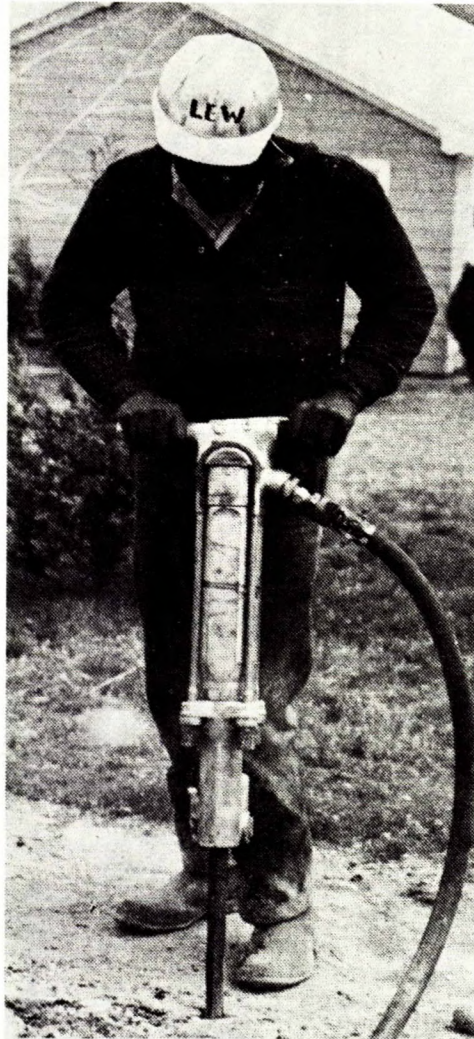


Figure 2. Hand-Held Drill
Courtesy - Joy Manufacturing Co. (Canada) Ltd.,
Cambridge, Ontario



Figure 3. Ram Track Drill
Courtesy - Joy Manufacturing Co. (Canada) Ltd.,
Cambridge, Ontario

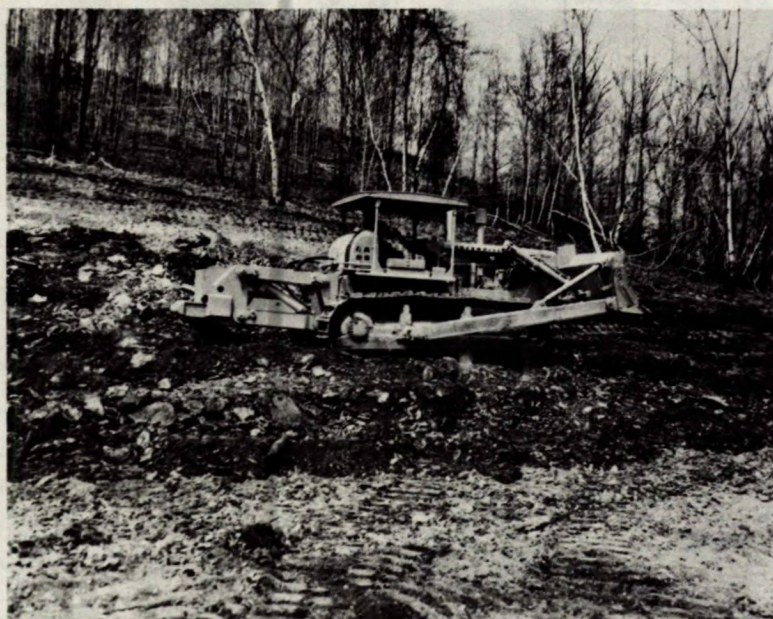


Figure 4. Crawler-Mounted Tractor Equipped with
Bulldozer Blade and Ripper
Courtesy - Caterpillar of Canada Ltd.,
Mississauga, Ontario

The material can be moved from the quarry to the plant by various means; the truck being the most maneuverable and versatile means of transport. The belt conveyor is usually a relatively fixed apparatus and must be fed by some other equipment. Nevertheless, it can be extended or moved periodically as the point of loading has to be moved.

Generally, quarrying is done during an 8-hour period, whereas the plant operates for the full 24 hours. Particularly if the raw material is a clay, inclement weather, such as rain or snow, could make it impractical to quarry, and storage space should be provided to maintain raw material feed to the plant.

Preparation of Raw Material

Preparation primarily involves crushing and sizing. The crushing can be done by jaw, rolls, gyratory or cone crushers, or by hammer or impact mills. The type of crusher used depends on the crushing characteristics of the material and the size desired, the optimum shape of the crushed particle being a cube. The shape is important because it governs the shape of the resulting aggregate. Crushing might be done in a single operation or it might include secondary crushing combined with screening before the desired sizing is achieved. Vibratory screens are usually employed.

The jaw crusher is the most popular primary crusher for shales, slates and relatively dry clays. Wet or sticky clays would tend to plug this type of crusher. Figure 5 is a sectional photograph of a jaw crusher.

There are several types of roll crushers. Single roll

crushers usually have knobs or teeth around the periphery of the roll, which abrade and spall the material against a concave breaker plate. This is not a common type of crusher. It is useful on semi-hard or slightly wet material. Double-roll crushers are either smooth, corrugated, or toothed. They are effective on semi-hard and wet material. If the clay is sticky it is advantageous for one roll to rotate more rapidly than the other. The rolls rotating at unequal speeds tend to shred the clay.

Conical rolls can be used to remove stones from a clay. The stones move to the end of the rolls. Figure 6 is an illustration of a stripped-down double roll crusher showing the spring mounting of one roll, which prevents jamming of material between the rolls. The space between the rolls is adjustable.

There are many slight variations of gyratory crushers, differing in the slope of the cone. The cone in a gyratory crusher has a steep slope, whereas in the cone crusher the slope is flatter. The cone crusher is generally used as a secondary crusher on hard material.

Figure 8 shows a sectional view of a typical hammer mill. The rotor, equipped with hammers, revolves at high speed. The material is crushed by both the impact of the hammers and by being thrown against the breaker plates. When the material has been crushed sufficiently, it passes between the screen bars at the bottom of the machine. It can be used on a variety of materials.

An impact mill differs from a hammer mill in that the rotor revolves at higher speed and the machine does not contain screen bars.

Figure 9 illustrates the construction of a double-deck vibratory screen. The screen, as illustrated, will produce three size-fractions of material. The screen may have to be electrically heated if the material has a tendency to blind the screen when damp.

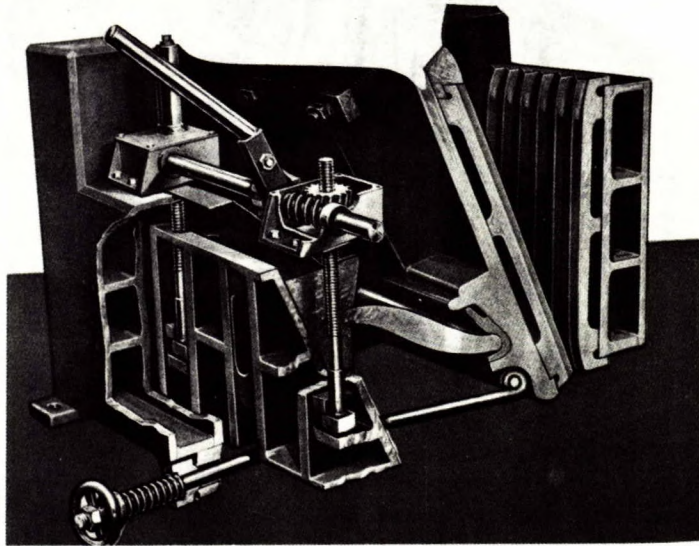


Figure 5. Jaw Crusher

Courtesy - Pioneer Div. of Portec Inc.,
Minneapolis, Minn.

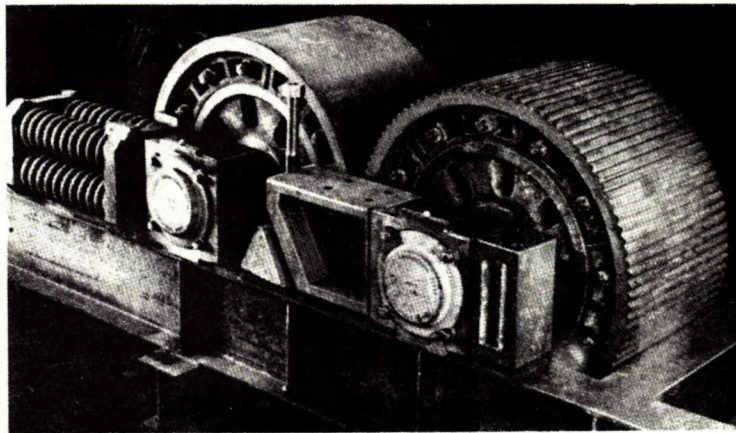


Figure 6. Double Roll Crusher

Courtesy - Pioneer Div. of Portec Inc.,
Minneapolis, Minn.

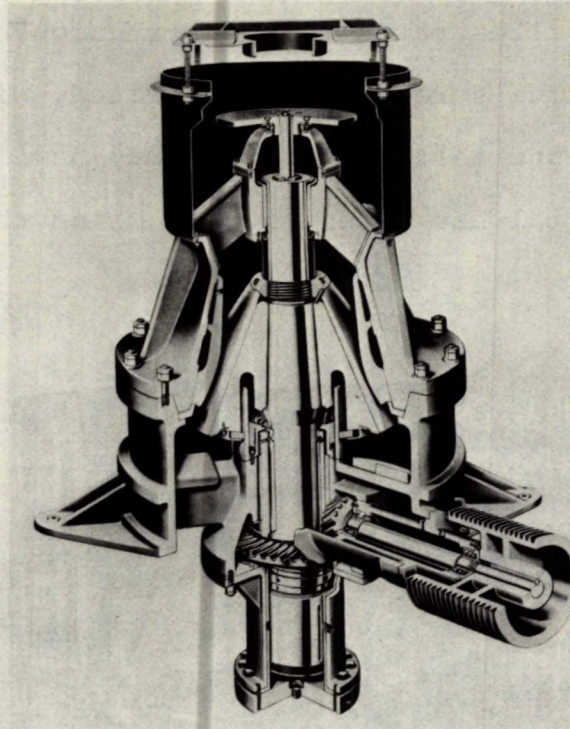


Figure 7. Gyratory Crusher (Hydra-Cone)
Courtesy - Canadian Allis-Chalmers Limited,
Lachine, Quebec

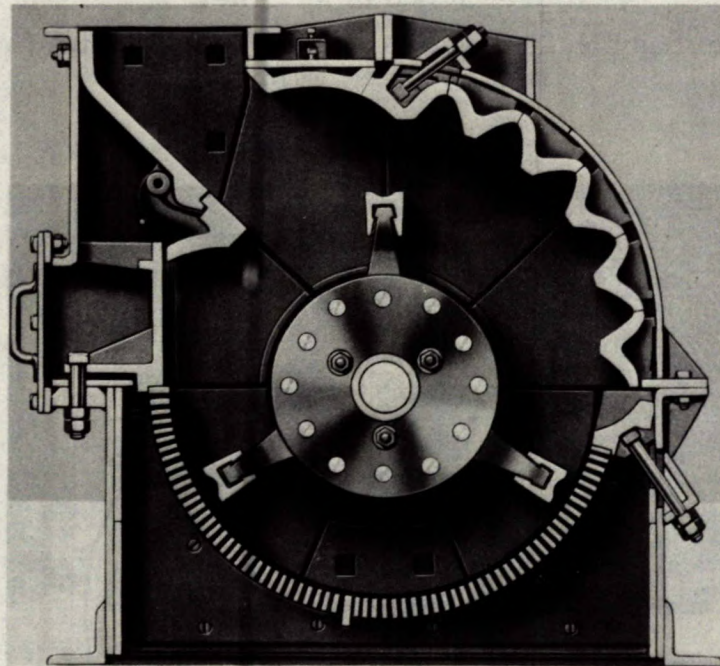


Figure 8. Hammer Mill
Courtesy - Canadian Allis-Chalmers Limited,
Lachine, Quebec

Depending on the firing characteristics of the material and the type of product desired, the material might have to be screened into fairly closely sized fractions. In one plant, shale is sized as follows: $\frac{3}{4}$ to $\frac{9}{16}$ in. (19.0 to 14.3 mm), $\frac{9}{16}$ to $\frac{5}{16}$ in. (14.3 to 7.9 mm), $\frac{5}{16}$ to $\frac{1}{8}$ in. (7.9 to 3.2 mm), and minus $\frac{1}{8}$ in. (3.2 mm). At another plant, shale is screened $1\frac{1}{2}$ to $\frac{1}{8}$ in. (38.1 to 3.2 mm). In the former case, each size is fed into a different rotary kiln. The kiln feed should be sized so that the product from the kiln requires a minimum of crushing to produce the desired sizes of aggregate.

With shale or slate as the raw material, the crushing and screening operations are usually all that are required to prepare the feed for the kiln. This also applies to some clays. Other clays however, are too soft or friable to withstand handling, and they crumble, resulting in too many "fines", while others are not sufficiently dense to entrap the bloating gases, resulting in a poor product. It may be necessary to blend two or more clays and, in cases such as these, the clay is pelletized. There are three popular types of pelletizing equipment used: the balling drum, the pelletizing disc, and the extrusion machine.

The balling drum is the simplest and least expensive of the three. It is a nearly horizontal revolving drum, into the higher end of which crushed clay is fed. A perforated pipe sprays water on the clay as it moves through the drum. Many drums incorporate a shaft with attached blades rotating in the reverse direction to the drum. The action pelletizes the material; the size of the pellets being controlled, to a degree, by the rate of feed

of clay, the speeds of the drum and shaft, and the amount of water added. A screen at the discharge end of the drum removes the undersized particles which are fed back into the drum. The drum is frequently lined with loosely attached rubber which flexes as the drum revolves and prevents the material building up on the wall.

The pelletizing disc or pan is an inclined disc (about 45 degrees) revolving about its central axis and having a rim extending above the surface of the disc. The rim may be perpendicular to the disc, may slope outward or may rise in steps. The action as the disc revolves is an alternate wetting of the particles with a water spray and a coating of dry material. This action causes a snow-balling effect as the particles gradually increase in size.

The largest spheres move to the periphery of the disc and discharge over the rim when they have reached the desired size. The size, which can be controlled much more closely in this machine than in the balling drum, depends on the slope and rotational speed of the disc, the height of the rim, and the points of introduction of the dry material and the water. Figure 10 illustrates one type of pan pelletizer.

The extrusion machine is a horizontal tub in which a shaft incorporating a series of knives or blades along its length, mixes clay and water until the clay reaches the plastic state. The knives are set at an angle so that, as well as mixing, they move the material along the tub. An enclosed auger on the end of the shaft picks up the plastic clay and extrudes it through a die.

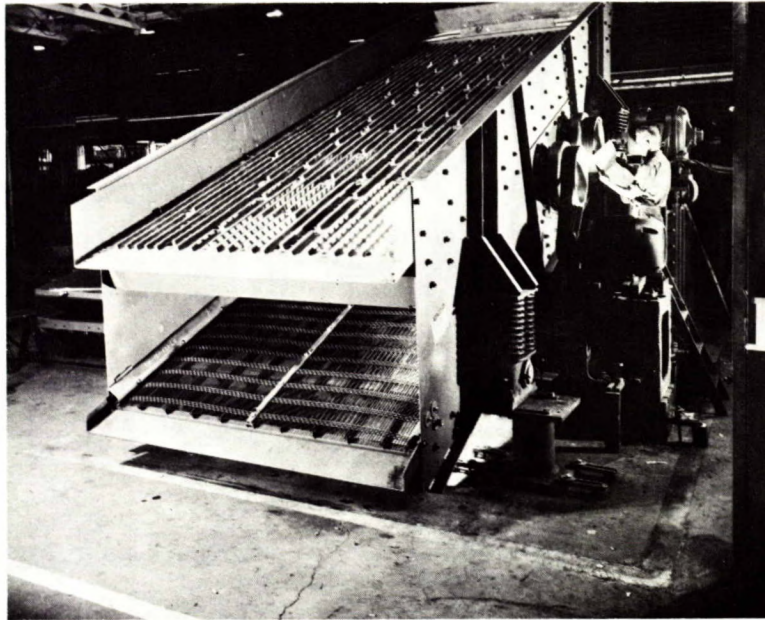


Figure 9. Double-Deck, Vibratory Screen
Courtesy - Canadian Allis-Chalmers Limited,
Lachine, Quebec

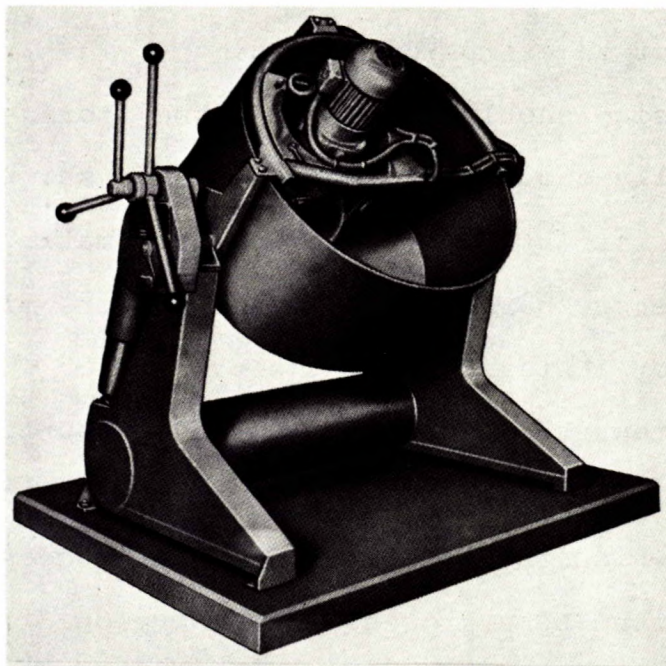


Figure 10. Pan Pelletizer
Courtesy - Maschinenfabrik Gustav Eirich,
Hardheim, Nordbaden, West Germany

The tub may contain two shafts with knives. These shafts, which rotate in opposite directions, are used when the clay has low plasticity and they should give better mixing and pugging than the single shaft. The machine may also incorporate a vacuum chamber. The plastic clay drops from the end of the tub into a chamber from which air is extracted by a vacuum pump. An auger in the lower portion of the chamber extrudes the deaired clay through the die. Deairing the clay makes it more dense and usually results in a better bloated material.

The die may be either a perforated plate or a heavy-wire screen. The streams of clay issuing from the die are cut off by a revolving knife or break off under their own weight. The extruded pellets are more dense than those made by the other machines and in most cases result in greater bloating. Figures 11 and 12 show two views of an extrusion machine.

Provision should be made for the storage of prepared raw material. Usually enough is prepared in one shift to keep the plant operating for three shifts. Prepared material should be on hand in case the crushers or pelletizer require minor repairs. Thus, storage for at least one day's production should be provided.

The prepared feed passes through a surge bin and into the rotary kiln. The surge bin permits feed to the kiln at a constant rate, which is very important to a successful kiln operation. The patented Leca process (13), developed in Europe, does not make use of separate pelletizing equipment. The raw material is ground, mixed with water (and in some cases a small amount of a bloating agent) and introduced into the kiln in the plastic state.

The lumps of clay are broken down and are pelletized as they travel through the kiln.

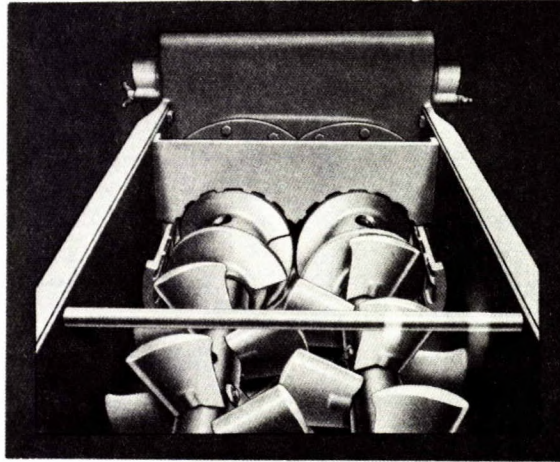


Figure 11. View of Extrusion Machine Tub
Courtesy - Fate-Root-Heath Company,
Plymouth, Ohio

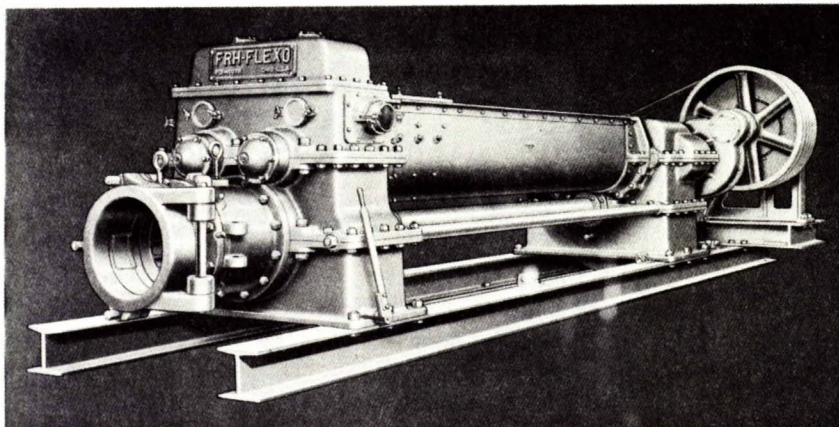


Figure 12. Extrusion Machine
Courtesy - Fate-Root-Heath Company,
Plymouth, Ohio

The sizing of the feed is very important to the quality of product; the larger lumps or pellets require more heat than do the smaller pieces to give equivalent bloating. Depending on the particular raw material, the feed may have to be sized closely and different sizes fired in separate kilns. With other materials, if the sizing effect is not as great, a size range of $1\frac{1}{2}$ to $\frac{1}{8}$ in. (38.1 to 3.2 mm) feed into one kiln would be acceptable.

By the Liapor process (14), developed in Germany, lightweight aggregate sized $\frac{5}{16}$ to $\frac{5}{8}$ in. (7.9 to 15.9 mm), can be produced at unit weights of 19 to 50 lb/ft³ (300 to 800 kg/m³). The raw material is ground to about 170 mesh (90 μ m) and pelletized, the pellets being sized within narrow limits. To produce an aggregate of low unit weight a bloating agent is added in the pelletizing operation and the pellets are coated with a material that prevents agglomeration in the kiln. The firing operation is controlled closely to obtain an extremely uniform product.

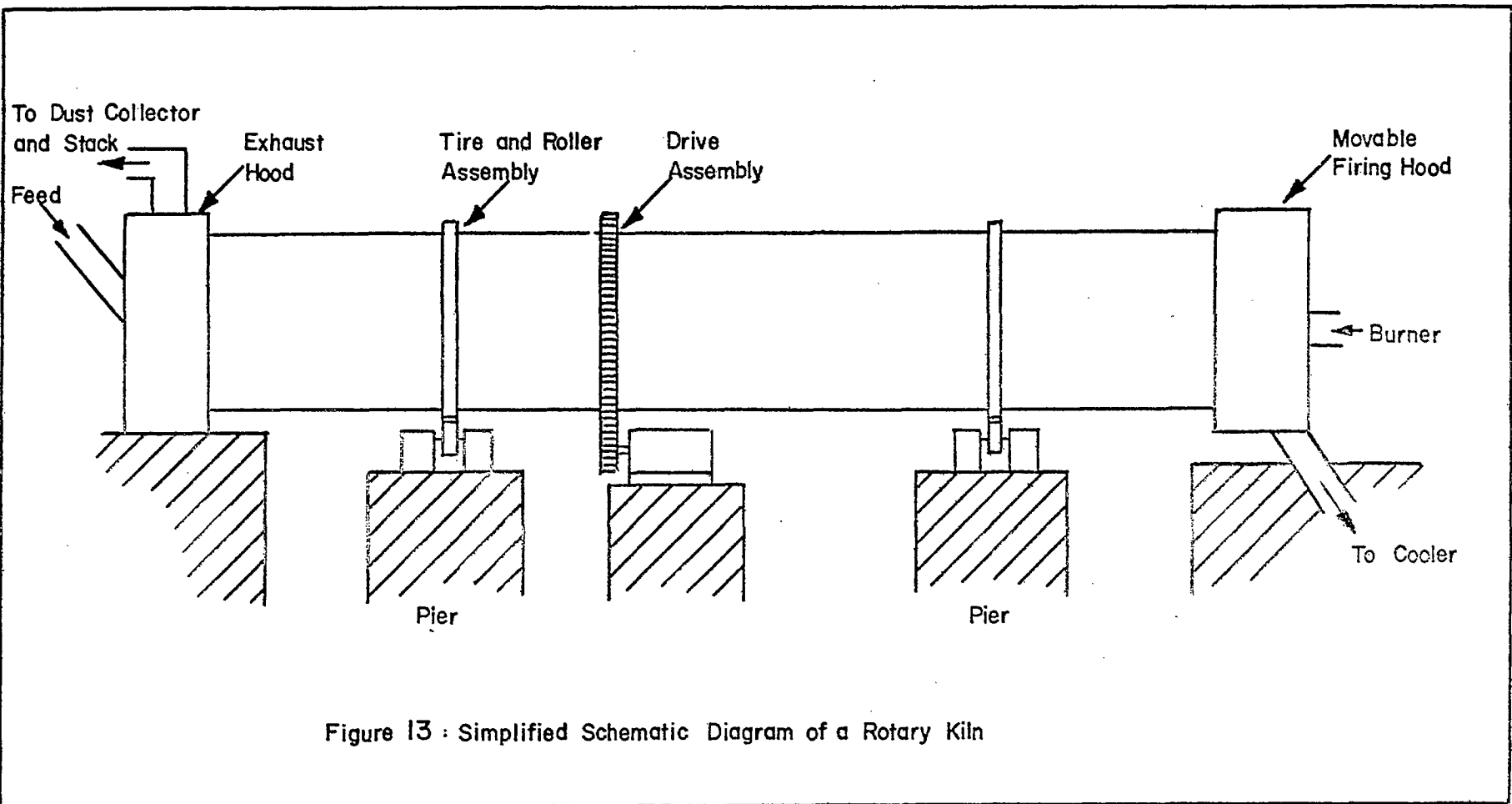
Firing

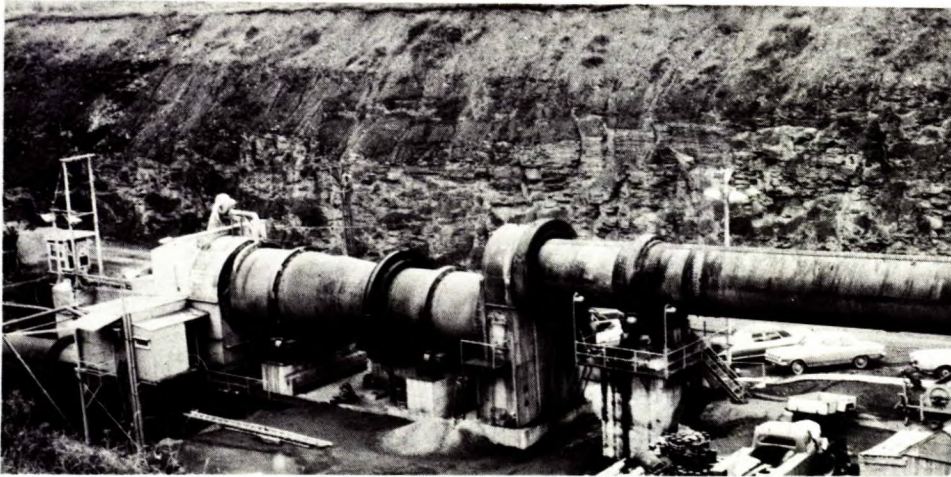
The rotary kiln, in its simplest form, is a nearly horizontal refractory-lined cylinder, rotating about its longitudinal axis. The raw material is fed into the upper end and the heat is applied at the lower end, the material travelling counter-current to the heat flow. The material is heated in about 30 to 60 minutes, depending on the length, diameter, and rotational speed, to a maximum temperature of between 1050° and 1200°C (1920° and 2190°F). The heating rate is gradual for about $\frac{2}{3}$ the length of the kiln, then it increases rapidly until the maximum is reached;

thus heating the interior of the particles so that gases will be liberated to be trapped by glass formed nearer the surface of the particles.

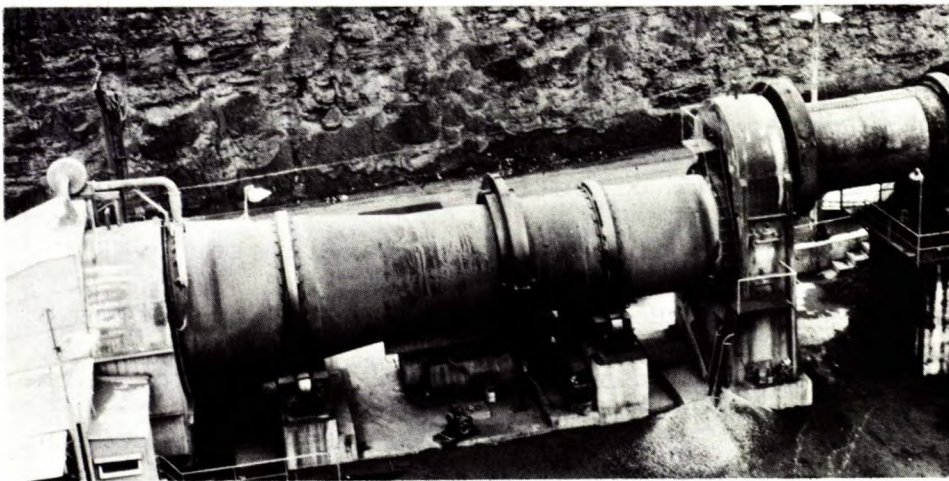
The kilns used in existing plants are of various lengths, from 60 to 225 ft (18.3 to 68.6 m), and diameters, from 6 to 12 ft (1.8 to 3.7 m). Most kilns are of one diameter throughout the entire length, (Figure 13), but some are of two diameters, the larger diameter being at the bloating zone. The material moves more rapidly in the smaller preheat zone than in the larger bloating zone. By slowing the rate of travel in the bloating zone, more uniform bloating is achieved.

Figure 14 shows two views of a plant incorporating preheat and bloating kilns, and a rotary cooler.





(a)



(b)

Figure 14. Two Views of a Rotary Kiln Plant

- (a) Preheat and bloating kilns and rotary cooler (extreme left)
- (b) Junction of preheat and bloating kilns

Former Cell-Rock Inc.,
Lafleche, Que.

Some plants incorporate a two-kiln system, a pre-heating or drying kiln and a bloating kiln in series. The heat can be applied in various ways. Both kilns may be fired by a single burner at the lower end of the bloating kiln, the heat flowing from the bloating kiln through a breaching into the preheating kiln (Figure 14), or the two may be heated by a burner in each kiln, the heat also flowing from the bloating kiln into the pre-heating kiln. One process (15) uses a single burner in the pre-heater and one in each end of a short bloating kiln. These types of heat application are used to improve the transfer of heat to the material in the kiln and to obtain more uniform bloating.

The circulation streaming process (16,17) does not make use of a rotary kiln, but the principle of producing a bloated lightweight aggregate is the same. The clay is ground, then pelletized in a disc pelletizer, and the pellets are dried at 200°C (400°F). The dried pellets are held in a feed sluice and a volumetric batched quantity of pellets is fed to a vertical furnace of 8 ft diameter by 26 ft height (2.5 m diameter by 8.0 m height). The material is hit by a turbulent flame in the bottom of the furnace. The pellets are repeatedly thrown upward by the flame and fall back to the bottom. This circulation is continued for 45 seconds, then the material is discharged from the furnace, in a bloated condition. The process is repeated with fresh, dried pellets every 50 seconds. At 220 lb (100 kg) per charge, the capacity of the furnace is about 8 tons/hr, consuming 1800 Btu/lb (4.2×10^6 j/kg) of aggregate.

Rotary Kiln Efficiency

The rotary kiln is an inefficient heat exchanger. In some plants only about 10 per cent of the heat applied is actually used to bloat the material. The remainder of the heat is lost through:

- (a) the combustion gases and moisture exhausting from the kiln;
- (b) radiation from the kiln shell;
- (c) retention in the aggregate discharged from the kiln.

With continuing increases in the cost of fuel, the efficiency of the bloating operation is becoming of great importance to the producer. Various means of reducing the heat losses are possible. Longer kilns reduce the temperature of the exhaust gases, more of the heat being absorbed by the material; the radiating surface at the kiln is increased however. Smaller diameters reduce both the unoccupied kiln volume and the radiating surface of the kiln. Product coolers recover some of the heat contained in the aggregate discharged from the kiln, the heated air from the cooler being introduced into the kiln usually as secondary combustion air. Rotary coolers are typically in the range of 4 to 10 ft (1.2 to 3.1 m) in diameter by 40 to 120 ft (12.2 to 36.4 m) in length; they are usually refractory lined for at least half the length. Travelling grate coolers are more flexible than rotary coolers in that the quantity of air flowing from the grate cooler into the kiln can be regulated, whereas all the air from the rotary cooler goes into the kiln. The grate cooler is a more efficient heat exchanger than the rotary cooler. A third method of heat recovery uses planetary coolers.

There are usually 10 cylindrical coolers about 4 ft (1.2 m) in diameter by 25 ft (7.6 m) long, mounted around the shell of the kiln at the discharge end.

Another, and more recent approach to the problem of heat loss is to recover heat from the exhaust gases by using a raw material preheater. This can be a single or multiple chamber arrangement in which the material is in more intimate contact with the flue gases than in the kiln and better heat transfer is attained. It is installed immediately preceeding the kiln. Mirkovich (18) showed, by the use of a heat balance, that 36 per cent of the heat being consumed in a particular lightweight aggregate operation could be saved through the use of a preheater. Wilson (19) used a laboratory model simulated rotary kiln to show that the material used in this operation could be preheated to 500°C (930°F) without decreasing or increasing the bloating presently being achieved in the rotary kiln.

A further approach to this problem of heat wasted with the exhaust gases involves kiln internals such as lifters, dams, or quadrants. The principle of internals in the feed end of the kiln is similar to that of a preheater: the material is in more intimate contact with the hot gases and better heat transfer is accomplished. Biege and Cohen (20) found that internals produced a fuel saving of approximately 564,000 Btu/ton (650,000 j/kg) of product, or 21 per cent. Figure 15 illustrates kiln lifters and quadrants.

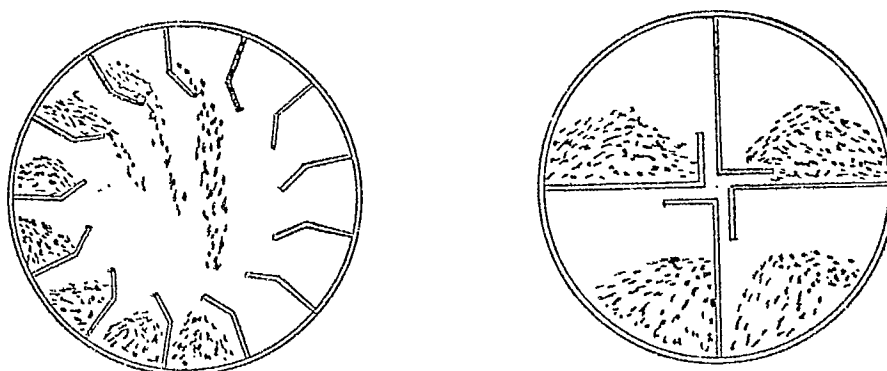


Figure 15. Kiln Internals

The adjustment of the burner or burners in a rotary-kiln installation will affect the efficiency of the process as well as the quality of the product. The fuel:air ratio in the burner will affect the atmosphere in the kiln, and could have a marked effect on the glass-forming temperature of the raw material which is lower in a reducing atmosphere (the fuel is not completely burned). This could result in improved bloating over that achieved under oxidizing conditions (complete combustion). A reducing condition is usually accompanied by smoke, a condition unlikely to be acceptable under environmental regulations. The direction and shape of the flame within the kiln will affect the heat transfer from the flame to the bed of material. A long thin flame will transfer its heat over a greater length of the kiln than will a shorter, broader flame. A very short flame that liberates all its heat in the first few feet of the kiln will result in a high surface heat in the material, whereas the interior of the particles would

obtain insufficient heat to provide for proper expansion. Most commercial burners have built-in adjustability and a variety of conditions can be used until the best has been obtained. The bloating-temperature range of a clay or shale is the range between that temperature at which minimum acceptable bloating occurs and that at which agglomeration of the particles is excessive. It could be as little as 30 Celsius deg (50 Fahrenheit deg), and then extremely accurate temperature control would be required. The bed of material would have to be uniformly heated to produce a uniform lightweight aggregate.

The more efficient rotary kiln plants consume about 1.5 million Btu/yd³ (2070×10^6 j/m³) of product. Pulverized coal, fuel oil and natural gas have all been used to supply heat, and the economies of the various fuels available should be considered. Oil and gas are the most commonly used fuels.

Natural gas has a heating value of 1000 Btu/ft³ (37.4×10^6 j/m³). Theoretical air required for combustion is 10.2 ft³ per ft³ of gas (10.2 m³ per m³). At 20 per cent excess air, fuel and air requirements would be 2,000 ft³ (56 m³) of gas and 24,400 ft³ (690 m³) of air to produce one yd³ (0.76 m³) of lightweight aggregate.

Number 6 fuel oil (about 2 per cent sulphur), which is the grade of oil most commonly used in industrial installations in Canada, has a heating value of 18,330 Btu/lb (42.8×10^6 j/kg). The theoretical air requirement for combustion is 1825 ft³/imperial gal (11 m³/l). With 20 per cent excess air, the oil and air required to produce the aggregate would be 11.0 gal (imperial)

(50.0 litres) and 2000 ft³ (57 m³) of air per yd³ (0.76 m³).

This oil is of too high a viscosity to be atomized and burned at normal ambient temperatures, and must be preheated to about 120°C (250°F). Heating can be done by electricity, by utilizing waste heat from the kiln, or by steam.

The use of an aggregate cooler from which heat is recovered and introduced into the kiln through the combustion air increases the temperature of the flame and also reduces the total heat input required. The efficiency of the rotary cooler could be increased by either internal or external insulation, or by erecting a stationary shield around the hot end.

In a rotary kiln plant, control of the draft through the kiln is important. Fluctuation in draft will result in fluctuation in temperature, and consequently variation in the quality of the product. The most positive way of controlling draft is to make use of a fan in the exhaust system, equipped with a mechanically or electronically-controlled damper. The controls on the damper sense changes in draft due to changes in conditions in the kiln and compensate to continuously regulate the draft.

If the plant is situated in a populated area, it is certain that the dust would have to be removed from the stack gases. Even if the area is not populated, the dust would probably become undesirable and should be collected. A cyclone or series of cyclones are effective in collecting the coarse particles in the dust, while electrostatic precipitators, wet scrubbers and glass bag collectors are most efficient in removing the fine dust from the gases. The electrostatic precipitator cannot be used

effectively in all applications because many clays and shales exhibit resistivity to an electrostatic charge. The wet scrubber necessitates a supply of water and an area for a settling pond. The glass-bag collector is the most universally efficient dust collector (above 99 per cent). The efficiency of the electrostatic collector is partly dependent on the moisture content of the gases, and the efficiency of the scrubber depends on the velocity of the gases. The temperature of the gases is critical in the bag collector; above 315°C (600°F) the bags may be burned, and below 175°C (350°F) condensation of moisture may be a problem (21).

Figure 16 is an aerial view of a complete aggregate and concrete plant with raw material preparation upper left, kiln and cooler centre, aggregate preparation and stock piles right, and concrete batching plant in the background.

Preparation of Aggregates

Aggregates for structural lightweight concrete are usually sized minus $\frac{3}{4}$ in. (19.0 mm). For most structural applications, lightweight concrete is in reality semi-lightweight. The coarse aggregate, $\frac{3}{4}$ in. to 4 mesh (19.0 to 4.8 mm) is lightweight and the fine aggregate, minus 4 mesh (minus 4.8 mm) is normal weight.

If the lightweight aggregate discharges from the kiln as discrete particles, it is classified as "coated". All the Canadian plants produce this type of lightweight aggregate. If the particles are of the desired sizes, they only require screening into the various size fractions. If any of the particles are

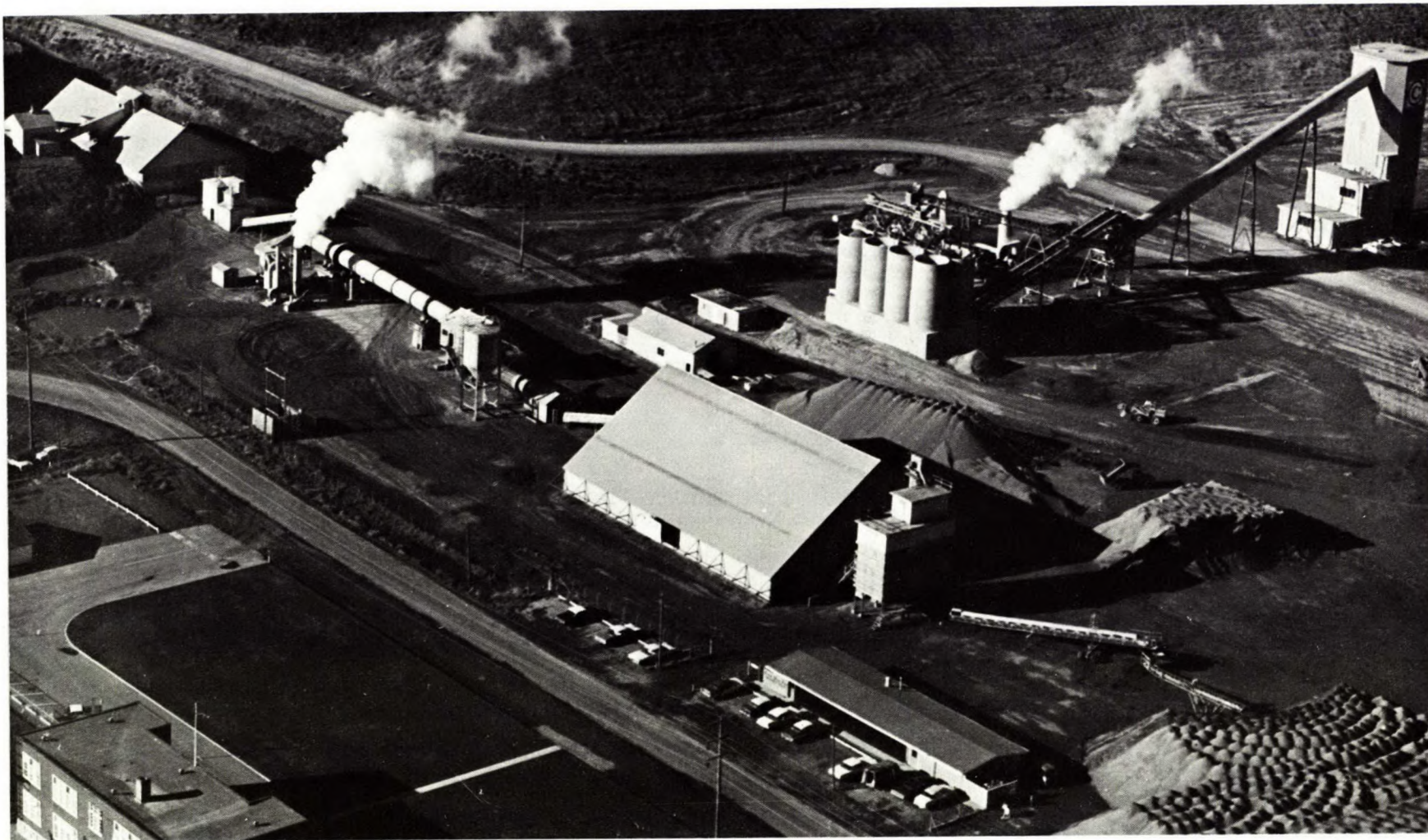


Figure 16. Aerial View of Complete Plant

Upper Left: Row material preparation	Centre: Kiln and cooler
Right: Aggregate Preparation and stock	Background: Concrete batching plant

Courtesy - Consolidated Concrete Limited,
Calgary, Alberta (1967)

over-sized, or if the particles agglomerated in the kiln, crushing will be required before screening. For structural concrete, a coated lightweight aggregate is considered superior to a crushed aggregate because the coated aggregate generally has lower absorption and gives a concrete better workability for an equivalent cement and water content.

Aggregate for lightweight concrete masonry units is normally sized minus $\frac{1}{2}$ in. (12.5 mm) or minus $\frac{3}{8}$ in. (9.5 mm). The aggregate is usually all lightweight. This aggregate can be the crushed variety because workability is relatively unimportant and the concrete mix is drier than that for structural concrete.

A variety of crushing equipment can be used, such as jaw, rolls, cone, gyratory or impact crushers. The choice of crusher could effect the shape of the crushed aggregate as well as the grading, the optimum shape being a cube. The crusher should be selected so that a single crushing operation would give the desired grading, if possible. Crushing should be done in circuit with screens so that over-sized particles can be returned to the crusher.

Storage of the sized lightweight aggregate is important. The finer the size of the aggregate, the higher is the specific gravity, and this difference in specific gravity could result in segregation in storage. It can be reduced by storing in closely-sized fractions. This also gives more flexibility in grading when the fractions are combined. There should also be storage for unscreened aggregate to be used when the kiln is not in operation.

Figure 17 shows the interior of a particle of "coated"

lightweight aggregate produced from bloated shale in a rotary kiln.

Figure 18 is a simplified flow sheet diagram of a typical rotary kiln plant. The raw material shown is a shale, but the diagram would apply to a clay.

The process includes feed to the kiln of minus $\frac{3}{4}$ in. (19.0 mm) and also, equipment to pelletize the minus 8 mesh (2.4 mm) material, if required.

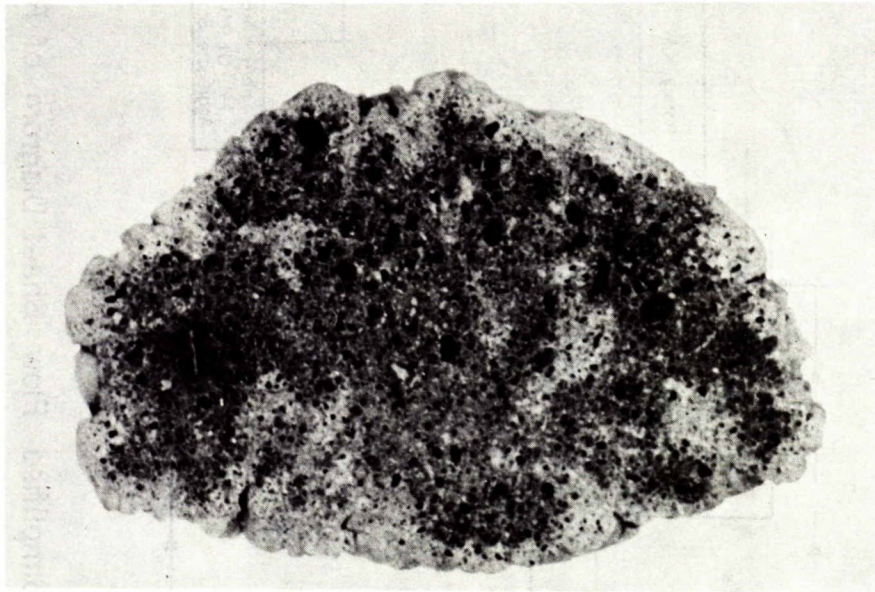


Figure 17. Interior of Bloated Shale,
reflected light, x 4

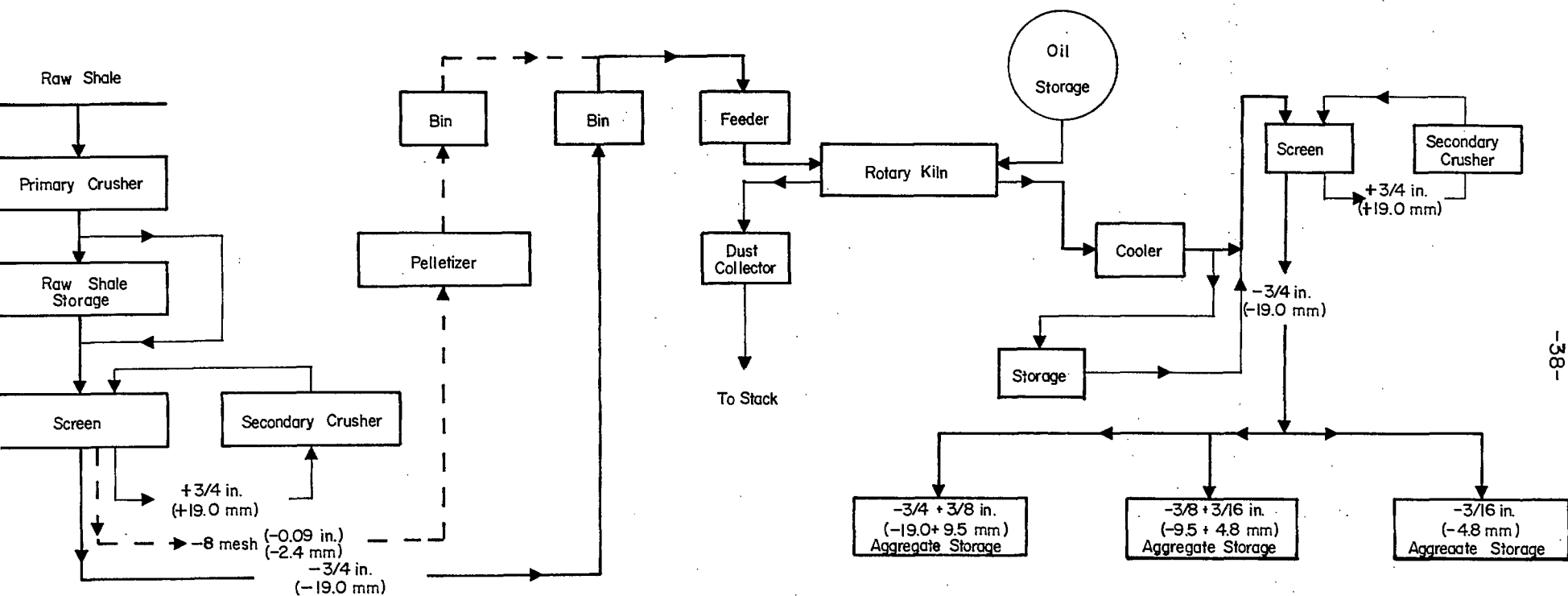


Figure 18 : Simplified Flow Sheet Diagram of Rotary Kiln Process

Sintering Process

The same methods of quarrying and transporting the clay or shale would be used for this process as for the rotary kiln process.

Preparation of Raw Material

The characteristics of the raw material govern, to a degree, the preparation and processing details. Generally, it is ground to about minus $\frac{1}{2}$ in. (12.5 mm), or less in some cases, and is mixed with 2 to 10 per cent of $\frac{1}{4}$ in. (6.4 mm) coke or coal, up to 30 per cent returned sinter fines, and 5 to 10 per cent water, in a balling drum, pug mill, or disc pelletizer. This is not usually a true pelletizing operation, as in the rotary kiln process, but is done to achieve a uniform mixing and agglomeration of the ingredients. The sizes and proportions of the ingredients, and the degree of pelletization will affect the sintering rate and the quality of the product.

Another raw material which is used in this process is fly ash, the finely divided particles of ash formed in the boilers of coal fired steam-generating electric power plants. It is a waste material at the electric power plants and frequently causes a disposal problem. Fly ash generally contains sufficient unburned fuel to be sintered. The amount of fuel can vary considerably depending on the requirement for electricity and the subsequent load on the boiler in which the fly ash is formed. This variation in fuel can cause problems in the sintering operation. The preparation of fly ash for sintering differs from that of

clay or shale in that the fly ash is generally pelletized rather than agglomerated.

Heat Treatment

The pelletized raw material-fuel mixture is placed on a grate as a permeable bed. The fuel is ignited at the surface, and the combustion is supported by a flow of air through the bed causing it to sinter to a clinker, which is crushed to aggregate size. The bed is usually from 6 to 12 in. (152 to 305 mm) in depth.

In the usual down-draft process, the bed of material passes under an ignition hood where the fuel at the top is ignited. The bed progresses over a series of wind boxes that draw a large quantity of air down through the bed. This air supports the combustion of the fuel, and by the time the bed has reached the end of the sintering machine, the fuel has been consumed, and the particles have agglomerated to a porous clinker. One installation uses an up-draft process; after a layer of fuel is placed on the grates and ignited, a bed of material is put on top of the fuel. Air passing up through the bed supports combustion of the fuel. The down draft process is the more common of the two. If fly ash is sintered, the pellets do not usually form a clinker, but are recovered as heat-hardened pellets.

Anthracite coal has an average heating value of about 12,700 Btu/lb or 25.4 million Btu/short ton (29.4×10^6 j/kg) (22). Theoretical air requirement for complete combustion is about 136 ft³/lb (8.5 m³/kg) of coal. Assuming that 20 per cent excess air

is supplied for combustion and that the aggregate has a density of 1700 lb/yd³ (1000 kg/m³), requirements to produce 1 yd³ (0.76 m³) of aggregate would be 157 lb (71 kg) of fuel and 25,700 ft³ (728 m³) of air.

Bituminous coal has an average heating value of 13,100 Btu/lb or 26.2 million Btu/short ton (30.4×10^6 j/kg). Theoretical air requirement is 138 ft³/lb (8.6 m³/kg). Again assuming the density of the aggregate is 1700 lb/yd³ (1000 kg/m³), fuel and air requirements per cubic yard (0.76 m³) would be 153 lb (69 kg) and 24,700 ft³ (700 m³), at 20 per cent excess air.

The amount of fuel required in sintering depends on the sintering characteristics of the raw material. The amount of air required will depend on the fuel and the sintering rate. Some raw materials, such as coal mine wastes, contain sufficient combustible matter to be used without further addition of fuel.

The wind boxes in a sintering machine each extend the width of the grates, and from 8 to 11 ft (2.4 to 3.4 m) along the length of the strand. The volume of air required to support combustion depends on the sintering characteristics of the bed, but would probably be between 8,000 and 14,000 ft³/min (225 and 375 m³/min) per wind box.

The actual sintering at any time during the process takes place in a thin zone between the cooling product and the zone containing unburned fuel. The temperature within the sintering zone may be as high as 1650°C (3000°F).

Figure 19 shows a typical heating-cooling curve for a point within the bed on a down-draft sintering machine.

The maximum temperature reached near the surface will be less than further down in the bed because of the cooling action of the incoming air at the surface. This will probably result in slightly different strengths between the surface layer and that of material further down in the bed. The maximum heat reached at the bottom close to the grate will also be lower.

All sintering processes produce some unsintered material. Heat losses at the top, bottom and sides of the machine result in some material not being fused into a clinker. This material is screened out of the product and recirculated to the machine.

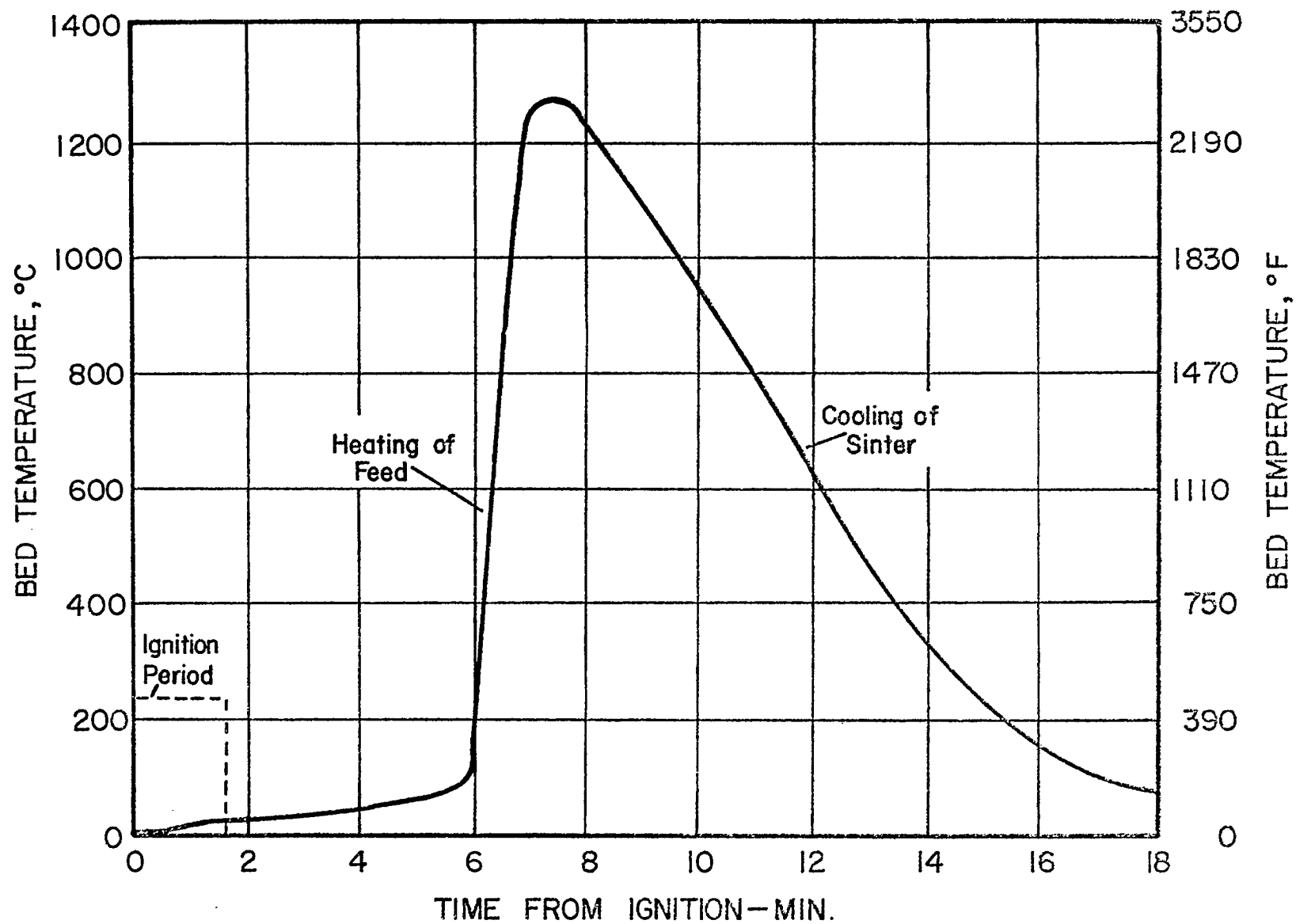


Figure 19. Heating-Cooling Curve of a Point in the Bed During Sintering.

The moisture in the bed is an important factor in sintering, from two aspects. In a physical sense, it preserves the permeability of the bed; an increased moisture content (up to an optimum) increases the permeability because the particles tend to form a more open bed. Above the optimum, the agglomerated material will not hold together and the permeability decreases. The second aspect of the moisture content is its effect on the shape of the heating-cooling curve. The higher the moisture content up to the optimum, the steeper is the heating curve. The maximum temperature reached is also higher, since moisture retards the heat flow in advance of the flame front (ignition zone) and allows the heat release to be concentrated in a narrower zone. However, if an excess of moisture is present, the rise in temperature is almost instantaneous, and the flame will be extinguished. Thus, the moisture content should be high enough to give the bed adequate permeability for rapid sintering and for liberating the optimum heat required (23).

The temperature reached in the bed should be sufficient to produce aggregate of optimum strength and unit weight. Hence, the fuel content must be adjusted to meet the existing operating variables. As mentioned previously, the heat liberated in the upper surface of the bed is less than that further down in the bed. By preheating the air entering the bed while the flame front is near the surface, the maximum temperature would be raised. This would in turn raise the maximum temperature farther down in the bed where it normally receives preheated air. To prevent overheating, the fuel content would have to be decreased. Exhaust

gases could be used to also preheat the bed prior to ignition.

The sintering operation was originally developed for use on metallic ores which normally show some shrinkage during sintering. Some clays and shales also shrink during sintering. If this occurs, the air pressure applied (either forced or induced) must be gradually decreased as the bed moves along in the machine to maintain a constant volume of air flowing through the bed. As the material shrinks, the void spaces between the pellets are enlarged. If a single exhaust fan is used, dampers in the ducts from the wind boxes would be adjusted to regulate the air flow through the bed. The draft pressure could vary as much as from 2 to 30 in. (50.8 to 762.0 mm) of water from one end of the machine to the other. In some plants, individual fans are connected to the wind boxes.

Many clays and shales will expand or bloat during sintering because of the formation of gases within the agglomerated material as in the rotary-kiln process. In this case, the draft of the air would have to be gradually increased as the void spaces in the bed become smaller.

Sintering machines are made in a variety of sizes, from about 3 to 12 ft (0.9 to 3.7 m) in width and from 35 to over 150 ft (10.6 to 45.7 m) in length. The size of the machine and the sintering rate of the material will govern the production. Existing plants produce about 2 yd³ of aggregate per sq ft of grate area (16.5 m³/m²). The machine vary in size from 200 to 500 ft² (18.6 to 46.5 m²) of grate area.

Figure 20 is a simplified schematic diagram of a sintering machine.

The section dealing with dust collection in the rotary-kiln process, is also applicable to the sintering process.

Preparation of Aggregate

As the sinter cake breaks off at the discharge end of the sinter strand, it passes over a grizzly. From there the unsintered fines are recovered and returned to the pelletizer for reintroduction to the process. The cake is allowed to cool before it is crushed and screened to the desired sizes. A sinter breaker may be used if the cakes are too large to be handled by the crusher which could be of the jaw or impact type. As in the rotary-kiln process, care must be taken in the selection of the crusher or crushers to produce aggregate of the proper grading and shape.

Figure 21 is a simplified flow sheet diagram of the sintering process.

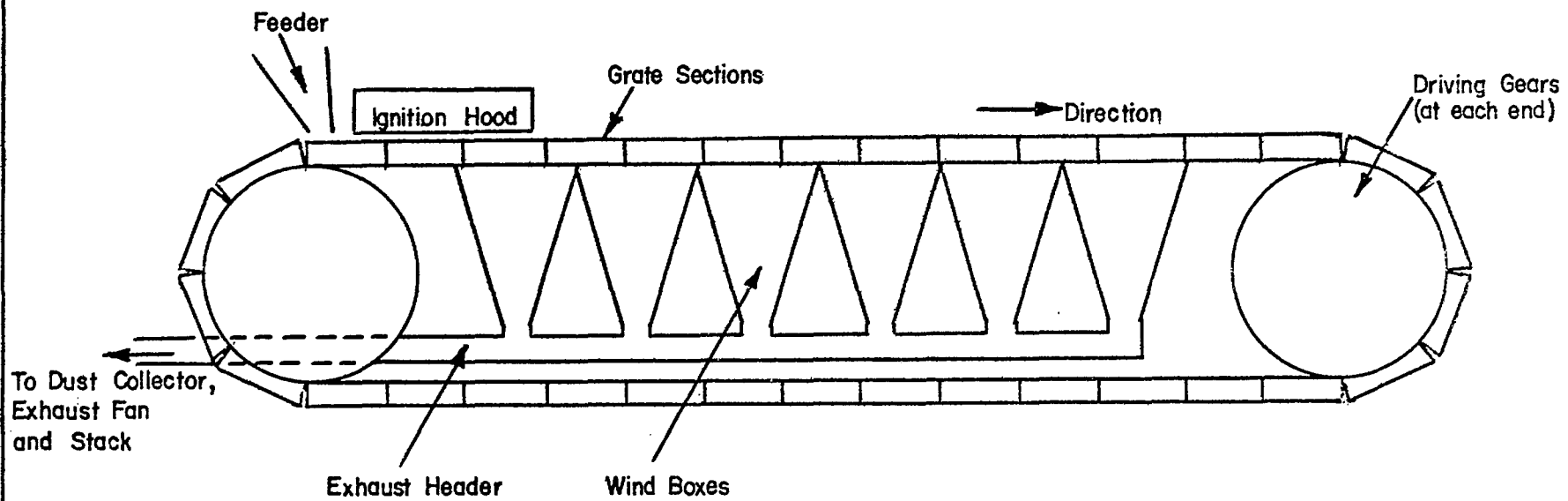


Figure 20: Simplified Schematic Diagram of a Down-Draft Sintering Machine

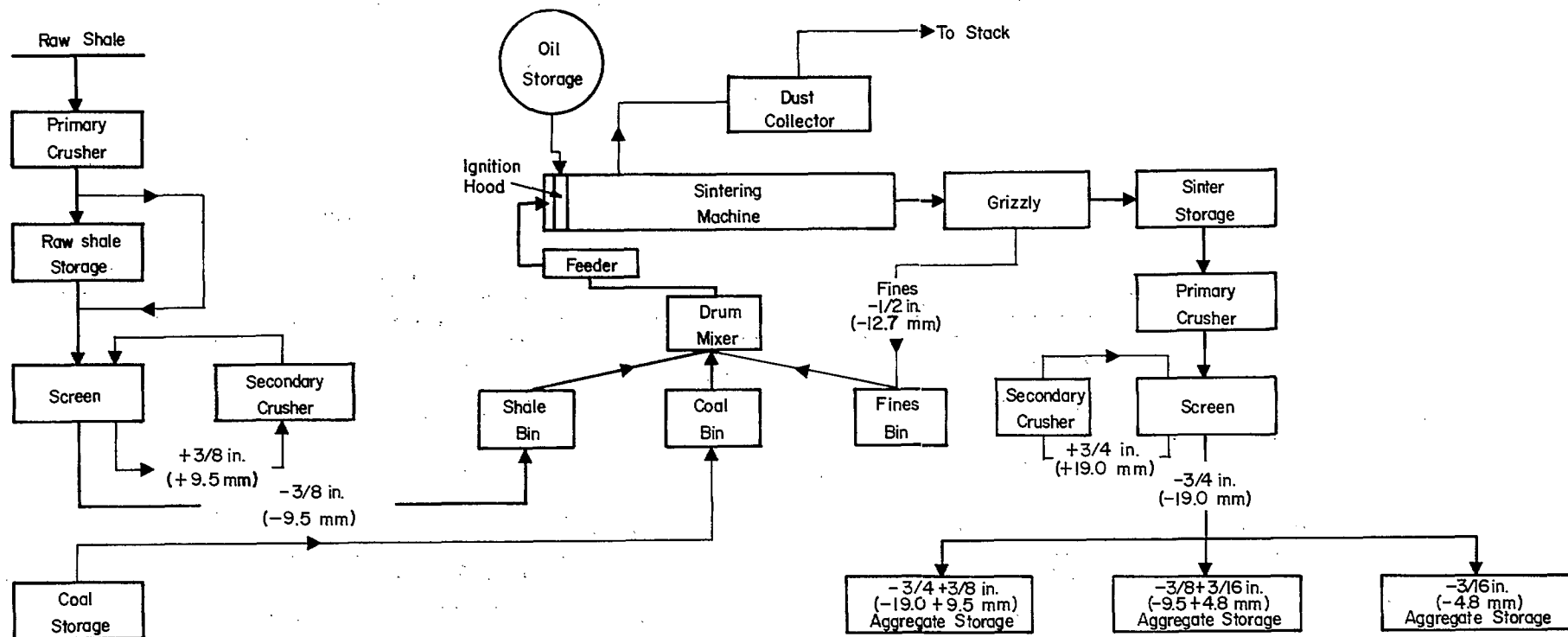


Figure 21 : Simplified Flow Sheet Diagram of Sintering Process

Plant Costs

Of prime importance to a potential producer of light-weight aggregate is the cost of erecting a plant and putting it into operation. The individual pieces of equipment and even complete processing plants are available in North America and in several countries in Europe. The cost of the plant would depend on the capacity and the degree of automation desired.

A rotary kiln plant to produce about 300 yd³ (230 m³) per day would cost between \$2 and \$3 million. The cost of erection of the plant, which is included in the above figures, would be about 20 to 30 per cent of the prime cost. A breakdown of the possible relative costs of the various components of the plant is as follows:

Quarrying	- 8 per cent
Raw material storage	- 8 "
Raw material preparation	- 12 "
Burning and dust collection	- 35 "
Cooling	- 7 "
Aggregate storage	- 2 "
Crushing and sizing	- 8 "
Buildings	- 6 "
Miscellaneous (including controls)	- <u>14</u> "
	100 per cent

The miscellaneous item includes electrical, plumbing and heating equipment, kiln setting, footings and foundations, shop, office and laboratory equipment, etc. The proportions would vary depending on the raw material, the plant site, and the degree of control desired. A clay would probably require less raw material preparation than would a shale, unless the clay was pelletized. Foundations of equipment and building would cost more if the plant were built on a soft clay rather than on a shale.

The prime cost of a sintering plant would be less than that of a rotary kiln plant for equivalent production. The cost would probably be \$1.5 to \$2.5 million, depending on the capacity and sophistication of the plant. The difference in the costs of the two types of plants would be in the burning and cooling operations.

The cost of production would comprise the costs of

- Labour
- Fuel
- Electric power
- Depreciation of equipment
- Maintenance and repairs
- Taxes, etc.
- Interest
- Cost and development of property.

These individual costs could vary widely. The only ones that can be fairly closely estimated are fuel, electrical power, and maintenance and repair of equipment. The fuel consumption for an efficient rotary kiln plant or sintering plant would be 1.0 to 2.0 million Btu/yd³ of production (1380×10^6 to 2760×10^6 j/m³), while consumption of electrical power for motors, etc., would be 20 to 30 KWH/yd³ (72×10^6 to 108×10^6 j/m³). Maintenance and repairs could be estimated to be about 15 per cent of the operating cost.

Evaluation of Raw Materials

Not all deposits of clay or shale are suitable materials for the production of lightweight aggregate, hence a deposit should be sampled and evaluated to determine the characteristics and quality of aggregate it could produce. Preliminary sampling and testing should be done on a small scale first to determine whether

a material has any potential of being suitable. If it does not have suitable characteristics, further work can be eliminated. If it shows promise, further exploratory work should be done, and tests made to determine the extent of the deposit and the quality of aggregate that could be produced. A deposit should be of sufficient extent and uniformity to be a source of material for at least fifteen years' production.

Preliminary sampling could be done with the aid of a hand shovel, hand auger or pick, depending on the hardness of the material. Representative sampling is easiest where the material outcrops, such as in a river bank, where road or highway construction has been done, or in an existing quarry; overburden or weathered material should be removed prior to sampling. When a vertical exposure can be revealed, samples should be taken by trenching over a vertical distance of several feet to obtain a representative sample. If a vertical exposure cannot be made, an auger hole or pit should be dug to recover sufficient material. Samples of about 20 lb (9 kg) would be adequate for preliminary testing; subsequent samples should be about 200 lb (90 kg) in weight.

If the material is well consolidated, tests could be made on pieces about $\frac{1}{2}$ to $\frac{1}{4}$ in. (12.7 to 6.4 mm). The material should be crushed and screened to obtain the sized material. The finer material could be mixed with water and pelletized by hand for further testing; material about minus 14 mesh (0.056 in., 1.41 mm) being satisfactory for pelletizing. The dry material should be thoroughly mixed with about 25 per cent water and rolled

into small spheres. Lumps and pellets should be dried at 110°C (230°F) prior to testing.

Preliminary expansion or bloating tests can be made in a stationary kiln heated by gas or electricity. There are many designs of small kilns that would be suitable for this work. The hearth of the kiln on which the material is placed should have an area of 30 to 40 in.² (0.02 to .03 m²). The kiln should be capable of attaining a temperature of about 1300°C (2370°F).

The prepared raw material should be fired at temperatures between 1030°C and 1260°C (1890°F and 2300°F), in intervals of 30 Celsius degrees (54 Fahrenheit degrees). By firing the materials for times of 5, 10 and 15 minutes at each temperature, a complete picture would be obtained on the degree of bloating and on the temperature range through which bloating occurs. Tests should be started at the lowest temperature, and continued until the lumps or pellets of material agglomerate during the firing. The kiln should be preheated to the desired temperature, and a few pieces of the material inserted into the kiln and removed at the end of the predetermined time interval. To maintain the temperature as constant as possible during each firing, a small refractory tray should be first heated in the kiln, removed when the desired temperature is reached, and returned to the kiln with the sample of material in it for the desired time interval.

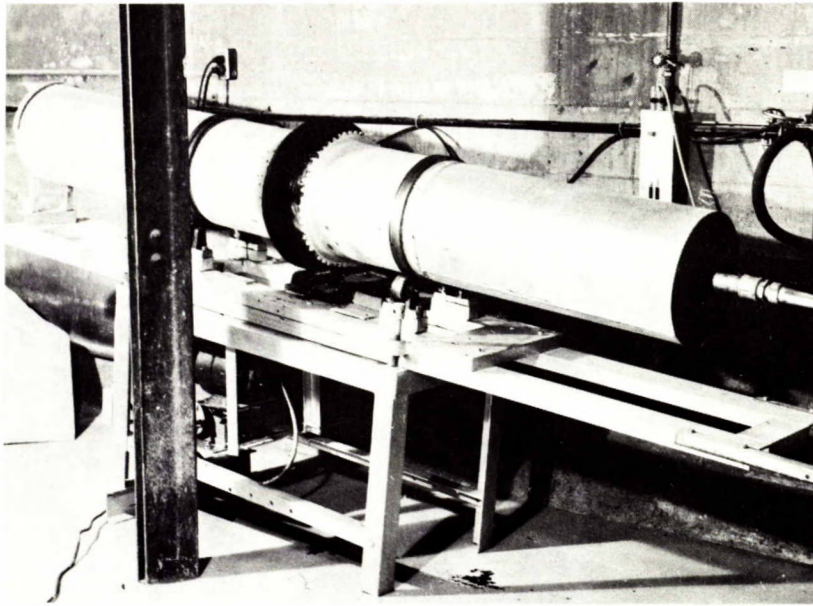
Visual examination of the products of the tests will show whether the material has bloated. The degree of bloating can be determined by finding the bulk density of the product from each firing by measuring the volume and weight of each product. The

degree of expansion and the temperature range through which expansion takes place can thus be determined. The bloating or expansion range can be considered to be the temperature interval between the beginning of appreciable expansion and agglomeration. This interval should be about 40 Celsius degrees (72 Fahrenheit degrees) or more for rotary kiln production.

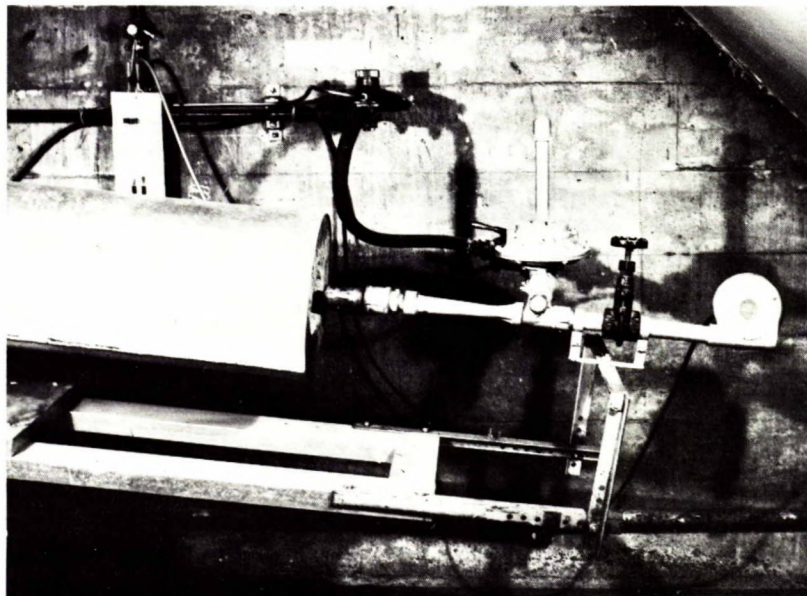
These tests indicate whether the material has potential for use in the rotary kiln process, but do not show what qualities the aggregate would possess. Further testing should be done in a small rotary kiln.

Figure 22 shows the laboratory rotary kiln used by the Mineral Sciences Laboratories, CANMET, Ottawa. It has an internal diameter of 5 in. (127.0 mm), an outside diameter of 12 in. (304.8 mm) and a length of 8 ft (2.4 m). The 3 1/2 in. (88.9 mm) lining of the barrel is of castable fire-clay refractory. The slope of the barrel is adjustable by four levelling screws, and the barrel is driven through a variable speed drive. Thus slope and rotational speed and consequently the retention time can be varied. This rotary kiln, which is heated with propane gas, has the capability of firing various sizes of material at a rate of 15 to 20 lb/hr (6.5 to 9.1 kg/hr). Hence, it can produce sufficient lightweight aggregate to determine the physical properties of the aggregate, such as unit weight, crushing strength, specific gravity, and absorption, and thus enable a given deposit to be evaluated as a potential source of lightweight aggregate; the optimum temperature and retention time for the material in the deposit having been determined in stationary kiln tests.

Tests performed in a small sintering pot would indicate the sintering characteristics of a raw material. The pot should be about one square foot (0.09 m^2) in area, either square or circular, and about 8 in. (203 mm) deep, with a grate in the bottom, and connected to a stack through an induced draft fan. The plenum should have a hole below the grate to permit the insertion of a thermocouple into the exhaust gas stream to measure its temperature. A manometer attached to the flue, between the pot and fan, could measure the draft, which can be varied by a damper located in the same section of the flue. A moveable ignition hood should be positioned over the pot to start ignition in the charge. It should be constructed so that the heat supplied will be uniform over the surface of the charge, and it should be moveable so that it can be moved away from the pot after ignition. The charge of material for the pot could be prepared in a small concrete mixer, in which raw material, fuel and water can be mixed. The charge is put in the pot without compaction, and the fuel at the surface is ignited for about one minute under low draft. The ignition is then turned off and the draft increased. Several runs would have to be made to determine the conditions under which the best results would be obtained. A rapid increase and then a decrease in temperature in the plenum below the pot, shown by the thermocouple, indicates completion of sintering. Figure 23 illustrates the sintering pot used in the Mineral Sciences Laboratories, CANMET, in the sintering of clays.



(a)



(b)

Figure 22. Two Views of the Laboratory Rotary Kiln,
Used by CANMET

(a) Kiln construction (b) Burner arrangement

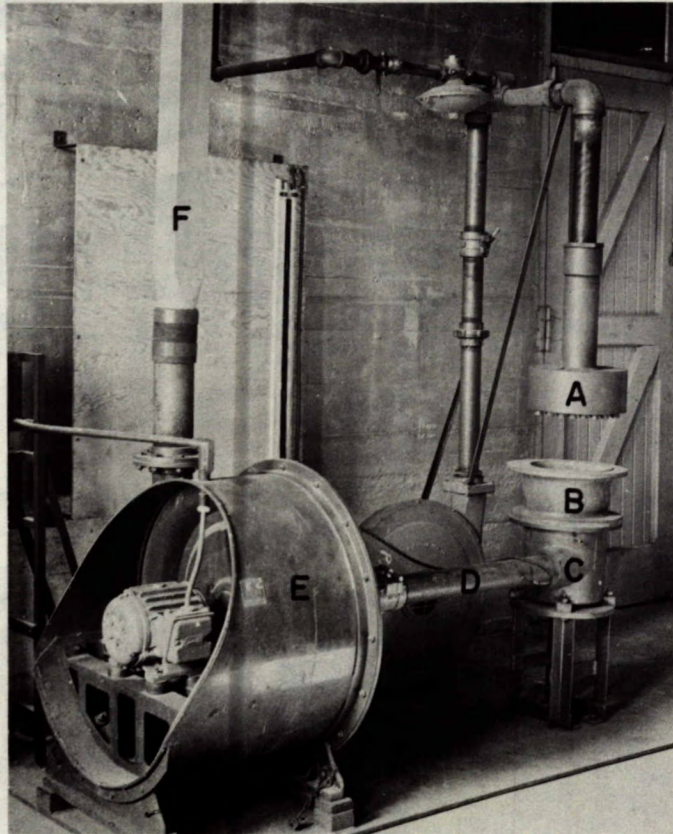


Figure 23. Laboratory Sintering Pot, Used by CANMET

- | | |
|------------------|----------------------|
| A: Ignition Hood | D: Flue |
| B: Sintering Pot | E: Induced Draft Fan |
| C: Plenum | F: Exhaust Stack |

The aggregate obtained from the rotary kiln will be primarily discrete particles; whereas the product from the sintering pot will be in the form of a clinker. To measure the properties of the lightweight aggregates, the products will have to be screened and/or crushed to produce a graded lightweight aggregate. The properties should be determined on a consistent grading, so that direct comparisons can be made. A metal container of a specific fraction of a cubic foot or cubic metre, such as $\frac{1}{4}$, $\frac{1}{10}$ or $\frac{1}{25}$, should be used.

The crushing strength is the pressure required to compact the aggregate a certain amount in a cylinder of small diameter, such as 3 in. (76 mm). The cylinder is filled to a certain depth and compacted by a ram, to a certain degree, using a hydraulic or mechanical press. The crushing strength cannot be directly related to the strength of concrete, but can be used to compare lightweight aggregates.

The final step in the evaluation of a raw material is to produce sufficient lightweight aggregate to make concrete tests. A minimum of about 200 lb (91 kg) of aggregate would be required to make these tests.

Properties

Just as the raw materials differ in properties, so do the lightweight aggregates produced from them. In a discussion on properties, unless a particular aggregate is involved, only generalities apply, as each aggregate is unique.

In North America lightweight aggregates generally have

densities between 40 and 60 lb/ft³ (640 and 960 kg/m³), depending on their grading, and result in concrete with densities between 100 and 115 lb/ft³ (1600 and 1840 kg/m³). Conventional sand and gravel or crushed stone aggregates have densities of about 100 lb/ft³ (1600 kg/m³); the concrete weighing 140 to 150 lb/ft³ (2240 to 2400 kg/m³). In Europe the practice is to produce lightweight aggregate of lower density (20 to 50 lb/ft³ - 320 to 800 kg/m³) than in North America; the thermal insulating property of the concrete being a prime factor. The density of this lighter concrete would be between 60 and 100 lb/ft³ (960 and 1600 kg/m³).

Ramos and Shah (24) used (a) cylinder (crushing strength) tests, (b) tension tests on individual particles, (c) shear compression tests on individual particles, and (d) lightweight concrete and mortar tests to relate the strength of aggregate to the strength of concrete. They found that only the concrete and mortar tests could correlate the strength of aggregate to the strength of concrete. They developed a formula that could be used to predict the strength of a particular lightweight aggregate concrete and to develop the optimum mix design.

Because of its cellular structure, lightweight aggregate has an absorption of 5 to 20 per cent. This is considerably higher than the absorption of normal-weight aggregate, and it must be considered when proportioning concrete mixes (25).

The most important property of a structural lightweight concrete is its strength-to-weight ratio. Evans and Dongre (26) showed that the compressive strength of a concrete incorporating a sintered lightweight aggregate was directly proportional to the

density of the concrete. The compressive strength of 6 in. (152 mm) cubes of the concrete varied from 3200 psi (22.1 MPa) at 90 lb/ft³ (1440 kg/m³) to 7200 psi (49.6 MPa) at 113 lb/ft³ (1810 kg/m³)*. They also found that a higher cement content was needed in lightweight concrete than in a conventional concrete of equivalent strength; the higher the strength, the greater the increase in cement. As an example, they showed that: for concrete with compressive strength above 6000 psi (41.4 MPa), 20 to 30 per cent more cement was needed; for compressive strengths between 4500 and 6000 psi (31.0 and 41.4 MPa), 10 to 20 per cent more cement was needed; and for compressive strengths of about 3000 psi (20.7 MPa), less than 10 per cent more was required. They found that the direct tensile strength and modulus of rupture were about 75 and 60 per cent respectively of those of normal weight concrete of equivalent compressive strength.

They also found that the diagonal shear stress permissible in lightweight concrete beams was in accordance with the formula:

Shear stress = $0.03 \times \text{cylinder compressive strength} + 75$,
whereas for conventional concrete the permissible shear stress was represented by the formula:

Shear stress = $0.04 \times \text{cylinder compressive strength} + 100$.
Thus it is seen that with lightweight concrete the ratio of shear strength to compressive strength is lower than with conventional concrete. They also found that the absorption of the lightweight concrete is 30 to 40 per cent higher than that of the

*Compressive strength on a cylindrical specimen basis is 75 to 85 per cent of the strength of cubic specimens.

conventional concrete, but the permeability is about the same.

The American Concrete Institute's Guide for Structural Lightweight Aggregate Concrete (27) indicates that the modulus of elasticity of all-lightweight concrete may be less than $\frac{1}{2}$ to $\frac{3}{4}$ of that of reference normal weight concrete. Although this is generally true for most lightweight concretes, the modulus of a few lightweight concretes may exceed those of some normal weight concretes. Also, the replacement of the fines in lightweight concrete with normal-weight sand will increase the modulus (28).

Snideler (29) compared the properties of concretes incorporating eight American lightweight aggregates against one concrete of sand and gravel. He found that the modulus of elasticity of the lightweight concretes varied from 53 to 82 per cent of the modulus of 3.43×10^6 psi (2.36×10^4 MPa), for the sand and gravel concrete at 28 days. At 6 months, the modulus of the lightweight concretes varied from 44 to 63 per cent of the modulus of 5.01×10^6 psi (3.45×10^4 MPa) for conventional concrete.

Pfeifer and Hognestad (30) studied the incremental loading of high-strength lightweight concrete columns to simulate loading during a construction period of 50 weeks. The semi-lightweight concrete cylinders, at 28 days, had a compressive strength of 6360 psi (43.8 MPa) and a modulus of elasticity of 3.34×10^6 psi (2.30×10^4 MPa). At 90 days, the strength had increased to 6990 psi (48.1 MPa) and the modulus to 3.60×10^6 psi (2.48×10^4 MPa). At one year, the values were 7320 and 3.82×10^6 psi (50.4 and 2.63×10^4 MPa) respectively.

Nominally the modulus of elasticity of concrete can be

determined from the formula:

$$E_c = W^{1.5} \times 33 \sqrt{F'_c} \text{ psi}^* (31)$$

where E_c = static modulus of elasticity of the concrete, psi

W = air-dry weight of the concrete at time of test, pcf**

F'_c = compressive strength of the concrete at time of test, psi.

Lightweight concrete may comply with this formula only withing 15 to 20 per cent. The reduced stiffness of lightweight concrete is not always undesirable. In applications such as certain configurations of shell roofs, it may be more desirable than the stiffer normal weight concrete.

Both drying shrinkage and creep of all-lightweight concrete differ considerably between various lightweight aggregates, as they do between various normal weight aggregates. Generally they can be reduced by using normal weight sand, and by curing the concrete with steam (32).

Durability of lightweight concrete is also dependent on the aggregate used. As with normal weight concrete, air-entrainment is most desirable. Usually, the higher the compressive strength, the better is the durability. The use of normal weight sand also increases the durability. One example of extremely good durability is the lightweight concrete ship Selma, which is described later in this monograph. The hull of the ship had remained partially submerged in Galveston Bay, Texas from 1922. In 1953, samples of concrete were cut from three areas, and compared with the original specifications for the ship when it was constructed in 1919; the concrete originally had a 28-day

* 145.04 psi = MPa

**16.02 lb/ft³ = 1 kg/m³

compressive strength of 5,591 psi (38.5 MPa). Compression tests performed on these samples from the hull showed: concrete exposed alternately to salt water and salt air had a strength of 8787 psi (60.5 MPa); concrete exposed continuously to salt water had a strength of 11,204 psi (77.3 PMa); concrete from an interior rib exposed continuously to salt-laden air had a strength of 8125 psi (55.7 MPa). [The 1953 specimens were 2 in. cubes (51 mm); the factor of 0.85 being used to convert strength values to those for 6 by 12 in. (152 by 305 mm) cylinders.] Reinforcing steel was exposed and showed no pitting or corrosion. (33)

The thermal conductivity (K) of lightweight concrete is about $\frac{1}{2}$ of that of normal-weight concrete. The value is a function of the unit weight. Schulz (34) reported thermal conductivity of lightweight concretes of various densities, as shown in Table 1.

TABLE 1
Thermal Conductivity of Concretes

Density of Concrete		Thermal Conductivity (K)	
kg/m ³	lb/ft ³	W/m C [*]	Btu in./ft ² hr deg F
1100	69	0.35	2.42
1200	75	0.39	2.74
1300	81	0.43	2.98
1400	88	0.49	3.38
1500	94	0.54	3.70
1600	100	0.58	4.03

*Btu in./ft² hr deg F x 0.1442 = W/m C

He does not give the temperature at which the tests were made, but normal-weight concrete would probably have thermal conductivity coefficients between 6 and 9 Btu in./ft² hr deg F (0.87 and 1.31 W/m C) at ambient temperature. The moisture content of the concrete is an important factor in thermal conductivity. Forder (35) showed that lightweight concrete containing 1 per cent moisture had a K value of 0.24 W/m C; when the moisture content was 5 per cent, the K value increased to 0.32. The moisture obviously would be of greater importance with concrete having high absorption.

Zoldners and Wilson (36) studied the durability of a semi-lightweight concrete during 1000 cycles of freezing and thawing. Weight loss during the period was negligible. The volume expansion was 0.01 and 0.02 per cent of the original length. The flexural strength increased, but not as much as it did in the companion standard cured beams; the flexural strength of the lean lightweight mixes was 81 to 84 per cent, and of the rich mixes was 94 to 98 per cent of the standard cured beams after 1000 cycles.

Lightweight structural concrete can be pumped as can normal weight concrete. In the construction of the 27-storey Century Park Plaza office building in Los Angeles, California, concrete was pumped to a maximum height of 357 ft (109.2 m). The concrete mix contained 592 lb (268.2 kg) of cement, 14.5 ft³ (0.44 m³) of expanded shale coarse aggregate, 9.3 ft³ (0.28 m³) of lightweight fine aggregate, and 7.4 ft³ (0.22 m³) of natural sand fine aggregate. The unit weight of the concrete was 100 lb/ft³ (1600 kg/m³) and its compressive strength at 28 days was 3000 psi (20.7 MPa) (37).

Because of the porosity of lightweight aggregate, it is imperative that the aggregate be completely saturated before the concrete is mixed. An unsaturated aggregate will absorb water from the mix under pressure developed in the pump and the mix will become unpumpable. Vacuum saturation is probably the most effective means of saturation, although hydro-thermal saturation, soaking heated aggregate (about 150° to 250°C or 300° to 480°F), will also saturate the aggregate so that the mix can be pumped satisfactorily. (38). One aggregate was saturated by spraying water onto a stock pile for 72 hours.

The following is a typical structural lightweight concrete mix*, using lightweight coarse aggregate and natural sand fine aggregate. The lightweight aggregate is an expanded shale, produced in Canada; the quantities shown are per yd³ (m³).

Cement	: 550 lb (326 kg)
Coarse aggregate	: 920 lb (545 kg)
Fine aggregate	: 1390 lb (826 kg)
Water	: 330 lb (196 kg)
Air	: 5 per cent
W/C	: 0.60
Slump	: 3 in. (75 mm)

It would have the following properties:

Unit weight (fresh)	: 118 lb/ft ³ (1890 kg/m ³)
Unit weight (air dry)	: 114 lb/ft ³ (1825 kg/m ³)
Compressive strength (28-day)	: 4600 psi (31.7 MPa)
Tensile strength (28-day)	: 400 psi (2.8 MPa)
Shear coefficient	: 6.5-6.7
Modulus of elasticity (E _c)	: 2.7 x 10 ⁶ psi (1.9 x 10 ⁴ MPa)
Thermal conductivity (K)	: 4.6 Btu in./ft ² hr F (0.66 W/m C)
Thermal expansion	: 4 to 5 x 10 ⁻⁶ in./in. deg F (7.2 to 9.0 x 10 ⁻⁶ mm/mm deg C)
Drying shrinkage	: similar to normal-weight concrete
Durability	: similar to normal-weight concrete

*Information supplied by Domtar Construction Materials Limited, Mississauga, Ontario.

Applications

Because of the nature of lightweight aggregates, they have a variety of applications. The important properties are: (1) high strength-to-weight ratio, (2) moderate absorption, (3) cellular structure, (4) inert in normal usage, and (5) degree of refractoriness.

They are used as a soil conditioner to open up a dense clay soil and retain moisture. They are also used as loose insulation below ground level to reduce frost or heat penetration and to facilitate drainage; race tracks have been surfaced with lightweight aggregate. With refractory cement, they are formed into low temperature refractory bricks. Up to now, these applications have used relatively small quantities of lightweight aggregate. The large proportion is consumed in concrete masonry units and in structural concrete.

Another application which is gaining in acceptance is in highway surfacing because of the skid resistance that the lightweight aggregates impart to the highway. Many normal-weight aggregates become polished through wear, whereas lightweight aggregates continually expose irregular surfaces because of their cellular structure (39).

Concrete Masonry Units

Masonry units are made in many sizes, shapes, textures and finishes. They vary from conventional brick-size to 8 by 8 by 16 in. (203 by 203 by 406 mm) block. These units, being lighter in weight than units made with conventional aggregates, are easier

for the masons to handle and can be laid up in the wall at a faster rate. They can be plane-surfaced for functional purposes or can be formed with three-dimensional faces to create patterns or cast shadows on the wall for pleasing aesthetic effects. The texture of the face can be altered by varying the sizing of the aggregate and the cement content. The units may be left exposed in the wall, or they may be faced with other building materials such as brick or wall tile. They may also be glazed or painted to achieve more colour on the interior face of the wall.

Figure 24 illustrates the variations in texture that are possible, and Figure 25 illustrates some effects that can be achieved with three-dimensional faced blocks and directional lighting.

Although cement is the universally-used bonding agent, "all-clay" lightweight blocks have been produced, using ground clay as the binder (40). This type of block would be most practical in areas where cement is too costly. Another advantage is that colours can be produced that are unobtainable with cement as the binder. Also, the blocks can be faced with a ceramic glaze and used in exterior applications. The blocks would have to be fired after being formed, to develop a ceramic bond necessary to achieve sufficient strength. This type of product would be most applicable where the lightweight aggregate is produced in conjunction with a brick plant, where equipment and kilns are already available.

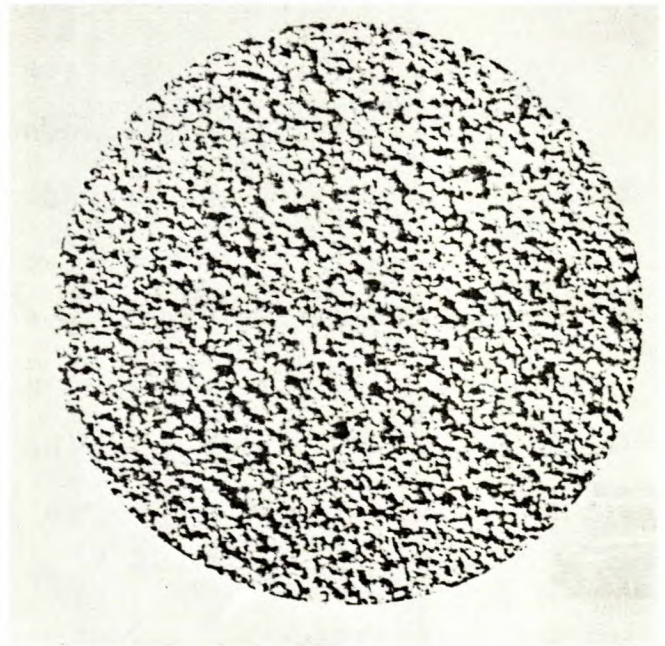
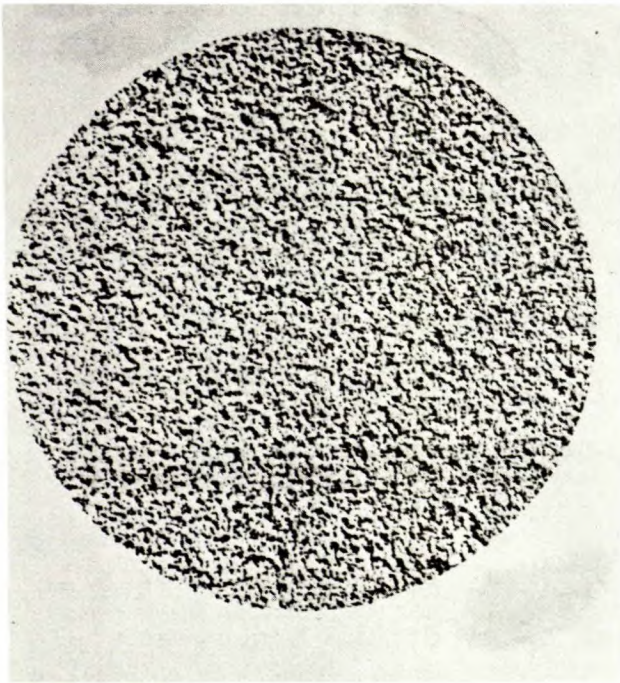


Figure 24. Fine and Coarse Texture Block Surfaces

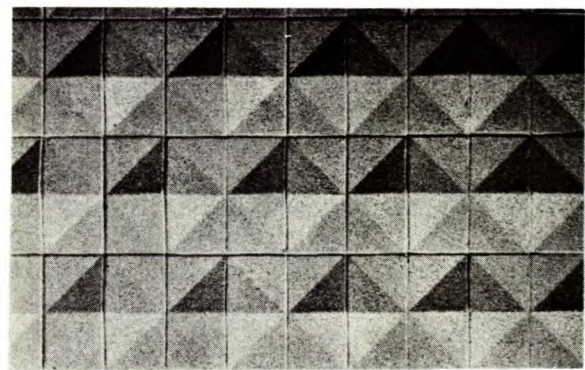


Figure 25. Patterns of Three-Dimensional Blocks

In many European countries, and to an increasing extent in the United States, prefabrication is used in the erection of buildings. In this field of construction, large panels are fabricated at a factory, transported to the building site and fastened together to form the walls of the structure. Lightweight blocks lend themselves ideally to this type of construction because of the greater ease of handling the fabricated panels. There are many variations on the means of prefabrication. In principle, the individual units are spaced within a frame and concrete or mortar is grouted between them. Concrete and/or tile may be incorporated on either or both faces of the panel, and reinforcing may or may not be required. The advantages of this method of erecting a structure are that unskilled and semi-skilled labour can be used to fabricate the panels, and when the panels have been made, the structure can be erected rapidly. The building may be closed in and interior work can proceed in spite of inclement weather.

Lightweight blocks are also used in post-tensioned structural concrete beams. To produce this type of member, the blocks are laid end-to-end, wires are centred in the core holes extending through the blocks, and tensioned. The cores are then grouted full of concrete through holes in the upper faces of the blocks. When the concrete has hardened, external loads on wires are released, and the tension stresses in the wires are assumed by the concrete, putting the beam into compression.

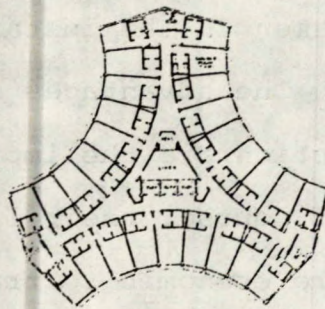
A relatively recent and valuable innovation to masonry construction is the engineered masonry structure. In the conven-

tional frame structure vertical loads are concentrated in and transmitted to the foundation by columns. In the engineered masonry structure the loads are accumulated in the bearing walls and transmitted to the foundation along the lengths of the walls. It is, in its simplest form constructing one room above another in a repetitive fashion. This need not result in a rectangular floor plant. A 9-storey motor hotel in Houston, Texas is a Tri-Arc design; the three major exterior walls are concave arcs. In Lansing, III., a 5-storey condominium apartment building has a 12-sided floor plan, each side being 32 ft wide. Photographs of the two structures and sketches of the floor plans are shown in Figures 26 and 27.

The major advantage of engineered masonry construction over frame construction is the speed with which construction can be completed. The lower floors can be closed in and finished while the upper floors are still being erected. More economic use can be made of trades craftsmen in the installation of utilities and in finishing the rooms. The advantages of the lightweight blocks in this type of construction are the improved fire ratings and acoustic properties. Of course, their lighter weight makes them easier to handle and more economic to transport.



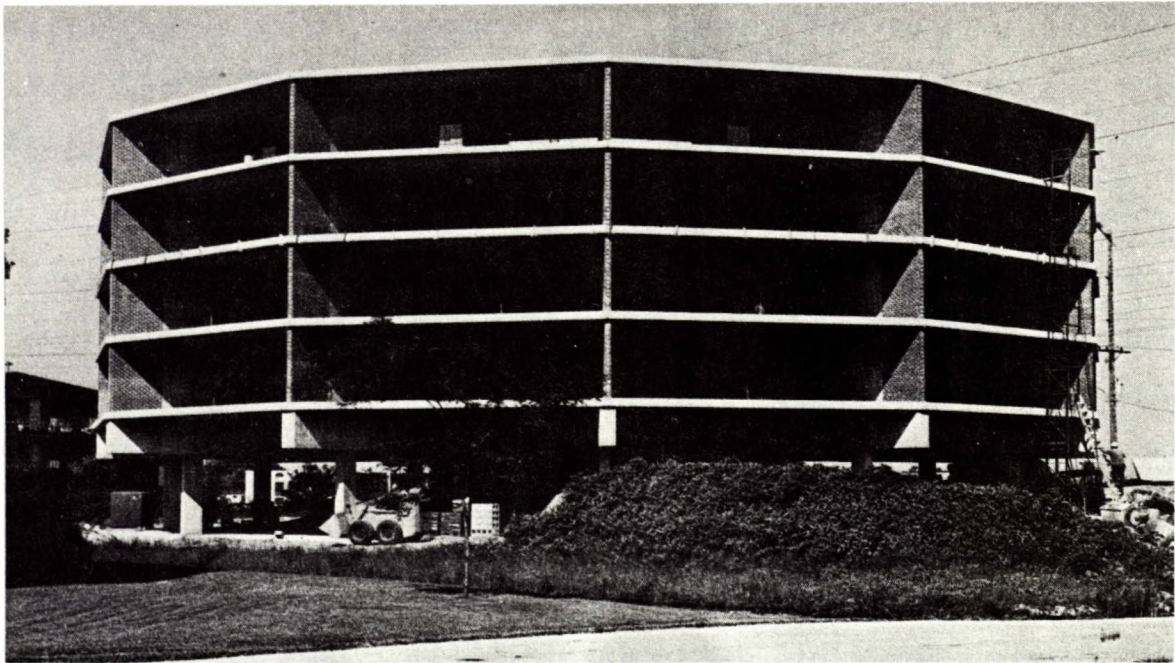
(a)



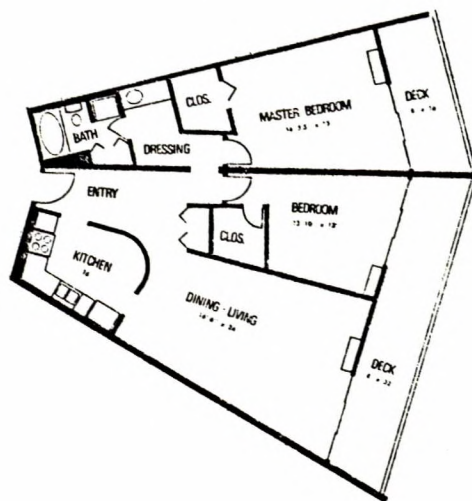
(b)

Figure 26. Engineered Masonry Construction of
Tri-Arc Design (41)

- (a) Front View
- (b) Floor Plan



(a)



(b)

Figure 27. Engineered Masonry Construction of Dodecahedral Design (41)

- (a) Elevation
- (b) Floor Plan

High-strength lightweight concrete blocks lend themselves ideally to engineered masonry construction. It is necessary to increase the cement content and the formation time of the blocks to achieve the required compressive strength of more than 3500 psi (net area) (24.1 MPa). The cement and time factors will be unique for each lightweight aggregate. Compared with the conventional lightweight block, the high-strength block will have a unit weight 7 to 8 per cent higher; the absorption will be 20 to 25 per cent lower; and the drying shrinkage will be 0.005 to 0.010 per cent higher (42).

Examples of this type of construction in Canada are:

St. Benedict Junior High School in Galt, Ont. This school, 55,400 ft² in area (5,150 m²) was erected in 1972 for \$15.74/ft² (\$169.36/m²) including mechanical and electrical costs. The load-bearing walls were of single wythe; the exterior face being sprayed with a plastic paint and the interior face with ordinary paint. The cells of the blocks were filled with exfoliated vermiculite to improve the thermal insulation (41).

The Lily Rose Apartments in Regina, Sask., made use of 50,000 lightweight blocks in a 6-storey structure. Steel joists and a light-gauge metal deck support the 2 in. reinforced lightweight concrete floor. The reinforcing extends into the masonry bearing walls. The single-core blocks were filled with lightweight concrete (41).

The 17-storey Heritage Place apartment tower, in Calgary, Alta., using an average of 11 masons and 5 helpers, was erected at the rate of one floor in four days. The total erection time

was 10 months, two months less than that of the equivalent building in frame construction. A total of 164,000 lightweight blocks was used to complete the tower containing 137 apartments and three levels of parking and commercial space (41). The building is illustrated in Figure 28.

Lightweight blocks need not be restricted to plane surfaces. In Calgary, Alta., eight aggregate silos, each 16 ft (4.9 m) in diameter by 32.5 ft (9.9 m) high, were constructed of blocks 6 by 8 by 24 in. (152 by 203 mm by 0.6 m). The 6 by 24 in. faces had been ground to conform to the curvature of the wall (43). Figure 29 shows the silos under construction, and the completed installation.

From the beginning, most of the aggregate has gone into concrete masonry units. Gradually, the quantity being used in structural concrete has increased, as confidence in its reliability has become stronger and its versatility recognized. It has been used in structural applications such as multistorey structural frames, floors, curtain and shear walls, shell and folded plate roofs. It has been used in bridge decks and girders and in precast and prestressed structural members.

The adoption of lightweight concrete has been greatest in the United States, where a great variety of structures have been built wholly or partly of lightweight structural concrete.

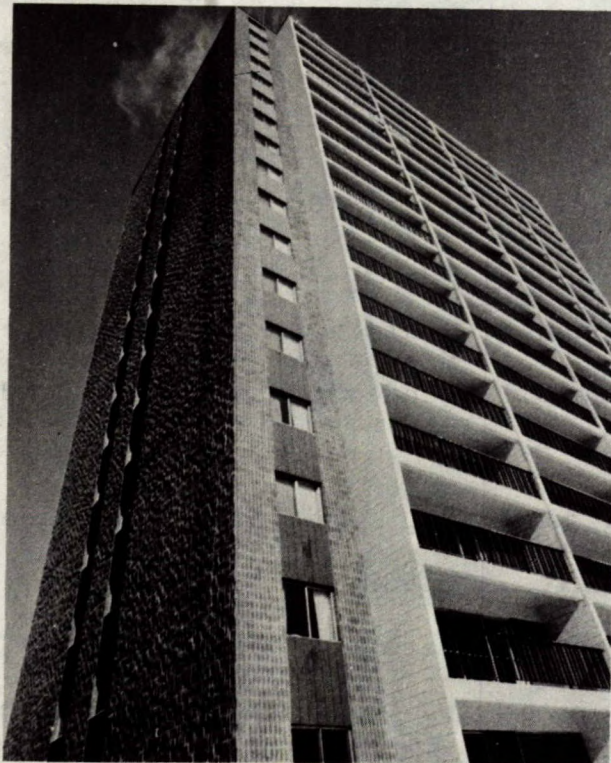
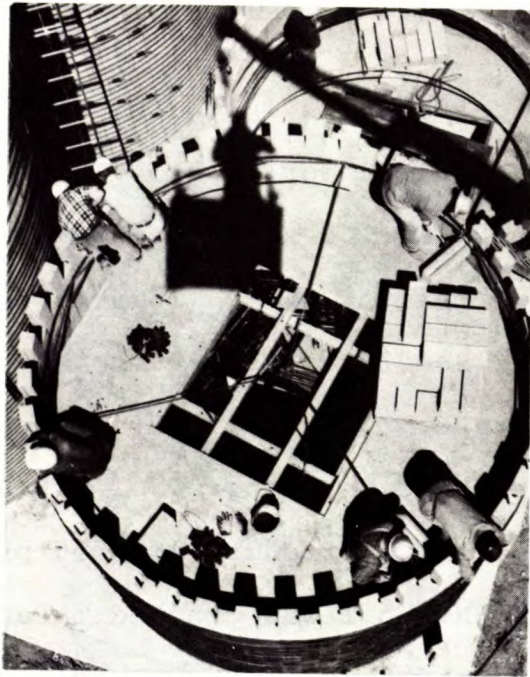


Figure 28. Engineered Masonry Apartment Building



(a)



(b)



(c)

Figure 29. Concrete Block Silos

- (a) Laying of blocks
- (b) Fastening reinforcing rods around silo
- (c) Finished installation

Cast-in-Place and Precast Concrete

One of the earliest applications was in the construction of concrete ships near the end of the First World War. The first such large ship was the Selma, a 7500 ton (68×10^5 kg) tanker, with a length of 434 ft (132.4 m), a beam of 54 ft (16.5 m) and full-cargo draft of 26 ft. (7.9 m). She required 2600 tons (23.6×10^5 kg) of lightweight concrete. Test cylinders prepared as the hull was being cast had an average wet density of 118.9 lb/ft³ (1905 kg/m³) and a 28-day compressive strength of 5590 psi (38.5 MPa). After 3 years service, the hull was cracked in a collision with a tanker and subsequently sank in the bay of Galveston, Texas (33). Figure 30 shows the partially submerged hull, in 1952.

Many bridge decks have been constructed of lightweight concrete (44). One example resulting in great economy is the San Francisco-Oakland Bay Bridge built in 1936. A \$3 million saving in steel resulted from the use of lightweight concrete.

The distinctive twin towers of Marina City in Chicago are each 60 storeys in height by 105 ft (32.0 m) in diameter. The floors are supported by beams extending radially from a central core. The beams are in turn supported by the core and two rings of columns. All floors and beams are of lightweight concrete. The concrete had a density of 105 lb/ft³ (1680 kg/m³) and 28-day compressive strength of 4500 psi (31.0 MPa) (45). A model of the towers is shown in Figure 31.

One of the more-recently constructed lightweight concrete buildings (1970) is One Shell Plaza in Houston, Texas, a 52-storey

structure built entirely of lightweight concrete. It is of tube-in-tube construction, with lightweight concrete joists spanning the distance between the outer framed tube and the inner shear wall tube. The soil conditions in Houston are such that tall buildings are normally built on a thick concrete pad. The pad, which extends 20 ft (6.1 m) beyond the exterior walls of the building was 232 by 172 ft by 8 ft 3 in. thick (70.8 by 52.4 by 2.5 m). The concrete that formed the pad, columns, and shear walls had a compressive strength of 6000 psi (41.3 MPa); that for the floor slabs was 4500 psi (31.0 MPa). The maximum dried density of all the concrete was 115 lb/ft³ (1840 kg/m³). In all, 90,000 yd³ (69,000 m³) of structural lightweight concrete was used (46). A model of this structure is shown in Figure 32.

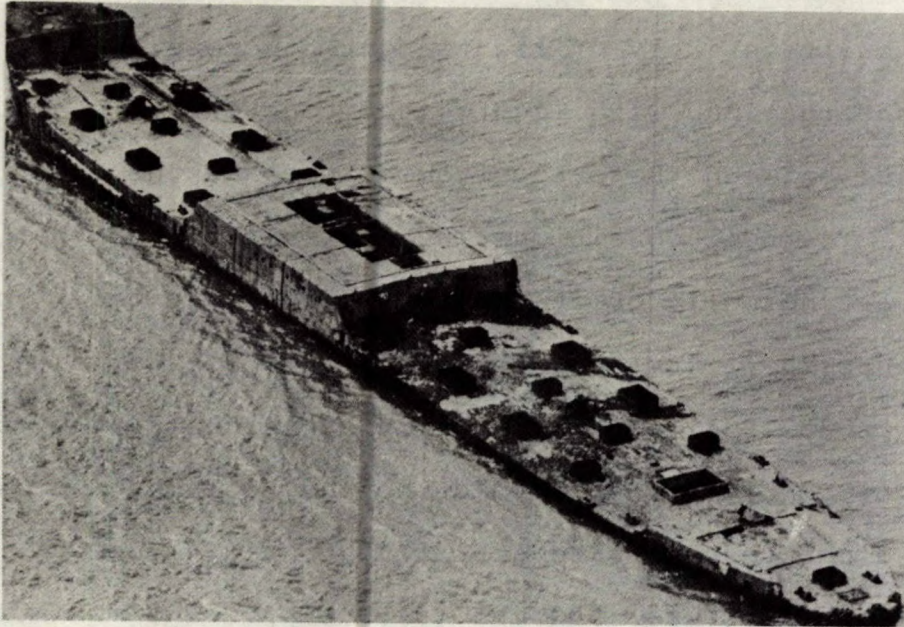


Figure 30. Hull of S.S. Selma in Galveston Bay

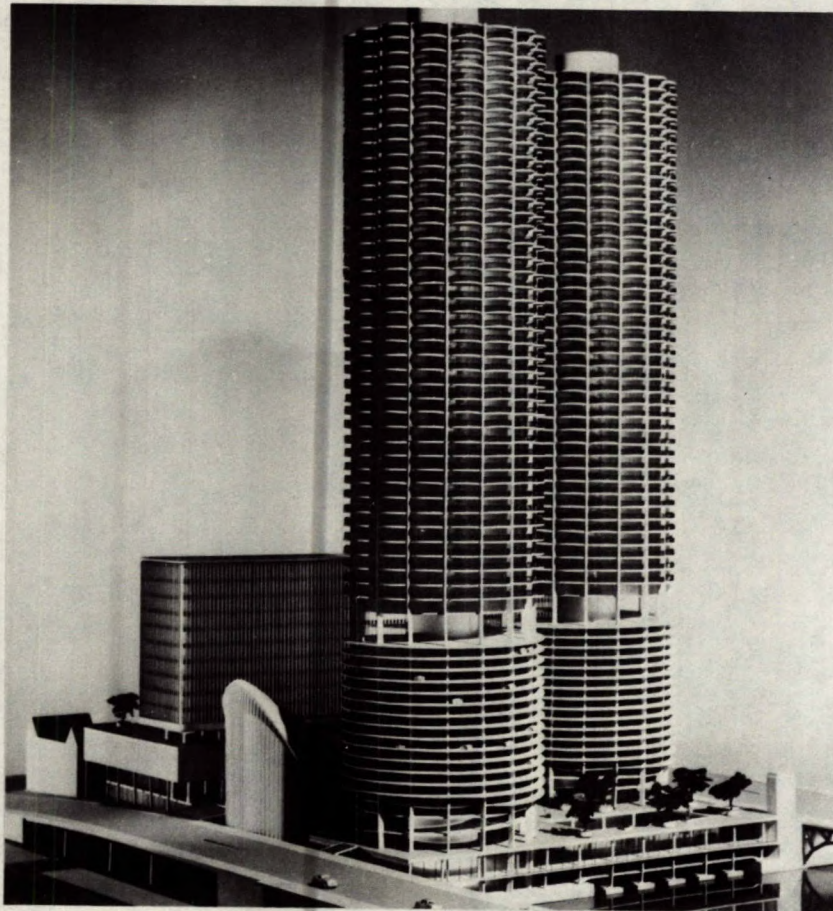


Figure 31. Model of Marina City, Chicago

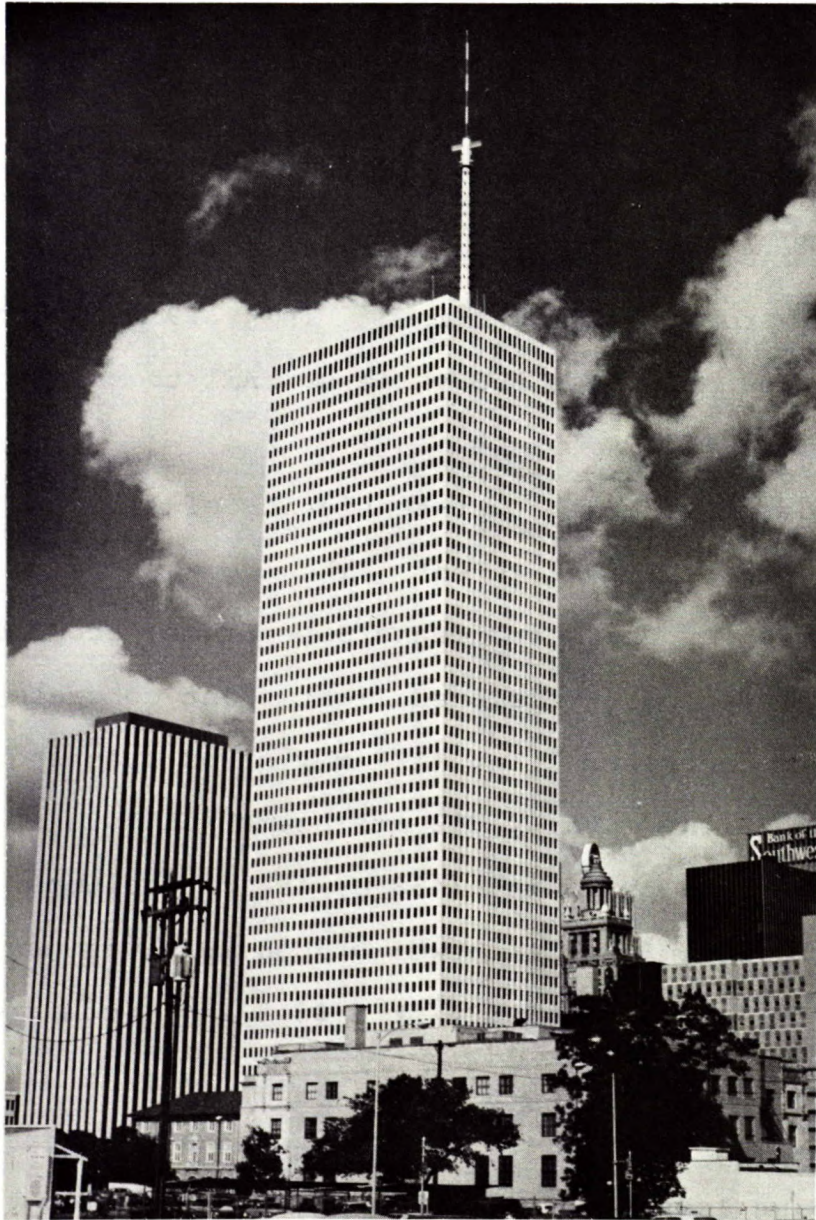


Figure 32. Model of One Shell Plaza, Houston

Another application in which the low density of lightweight concrete is of great value is in the dome of the Assembly Hall at the University of Illinois at Urbana, built in 1963. The dome, a folded plate roof, has a clear span of 398 ft (121.4 m) and rises 62 ft (18.9 m) from the spring. Over 3000 yd³ (2300 m³) of lightweight concrete, having a fresh weight of 106 lb/ft³ (1700 kg/m³) and a compressive strength of 4000 psi (27.6 MPa), was used. The roof was placed in 3½ in. (8.9 mm) thick slabs joined with ribs at ridges and valleys. All the slabs were at 45 degree slopes (47).

Prestressing and post-tensioning of lightweight concrete has been done to a limited extent. The beams and slabs of the parking garages for the New Orleans Superdome, accommodating 5000 cars, were of post-tensioned lightweight concrete. The framing system comprises 5 in. (127 mm) slabs spanning 18 ft (5.5 m) between 16 by 28 in. (406 by 712 mm) beams, in turn spanning 54 ft (16.5 m) between 18 by 18 in. (458 by 458 mm) columns. In all, 33,000 yd³ (25,200 m³) of lightweight concrete was used, resulting in an estimated saving of \$0.36/ft² (\$3.87/m²), compared to normal weight concrete (48).

One of the problems associated with prestressed concrete is prestressing losses due to shrinkage and creep of the concrete and relaxation of the steel. The Prestressed Concrete Institute (49) gives methods of calculating these losses for lightweight and normal-weight concrete.

For certain applications, lightweight concrete can be used in reinforced concrete pipe. In 1964, Southern California

Edison Company laid two cooling lines, 2600 and 2100 ft (793 and 640 m) long, into the ocean from El Segundo steam generating station. The 12 ft (3.7 m) inside diameter by 24 ft (7.3 m) long pipe sections were made longer than they would have been if normal-weight concrete had been used. Each section weighed 63 tons (57,100 kg), whereas, using normal weight concrete, they would have weighed 80 tons (72,600 kg).

In Canada, one of the earlier fully-lightweight concrete buildings is the 22-storey National Trust Building in Toronto, erected in 1962. With the exception of the fifth floor, all concrete above grade is lightweight; additional mass being required for the fifth floor for mechanical equipment. A total of 13,000 yd³ (9,900 m³) of structural lightweight concrete with an average 28-day compressive strength of 4770 psi (32.9 MPa) and a unit weight of 115 lb/ft³ (1840 kg/m³) were used. About 75,000 lightweight concrete blocks were used for partitions above and below grade (50). A view of the building during construction is shown in Figure 33.

More recent applications are the 51-storey apartment tower of the Manufacturer's Life Centre (1972) (51) and the 74-storey Bank of Montreal Building (1975), both in Toronto. The former, containing 800 apartment units, is the tallest reinforced concrete apartment building in Canada. It contains 23,000 yd³ (17,000 m³) of lightweight concrete, as all the floors above the third are of lightweight concrete. The floors of the Bank of Montreal Building, a steel frame structure, are of post-tensioned lightweight concrete. A view of the Manufacturer's Life Centre

is shown in Figure 34.

Other structures which incorporate post-tensioned lightweight concrete floors are the 21-storey Royal Bank of Canada Building in Calgary and the 45-storey Edmonton House in Edmonton (52). In the latter, a saving of \$45,000 for post-tensioning strands alone, and a reduction in dead weight of 8.9 million lb (4.04 million kg) were achieved, compared with normal-weight concrete. A total of 11,000 yd³ (8,400 m³) of structural concrete for the floor system and 15,000 lightweight concrete masonry units were used. It is illustrated in Figure 35.

Also in Calgary, the twin-tower, 400 unit Continental Apartments, the 35-storey International Inn, and the 36-storey, twin-tower apartment shopping complex, Place Concorde all have lightweight concrete in the floors, columns and shear walls. The latter was constructed at a rate of five floors every two weeks (52). The International Inn and the Place Concorde are illustrated in Figures 36 and 37.

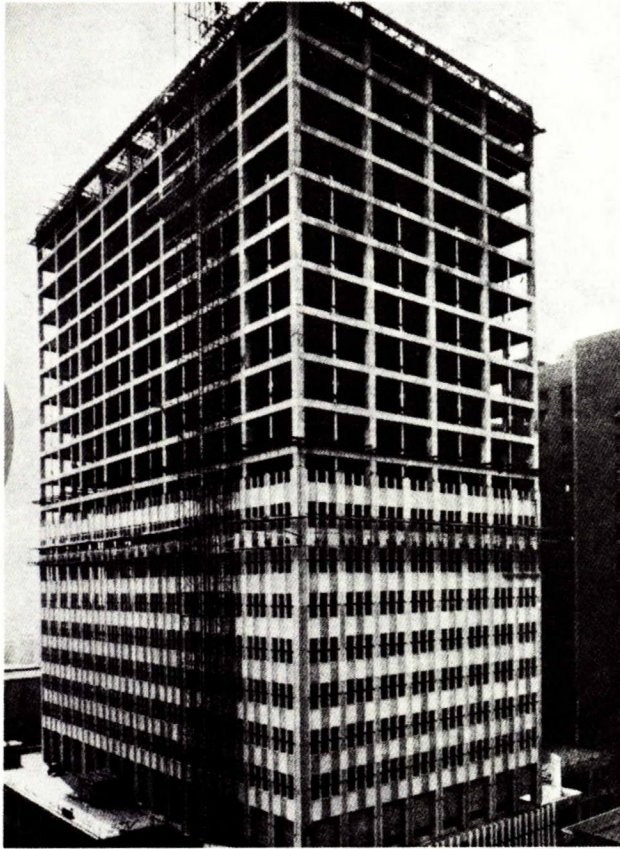


Figure 33. National Trust Building, Toronto

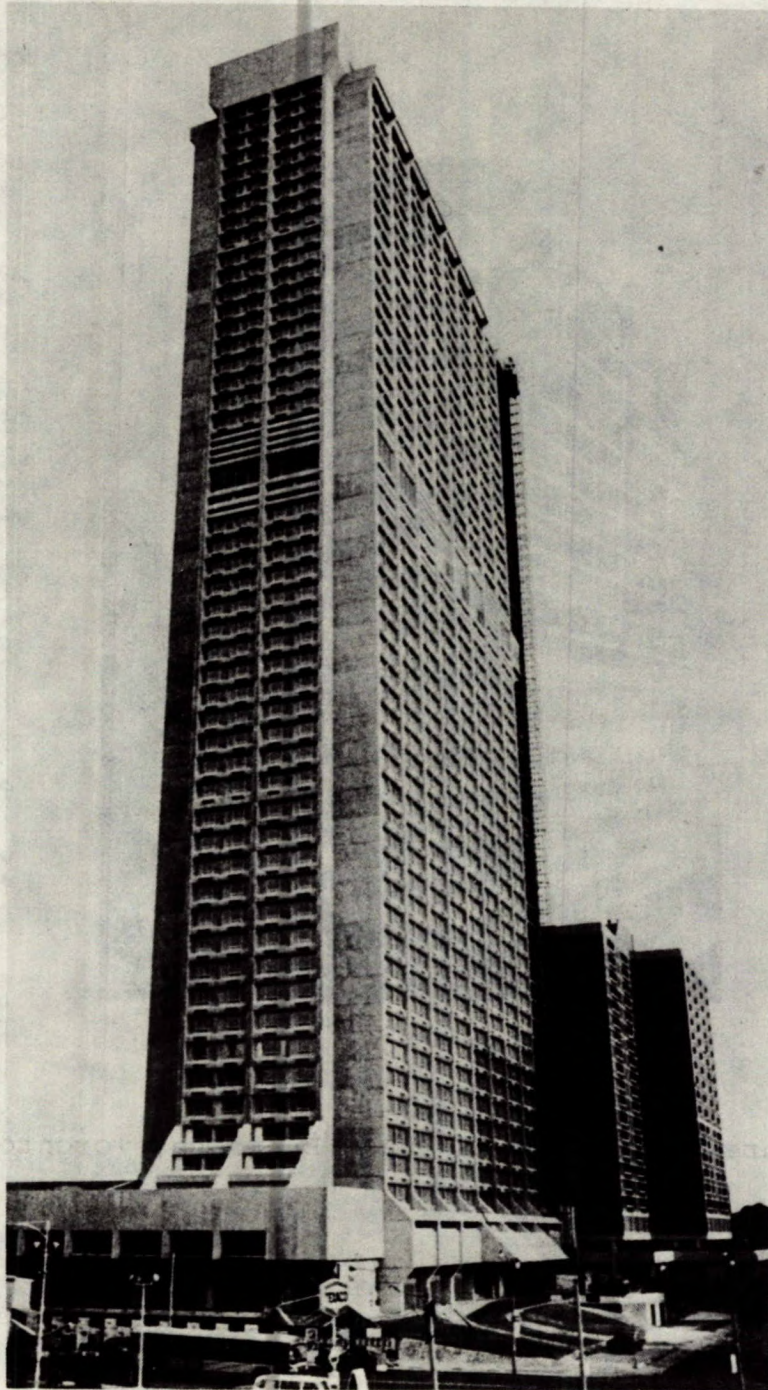


Figure 34. Manufacturer's Life Centre, Toronto

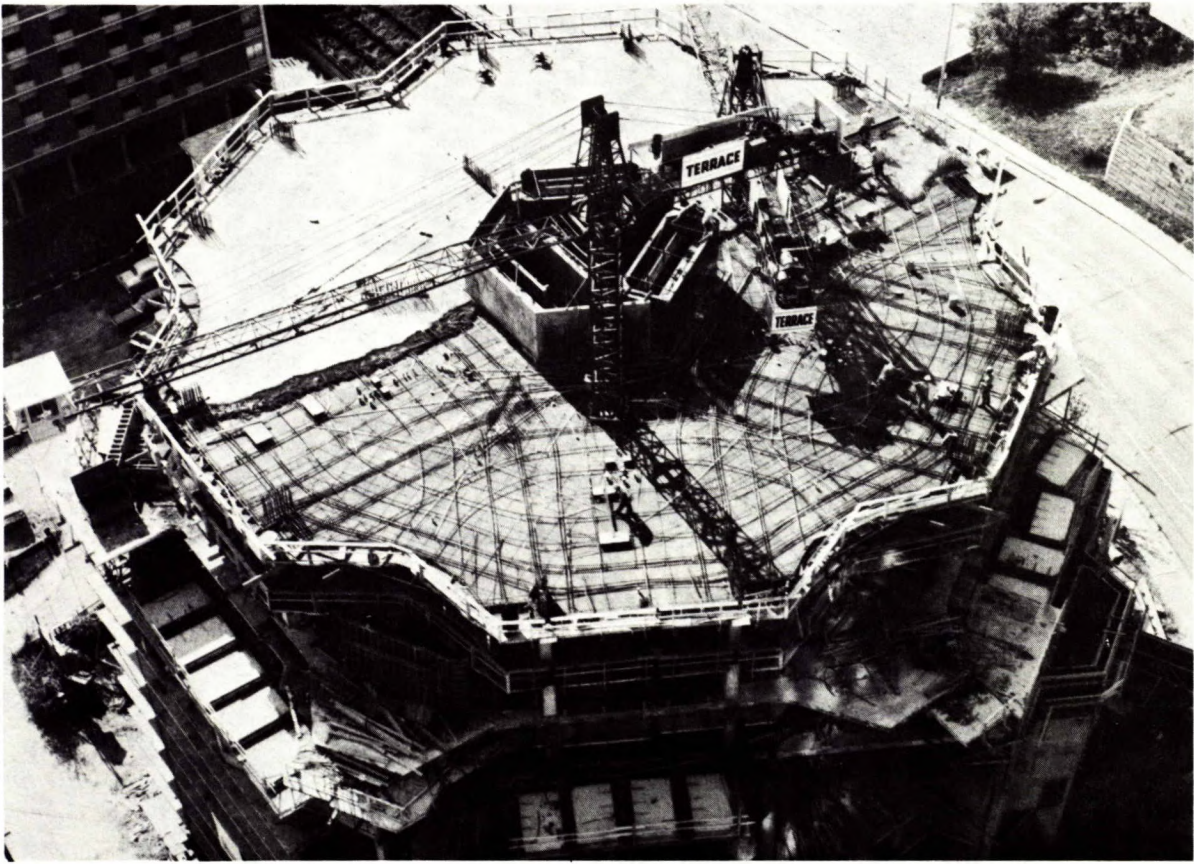


Figure 35. Floor Construction; Edmonton House, Edmonton



Figure 36. International Inn, Calgary



Figure 37. Place Concorde, Calgary

Figure 38 is of the Canadiana Apartment Building in Regina, which has lightweight concrete in the roof, floors, columns and piles. In addition, the exterior walls of the 14-storey building are of patterned lightweight block. The saving in reduced foundation and in steel, compared with a normal weight structure, amounted to \$40,000 or nearly 3 per cent of the cost of the building (52).

A saving of \$20,000 in reinforcing steel plus two extra floors were realized in an 8-storey office building in Don Mills, Ont. Soil conditions would have limited a normal-weight concrete structure to 6 storeys, but lightweight concrete floors made the 8-storey structure possible. The design of the floor system permitted 40 ft (12.2 m) clear spans in the offices.

The Heatley Avenue Overpass, in Vancouver, shown under construction in Figure 39, crosses 14 railroad tracks and 2 streets. The modified Y-shaped structure, built in 1964, is made of 60 lightweight concrete, prestressed I-shaped girders of 23 different lengths. The girders between 65 and 90 ft (19.8 and 27.5 m) long are 3 ft 7 in. (1.1 m) deep, and the girders between 90 and 110 ft (27.5 and 33.6 m) long are 4 ft 4 in. (1.3 m) deep. These are carried on 10 spans. The semi-circular portion of the Y is composed of five post-tensioned slabs 61.5 ft (18.8 m) long and 36 in. (0.9 m) deep. The concrete for the girders had a dry unit weight of 108 to 110 lb/ft³ (1730 to 1760 kg/m³) with a cement content (ASTM Type III) of 626 lb/yd³ (408 kg/m³). The mean cylinder strengths at 16 hours, 7 days, and 28 days were 4200, 4920 and 5790 psi (29.0, 33.9 and 40.0 MPa) respectively (53).

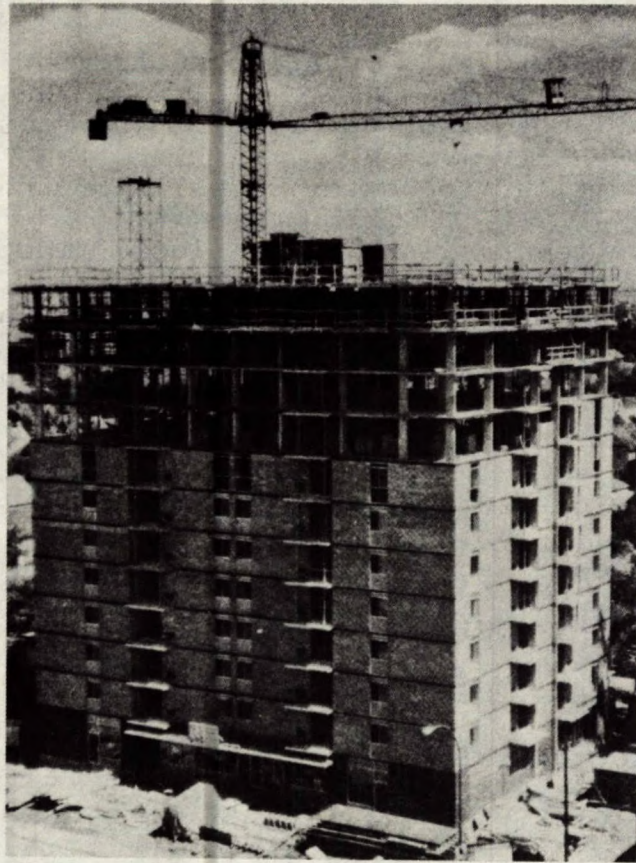


Figure 38. Canadiana Apartments, Regina

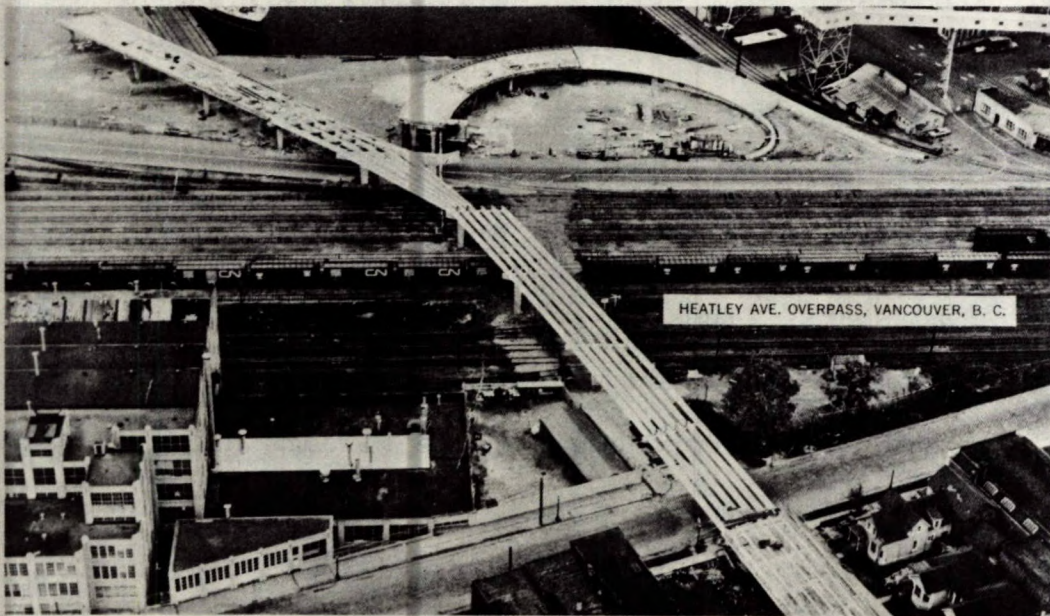


Figure 39. Heatley Avenue Overpass, Vancouver

The James MacDonald Bridge Project in Edmonton used precast channel-shaped components for the 870 ft (265.4 m) bridge. The components, 120 ft by 50 in. (36.6 by 1.3 m), each required 33 yd³ (25.2 m³) of 6250 psi (43.0 MPa) concrete. Lateral bracing was supplied by cast-in-place lightweight concrete horizontal diaphragms between the bottom flanges of the girders at the piers and vertical diaphragms between the girders at 40 ft (12.2 m) intervals.

Precast lightweight concrete panels were used in constructing a number of warehouses in Calgary, Alta.; the on-site precasting employed special forms hinged at one end. When the concrete, in the form, was 24 hours old, both were tilted up to about 85 degrees from the horizontal; then a crane removed the panel from the form and placed it in the wall of the warehouse. Panels of 16 by 27 ft (4.9 by 8.2 m), 16 by 8.25 ft (4.9 by 2.5 m), and 8 by 27 ft (2.4 by 8.2 m) were made and installed in this manner (54). Figure 40 illustrates the panel being removed from the form, and being transported to the installation.

Although most applications of lightweight structural concrete are primarily for its physical properties, there are instances where it has been used as much for its appearance as for its engineering features. The Burlington Central Library in Burlington, Ont., is a prime example (54). Lightweight structural concrete is used in all load-bearing walls, both external and internal. The external walls are bush-hammered on the exterior face, and lightly sand-blasted on the interior face. The architect designed the structure so that, both externally and internally,

it would relate to the sloping, wooded, park site in which it is located (55). This structure is illustrated in Figure 41.

At the other extreme from the high-rise apartment building in which lightweight-structural concrete has been used are the circular staircase in the Chinook Professional Building in Calgary (56) and the helicoidal staircase in the Yorkdale Shopping Centre in Toronto (57). The former was moulded in a single 16 yd³ (12.2 m³) placement. The latter is a 30 ft (9.2 m) diameter by 20 ft (6.1 m) high spiral of 100 lb/ft³ (1600 kg/m³) lightweight concrete and is 21 tons (19,000 kg) lower in weight than an equivalent normal-weight concrete spiral would have been. The dead load of the lightweight-structure was 79 tons (71,600 kg). The two staircases are illustrated in Figures 42 and 43.

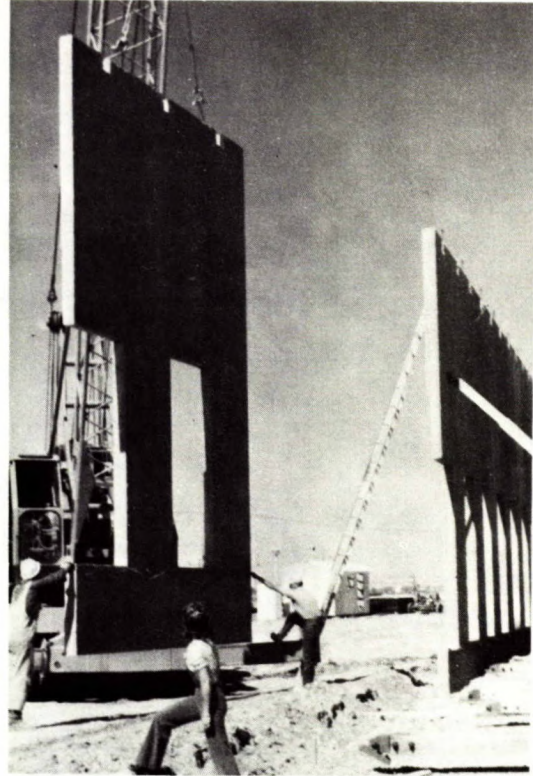
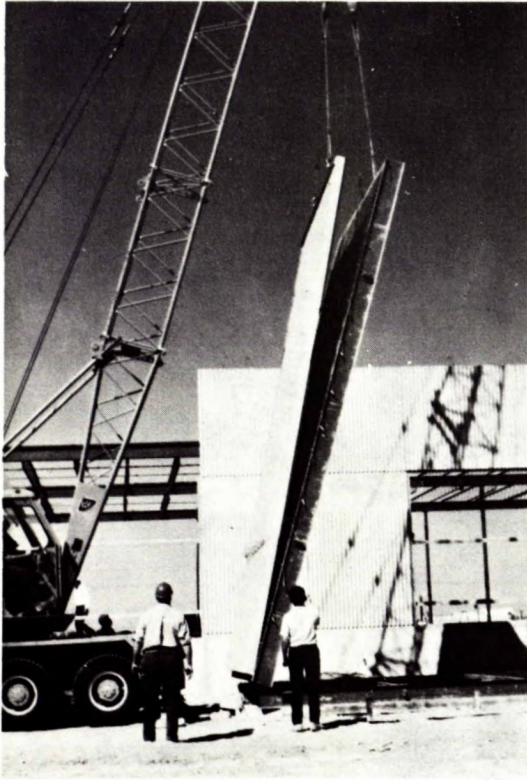


Figure 40. Views of Precast Lightweight Panels, Calgary

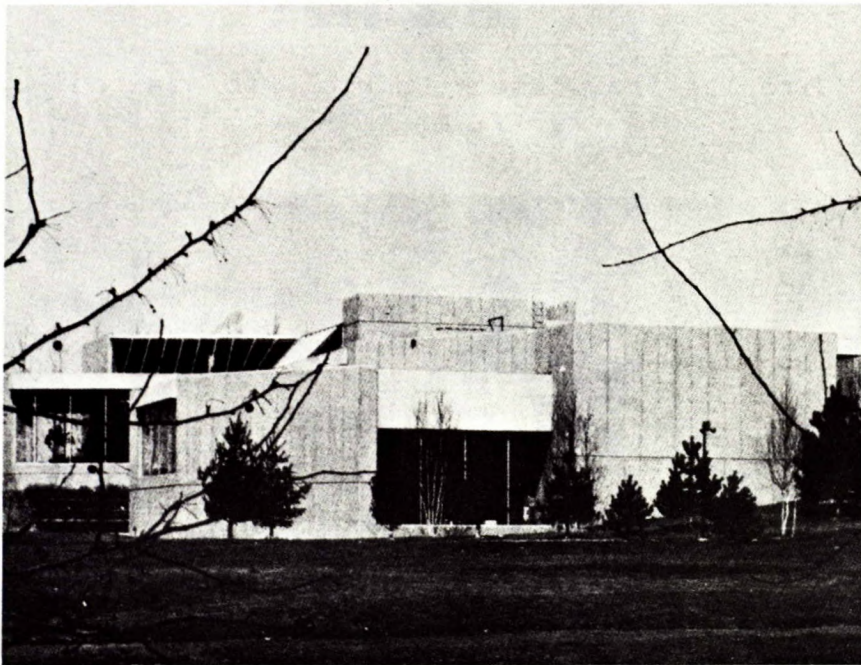


Figure 41. Burlington Central Library, Burlington

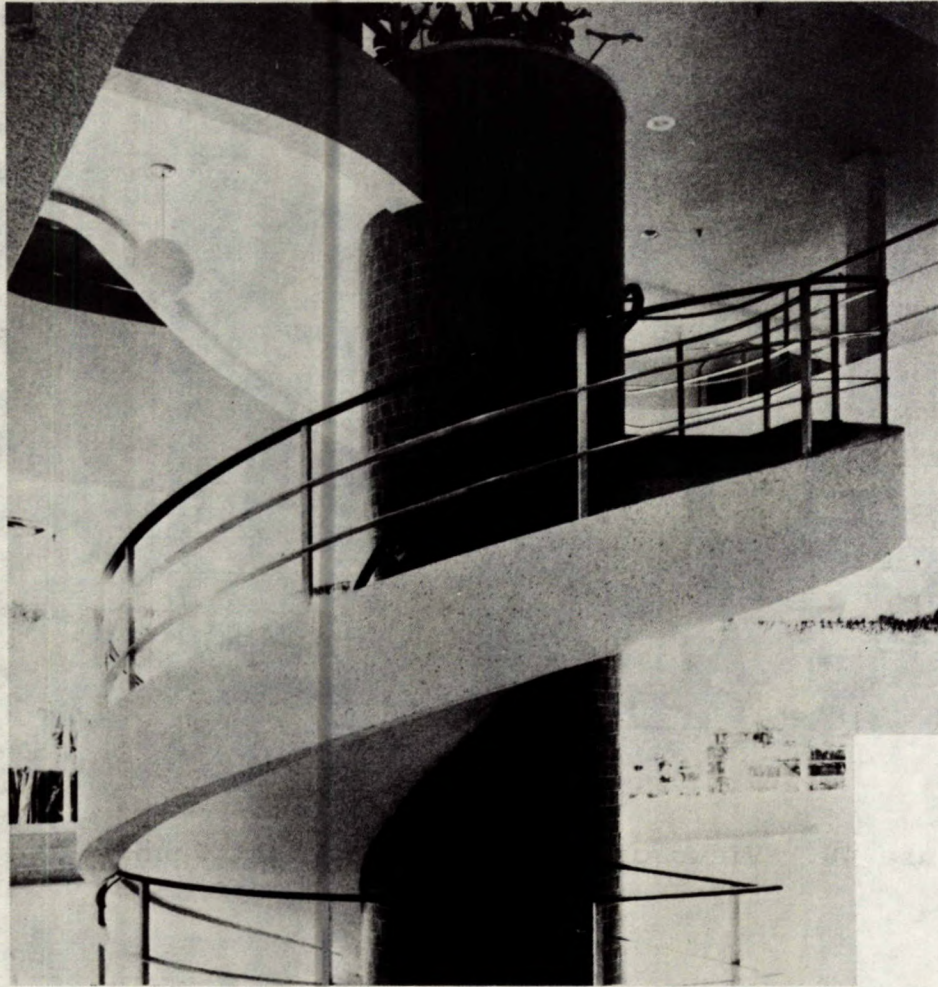


Figure 42. Circular Staircase - Chinook Professional Building, Calgary, Alberta



Figure 43. Helicoidal Staircase - Yorkdale Shopping Centre, Toronto, Ontario

Specifications

Specifications have been formulated in many countries to govern the quality of lightweight aggregates and the products into which they are incorporated. In Canada, normal-weight and lightweight aggregates and concrete are governed by the Canadian Standards Association (CSA) Standard on Concrete Materials and Methods of Concrete Construction (58). The sections which concern lightweight aggregate have been adopted from the Standards prepared by the American Society for Testing and Materials (ASTM). The three pertinent ASTM standards are:

C 330-75a; Lightweight Aggregates for Structural Concrete (59)

C 331-69; Lightweight Aggregates for Concrete Masonry Units
(60)

C 332-66; Lightweight Aggregates for Insulating Concrete (61)

The limitations regarding gradings and unit weights of aggregates for structural concrete are given in Tables 2 and 3.

The relationship between the unit weight of structural concrete and the splitting-tensile and compressive strengths are given in Table 4.

Other limitations include:

- (a) The aggregates shall not contain organic material that will do harm to the concrete.
- (b) The aggregate, on being subjected to the test for staining materials, shall not show "heavy stain" or darker, or on being tested chemically, shall not contain 1.5 mg or more of Fe_2O_3 .
- (c) Clay lumps in the aggregate shall not exceed 2 per cent by weight.
- (d) Loss on ignition of the aggregate shall not exceed 5 per cent.
- (e) Drying shrinkage shall not exceed 0.10 per cent.

TABLE 2

Grading Requirements for Lightweight Aggregates for Structural Concrete*

Size Designation	Percentage (by Weight) Passing Sieves Having Square Openings								
	1 in. (25.4 mm)	$\frac{3}{4}$ in. (19.0 mm)	$\frac{1}{2}$ in. (12.5 mm)	$\frac{3}{8}$ in. (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 50 (300 μ m)	No. 100 (150 μ m)
Fine aggregate:									
No. 4 to 0	...	...	...	100	85-100	...	40-80	10-35	5-25
Coarse aggregate:									
1 in. to $\frac{1}{2}$ in.	95-100	...	0-10	...	...	...	...	...	...
1 in. to No. 4	95-100	...	25-60	...	0-10	...	...	...	...
$\frac{3}{4}$ in. to No. 4	100	90-100	...	20-60	0-10	...	...	...	...
$\frac{1}{2}$ in. to No. 4	...	100	90-100	40-80	0-20	0-10	...	...	...
$\frac{3}{8}$ in. to No. 8	...	...	100	80-100	5-40	0-20	...	...	...
Combined fine & coarse aggregate:									
$\frac{1}{2}$ in. to 0	...	100	95-100	...	50-80	...	...	5-20	2-15
$\frac{3}{8}$ in. to 0	...	...	100	90-100	65-90	35-90	...	10-25	5-15

*From ASTM C 330-75a

TABLE 3

Maximum Unit Weight of Lightweight Aggregate*

Size Designation	Dry, Loose Unit Weight	
	lb/ft ³	kg/m ³
Fine aggregate	70	1120
Coarse aggregate	55	880
Combined fine and coarse aggregate	65	1040

*From ASTM C 330-75a

TABLE 4

Relationship Between Weight and Strength of
Structural Concrete*

Average Unit Weight, max		Average 28-day Splitting Tensile Strength, min		Average 28-day Compressive Strength, min	
lb/ft ³	kg/m ³	psi	MPa	psi	MPa
115	2	290	2	4000 or more	23 or more
110	2	290	2	3000	21
105	2	290	2	2500	17

*From ASTM C 330-75a

The limitations regarding the gradings of aggregates for concrete masonry units are given in Table 5, while the gradings of aggregates for insulating concrete are given in Table 6. Only the gradings for Group II aggregates are applicable to this discussion; Group I aggregates being expanded perlite and exfoliated vermiculite.

TABLE 5

Grading Requirements for Lightweight Aggregates for Concrete Masonry Units*

Size Designation	Percentages (by Weight) Passing Sieves Having Square Openings							
	$\frac{3}{4}$ in. (19.0 mm)	$\frac{1}{2}$ in. (12.5 mm)	$\frac{3}{8}$ in. (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 50 (300 μ m)	No. 100 (150 μ m)
Fine aggregate.								
No. 4 (4.75 mm) to 0	...	...	100	85-100	...	40-80	10-35	5-25
Coarse aggregate:								
$\frac{1}{2}$ in. to No. 4 (12.5 to 4.75 mm)	100	90-100	40-80	0-20	0-10	...	...	...
$\frac{3}{8}$ in. to No. 8 (9.5 to 2.36 mm)	...	100	80-100	5-40	0-20	...	...	...
Combined fine & coarse aggregate:								
$\frac{1}{2}$ in. (12.5 mm) to 0	100	95-100	...	50-80	...	...	5-20	2-15
$\frac{3}{8}$ in. (9.5 mm) to 0	...	100	90-100	65-90	35-65	...	10-25	5-15

*From ASTM C 331-69

TABLE 6

Grading Requirements for Group II Lightweight Aggregates for Insulating Concrete*

Size Designation	Percentage (by Weight) Passing Sieves Having Square Openings								
	$\frac{3}{4}$ in. (19.0 mm)	$\frac{1}{2}$ in. (12.5 mm)	$\frac{3}{8}$ in. (9.5 mm)	No. 4 (4.75 mm)	No. 8 (2.36 mm)	No. 16 (1.18 mm)	No. 30 (600 μ m)	No. 50 (300 μ m)	No. 100 (150 μ m)
Fine aggregate:									
No. 4 (4.75 mm) to 0	...	...	100	85-100	...	40-80	...	10-35	5-25
Coarse aggregate:									
$\frac{1}{2}$ in. to No. 4 (12.5 to 4.75 mm)	100	90-100	40-80	0-20	0-10	...	...	...	...
$\frac{3}{8}$ in. to No. 8 (4.75 to 2.36 mm)	...	100	80-100	5-40	0-20	...	...	...	...
No. 4 to No. 8 (4.75 to 2.36 mm)	...	...	100	90-100	0-20	....	...	...	...
Combined fine and coarse aggregate:									
$\frac{1}{2}$ in. (12.5 mm) to 0	100	95-100	...	50-80	...	...	...	5-20	2-15
$\frac{3}{8}$ in. (9.5 mm) to 0	...	100	90-100	65-90	35-65	...	...	10-25	5-15

*From ASTM C 332-66

The limitations for unit weight of aggregate, impurities and drying shrinkage of concrete masonry units and insulating concrete are identical to those of ASTM C 330-69.

The relationship between the unit weight and thermal conductivity of insulating concrete is given in Table 7.

TABLE 7

Unit Weight and Thermal Conductivity
of Insulating Concrete*

Maximum Average 28-Day Oven-Dry Unit Weight, lb/ft ³ (kg/m ³)	Maximum Average Thermal Conductivity, Btu in./ hr ft ² deg F (W/m K)
50 (800)	1.50 (0.22)
90 (1440)	3.00 (0.43)

*From ASTM C 332-66

The unit weight limitations are identical to those of ASTM C 330-75a.

Canadian Production

In Canada the production was limited to one plant from 1927 until 1953, when the second was built. By the end of 1954, four plants were in operation, and annual production amounted to 170,000 yd³ (130,000 m³). By 1960, there were 10 plants and 364,000 yd³ (27,800 m³) were produced, and in 1965, production was 511,000 yd³ (39,000 m³), from 9 plants. The steady increase in production from 1953 until 1965 did not continue after that year: production has tended to level off since then. In 1975, the 6 plants in production were:

Avon Aggregates Ltd.	- Minto, N.B.
Cindercrete Products Ltd.	- Regina, Sask.
Consolidated Concrete Ltd.	- Calgary, Alta.
Consolidated Concrete Ltd. Edcon Block Division	- Edmonton, Alta.
Domtar Construction Materials Ltd.	- Mississauga, Ont.
Kildonan Concrete Products Ltd.	- St. Boniface Man.

The locations of these plants are shown on the map, Figure 44.

Prices and Economics

The lightweight aggregates produced in Canada, from clays and shales, were available in 1974 at between \$6.00 and \$10.32 per yd³ (\$7.85 and \$13.50/m³), f.o.b. producing plant.

With the continually rising costs of materials and labour, it is of little value to compare costs of normal-weight and lightweight structures at any one time. A study, made in 1973 by the Portland Cement Association in co-operation with a Canadian producer of lightweight aggregate, showed that a lightweight floor system was more economic when: the dead load on the floor was high relative to the total load, the floor span increased, and the number of storeys increased.

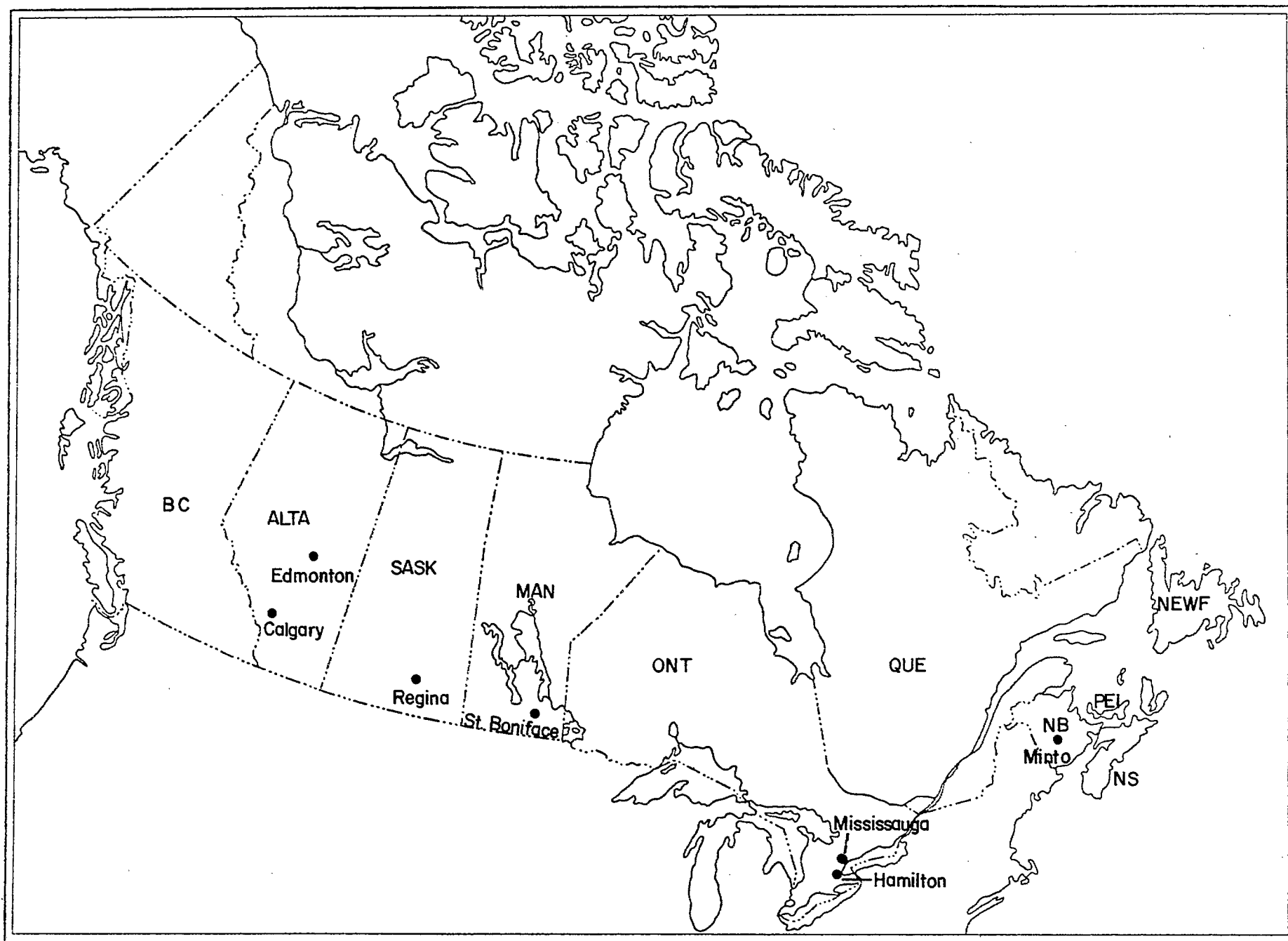


Figure 44. Locations of Lightweight Aggregate Plants.

BLAST FURNACE SLAG

Introduction

The American Society for Testing and Materials defines blast furnace slag as "The non-metallic product, consisting essentially of silicates and alumino-silicates of lime and of other bases, which is developed in a molten condition simultaneously with iron in a blast furnace" (62). It is formed in the process of reducing iron ore into pig iron. Slag has been produced since the first iron-smelting furnace was operated, but not until the eighteenth century was it put to any practical use. It was reportedly used to make cast-slag building blocks in England about 1728. It was later used in a form of cement in Germany in 1822, and it was used for road-building in England in 1813, and in the United States in 1830 (63).

In Canada, until about 1920, all the slag produced was a waste material or was used for land fill. By 1920, a small proportion of the air-cooled slag was being processed by crushing and screening for railway ballast and road construction.

Production of expanded slag began in the United States in the early 1930's; in Canada, production began in Sydney, N.S. in 1947. A second and larger plant began operation in Hamilton, Ont. in 1954. The original plant in Sydney was shut down in 1968 and, at the present time, the plant at Hamilton is the only one in Canada producing expanded slag.

Blast Furnace Slag Production

The present-day blast furnace has evolved from the crude

furnaces used in iron smelting as far back as 1500 B.C. It is a result of the gradual development of the art and later the science of ferrous metallurgy. The blast furnace is nearly cylindrical, about 100 ft (30.5 m) high and of varying inside diameters of up to 35 ft (10.7 m). It is composed of three principal sections; the stack or shaft, the bosh, and the hearth. Apparatus is included at the top of the stack to permit charging the furnace and also to collect the gases generated in the process. At the bottom, means are included to tap the molten iron and molten slag (54). A diagrammatic cross-section of a furnace is shown in Figure 45.

The charge to the furnace includes iron ore pre-reduced pellets, coke, and limestone and dolomite. The coke serves a dual purpose; to supply the heat required for the metallurgical reactions to take place, and to supply the reducing agent (carbon monoxide) needed to reduce the iron ore to metallic iron. The limestone and dolomite flux alumina and silica contained in the burden to form a fluid slag of a composition that will prevent such elements as silicon and sulphur from entering the iron phase.

As the burden of ore, coke and flux gradually move down in the furnace, they encounter a rising blast of heated air introduced through tuyeres in the bosh. The molten iron settles into the hearth with the lighter molten slag floating on top of it; the slag being formed from the gangue material in the ore, the ash remaining from the combustion of the coke, and the non-volatile portion of the fluxing stone.

The molten iron is tapped from the furnace about every 4 hours. If sufficient slag is formed, it is removed, between

iron casts, through the cinder notch. If only a relatively small amount of slag is formed it is removed through the tap hole. The iron alone flows from the tap hole first, and as the supply of iron in the furnace diminishes, the iron and slag flow from the hole together. The components can be separated as the slag still floats on the iron. The last part of the cast is slag alone; this slag may flow into pits adjacent to the furnace, or may be transported a considerable distance from the furnace in slag ladles.

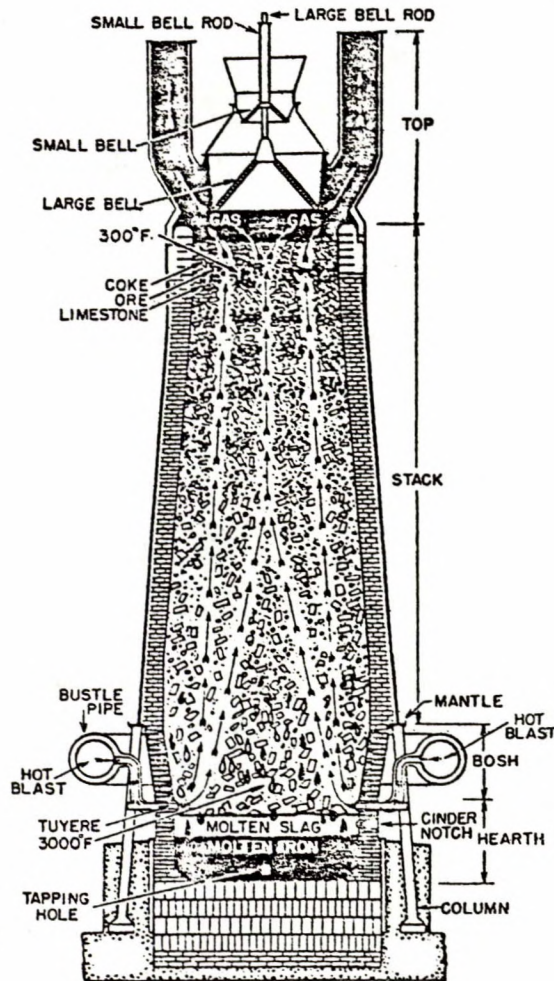


Figure 45. Diagrammatic Cross-Section of a Blast Furnace

Through the years, the productivity of the blast furnace process has been improved. Changes in the dimensions of the three sections of the furnace and in sizing and methods of preparation of the raw materials have increased the solid-gas contact and the burden permeability. Injection of oxygen, natural gas and moisture into the blast have reduced the coke consumption in some installations. As the productivity of iron increases, the slag volume per ton of iron decreases. It is as low as 450 lb of slag per ton (0.225 kg/kg) of iron at present.

Blast furnace slags are considered to be basic by the metallurgist because the ratio of the bases (CaO and MgO) to the acids (SiO_2 and Al_2O_3) is usually greater than one.

The maximum temperature in the blast furnace is about 1650°C (3000°F); Crystallization begins at about 1430°C (2600°F) as the slag cools. The most common minerals occurring in slags are (65):

Melilite Series	- solid solution from Akermanite to Gehlenite
Akermanite	- $2\text{CaO MgO } 2\text{SiO}_2$
Gehlenite	- $2\text{CaO Al}_2\text{O}_3 \text{ SiO}_2$
Anorthite	- $\text{CaO Al}_2\text{O}_3 2\text{SiO}_2$ (in low lime, high alumina slag)
Ca metasilicate	- CaOSiO_2 (sometimes found)
Ca orthosilicate	- 2CaOSiO_2 (in high lime slags)
Calcium sulphide	- CaS
Manganese sulphide	- MnS
Ferrous Sulphide	- FeS

The most common of these minerals in slag are those in the melilite series, a series of solid solutions extending from akermanite to gehlenite, all crystallizing in the same tabular

form as octagonal and rectangular plates. Orthosilicate is undesirable in slags; it is stable in the α form only above 1420°C (2590°F), at this temperature inverting to the β form, and then to the γ form at 675°C (1250°F). The inversion to the γ form is accompanied by expansion, causing disintegration of the slag. Orthosilicate can form in slags in which the lime content is high and the silica and magnesia are low: one criterion of potential formation is a lime content 10 per cent higher than the silica content.

The chemical composition of the blast furnace slag ranges within fairly narrow limits, as shown in Table 8.

TABLE 8
Composition of Slags

Silica (SiO_2)	- 33-42%
Alumina (Al_2O_3)	- 10-16%
Lime (CaO)	- 36-45%
Magnesia (MgO)	- 3-12%
Sulphur (S)	- 1- 3%
Iron oxide (FeO)	- 0.3-2%
Manganese oxide (MnO)	- 0.2-1.5%

Slag Processing

There are three types of processed slag, depending on the method of cooling: air-cooled or hard slag, granulated slag, and expanded or foamed slag.

Air Cooled Slag

Air-cooled slag is allowed to cool slowly, in pits either adjacent to the blast furnace or at a distance away. In either case, there are usually two pits together; one pit is filled with molten slag while the other is cooling or being excavated. Generally a pit will hold about one week's production of slag. The slag ladles used to transport the slag are either pulled on tracks by a locomotive or are mounted on a carrier which is pulled by a large truck. The ladles can transport up to 30 short tons of molten slag.

Once the slag has solidified, the cooling is frequently accelerated by spraying water on it. This treatment opens cracks in the slag, facilitating recovery. Slag cooled in this manner develops the greatest amount of crystallization, and is the strongest of the three types. It has a specific gravity of 2.0 to 2.5, and a graded concrete aggregate would have a compacted bulk density between 70 and 85 lb/ft³ (1120 and 1360 kg/m³). It is used in such applications as granular base for roads and parking lots, railroad ballast, bituminous pavements, cast-in-place and precast concrete, in concrete masonry units, on built-up roofing, and in mineral wool manufacture.

Granulated Slag

Granulated slag is the glassy granular product formed by rapid chilling of the molten slag, usually by immersion in water or by striking a stream of slag with a jet of water. In another method, the stream of slag is broken mechanically into

small particles and quenched with a relatively small amount of water. The water is evaporated by the residual heat in the slag, which remains relatively dry. Little, if any crystallization takes place before granulated slag has solidified. This type of slag can be used as: base material for asphalt or concrete pavements, floor fill, back fill around foundation walls and bridge abutments, a liming soil conditioner, and aggregate in concrete masonry units. When finely ground, the glassy granulated slag has cementing properties and is being used as blast furnace slag cement. The more crystalline slags do not possess adequate cementing properties.

Expanded Slag

The expanded or foamed type of slag is intermediate between the air cooled and the granulated slags in crystal growth and in strength. Fundamentally, the slag is expanded by a controlled amount of water rather than a large quantity as for most granulated slags.

Many methods of adding the water have been used over the years. One of the earliest attempts made in Germany in 1912, in which slag was poured over wet sand, was not successful because insufficient water was available for expansion.

The Brosius machine, developed in Germany, and first used in the United States in 1932, contains two enclosed, horizontal rotors. As the slag enters the machine, near the periphery of the upper rotor, jets add the proper amount of water to expand the slag. Paddles on the rotor break up the slag and throw it

against a buffer plate. It falls to a second rotor which repeats the treatment. The violent agitation plus the steam formed from the water expands the slag, which drops onto a pan conveyor and is transported to the crushing installation.

The Caldwell machine, was developed in the United States in 1932, with improvements continuing through 1939. This machine also contains a horizontal rotor; water being added to the molten slag in a chamber above the rotor. The water granulates and, to a degree, expands the slag. The granules drop onto the rapidly revolving rotor, which throws them into a collecting device, and as they are still pyro-plastic, they agglomerate in this device. The voids within and between the granules result in a cellular clinker, which is discharged from the machine when it is about one cubic foot in size. The clinker is conveyed to the crusher (66).

In 1943, the Gallai-Hatchard pit process was developed in Britain. This was an improvement on the unsuccessful method using wet sand. Gallai-Hatchard increased the water available for expanding by imbedding perforated water pipes in the sand. Slag was dumped rapidly from a ladle onto the pre-wetted sand and the water turned on. The water, turned to steam, foamed or expanded the slag blanket, which when cooled could be removed by a scraper arrangement. The sand bed was eventually replaced with a concrete bed. German adaptation of this process used a metal bed which could be tilted when the slag had hardened (in a matter of minutes) and the slag would slide off. This increased the frequency of usage. The important feature of this Gallai-Hatchard

process is that the slag had to be dumped rapidly into the pit to prevent steam escape (67).

The Kinney-Osborne process, developed about 1952 in the United States, expands the slag adjacent to the blast furnace. As the molten slag enters a chute from the cinder runner, it is struck by a jet of steam or low pressure air. This breaks the stream into small globules, which immediately encounter a fine water spray and expand. The expanded globules then strike a baffle plate where they agglomerate and fall onto a drag conveyor linked with the crusher (68).

One drawback to all of these methods of expanding slag is that during or after the foaming process, they give off sulphurous gases. Dependent upon the location of the expanded operation, it could be considered a pollution hazard. Most of the producers of expanded slag in the United States use a form of the Gallai-Hatchard pit process. This method has the advantage of the pit being installed at a convenient site some distance from the blast furnace, whereas the other methods generally use facilities installed adjacent to the blast furnaces. Figure 46 shows slag being dumped from a ladle into a foaming pit.

Composition and Expansion

The degree of expandability of slag will depend on the composition and the temperature at which it is expanded. A molten slag is not a simple mixture or solution of oxides but is formed mainly of more complex compounds of the oxides: CaO , SiO_2 , Al_2O_3 and MgO . These four oxides make up 90 to 95 per cent of the slag.

Minor compounds contain MnO and FeO. In general, at a given temperature, the viscosity of a slag will be lower: the higher the basicity (the ratio of $\text{CaO} + \text{MgO}$ to $\text{SiO}_2 + \text{Al}_2\text{O}_3$) the higher the MgO, the lower the SiO_2 , and the higher the CaO (69).

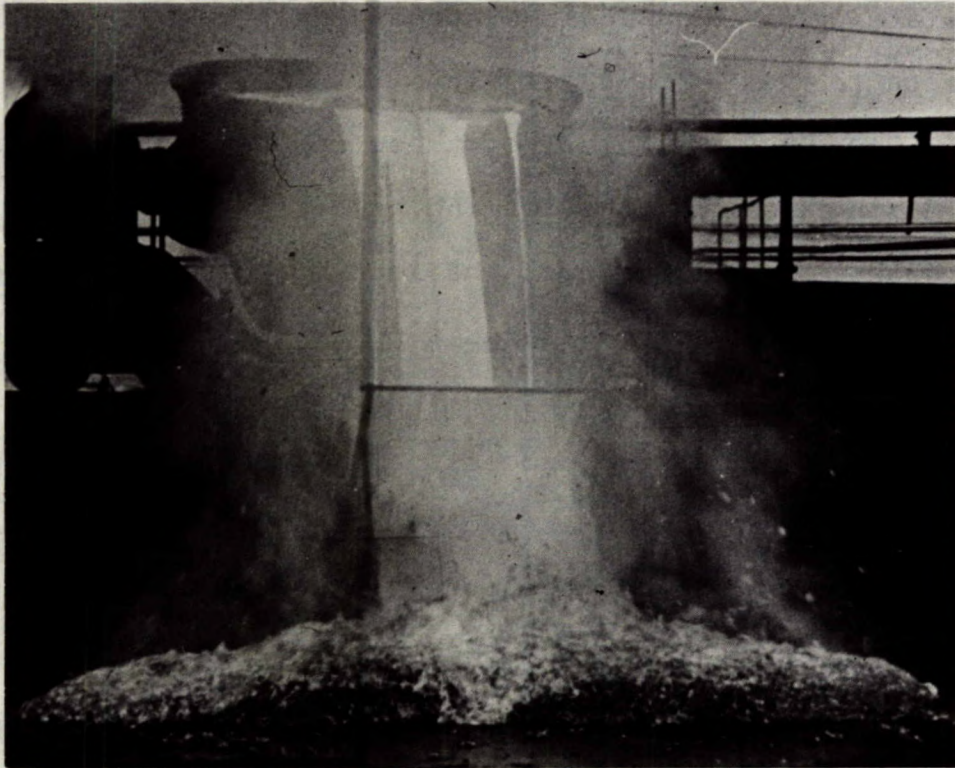


Figure 46. Expanding Blast Furnace Slag in a Pit

Feild and Royster (70) found that, generally, the viscosity decreased with increasing lime content, and the temperature coefficient of viscosity* was higher with increasing alumina content. They found that viscosity depended less on the chemical analysis and more on the mineralogical composition. They found four compounds that occur in only two combinations of three each:

- (a) calcium metasilicate (CaO SiO_2), gehleite ($2\text{CaO Al}_2\text{O}_3 \text{ SiO}_2$), and anorthite ($\text{CaO Al}_2\text{O}_3 2\text{SiO}_2$);
- (b) calcium metasilicate, gehlenite, and calcium sesquioxide (3CaO 2SiO_2).

Rait and Hay (71) found that anorthite and gehlenite tend to increase the viscosity while sesquioxide and disilicate reduce viscosity.

Layton (72) found that the minimum temperature at which slag will "foam" well is 1385°C (2525°F) regardless of the composition. He also found that MnO and FeO are foam depressants, with MnO being a much more active depressant than FeO . He concluded that foaming is not simply a mechanical phenomenon resulting from the formation of steam within a blanket of molten slag. Hence, as he felt that sulphur is a foam promoter, he allocated the sulphur in a number of slags to the MnO and to $\frac{1}{6}$ of the FeO . He then plotted the "remaining sulphur" against the fusion temperature and found the points agreed with the observations of actual foams obtained. The good foaming slags had high "remaining sulphur" and had fusion temperatures above 1385°C (2525°F).

*The temperature at which a slag has a specific viscosity.

Canadian Developments

The plant at Sydney, N.S. expanded slag from 1947 until 1968, using a pit-method of expansion. National Slag Ltd., Hamilton, Ont., originally used the Kinney-Osborne process, but in 1963, the company began to use a pit-method, utilizing a specially designed carrier to transport a 450 ft³ (12.6 m³) batch, containing 30 tons (27,000 kg) of slag, from the blast furnace to the expanding pits. These processes make an agglomerated slag which must be crushed to the desired size. The resulting crushed material is vesicular, and irregular in shape.

In 1968, the company developed a machine to produce a pelletized expanded slag. The molten slag is first expanded by water sprays on a feed plate, and then is passed over a rapidly revolving drum. The fins on the drum break the expanded pyroplastic slag into small particles and throw them into a collection area. During flight, the particles are formed into pellets. By regulating conditions at the machine, the size of the pellets can be controlled so that crushing to produce an aggregate for lightweight concrete is virtually unnecessary. A second important feature of this machine is that it almost completely eliminates the sulphurous fumes associated with most of the other expanding methods.

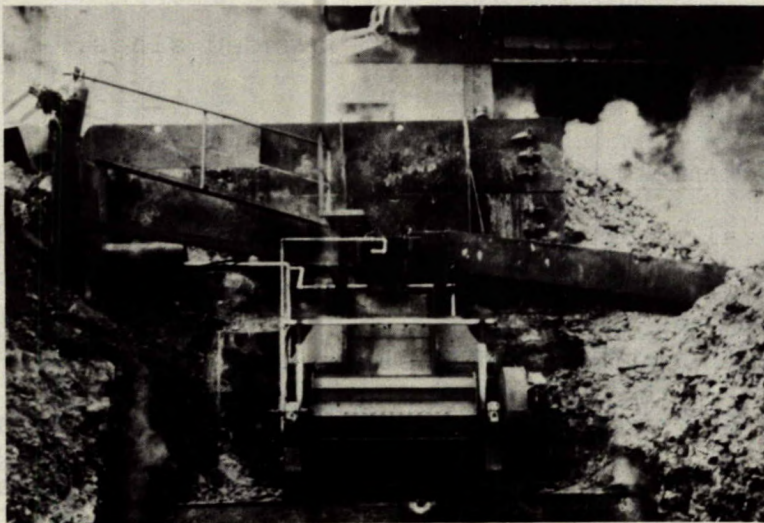
Several of these machines have been installed permanently or on a trial basis at expanding sites in the United States, England, Australia, Japan, Portugal, Finland, Luxembourg, Sweden, and Austria.

Figure 47 illustrates the pelletizing machine and the

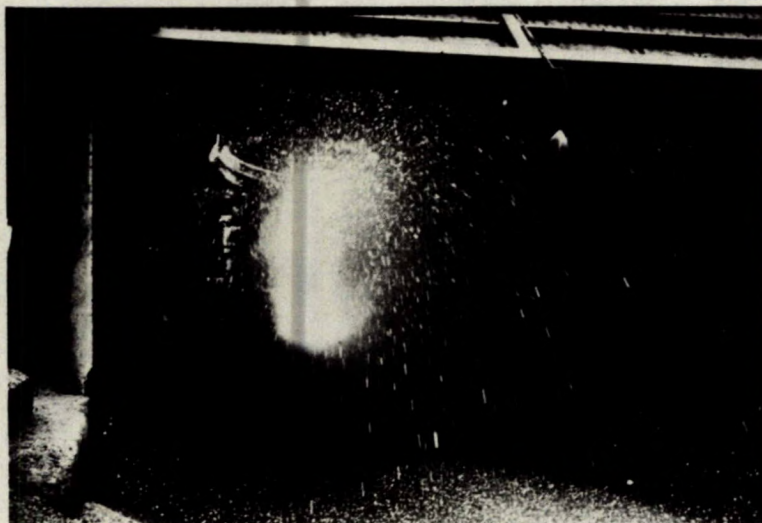
production of pelletized expanded slag, while Figure 48 illustrates pelletized and pit-produced expanded slags.

Mineralogical Examination

Several recently produced pellets were embedded in resin and one petrographic thin section was prepared. Internal structure of the pellets is illustrated in Figure 49. At higher magnification, and under polarized light, it is evident that the pellets are largely composed of glass. The few crystals that are evident are located near the surface of the pellets and around the vesicles. This is illustrated in Figure 50. The crystals appear around the vesicles near the top of the photographs, the white areas in photograph (b).



(a)



(b)

Figure 47. Slag-Pelletizing Machine

(a) Machine

(b) Pelletizing Slag



Figure 48. Pelletized and Pit-Produced Expanded Slag

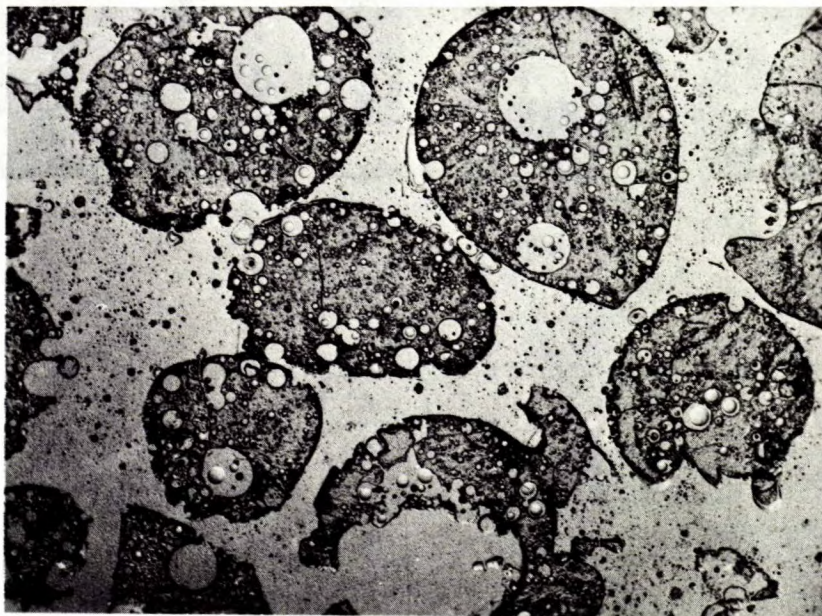
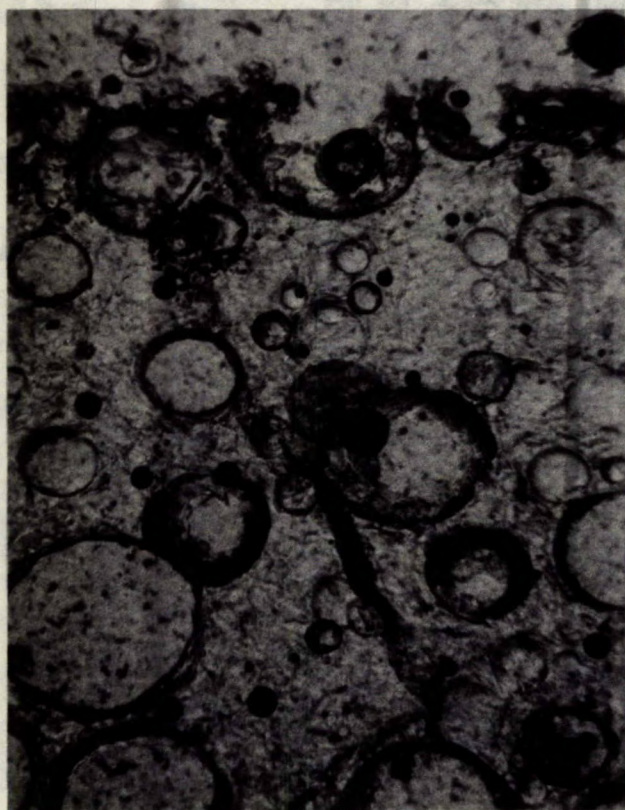


Figure 49. Internal Structure of Pelletized Expanded Slag



(a)



(b)

Figure 50. Photomicrographs of Thin Sections of Pelletized Expanded Slag

(a) Polarized Light, x 125

(b) Crossed Polaroids, x 125

Properties

The properties of expanded slag aggregate will depend on the composition of the slag and the method of processing. The blast furnace operator is concerned with producing iron, and to him slag is a by-product of little interest. Consequently, the composition and properties of the slag may vary as conditions in the blast furnace are changed. The degree of expansion and the size of the aggregate also govern the properties. Dependent upon the source and the gradation, the unit weight will range between 25 and 70 lb/ft³ (400 and 1120 kg/m³). The thermal conductivities of a coarse and a fine expanded slag aggregate, at various temperatures are shown in Table 9 (73).

TABLE 9

Thermal Conductivity of Expanded Slag

Coarse Expanded Slag 1/2 in. to No. 4 : 40 lb/ft ³ (12.5 to 4.8 mm : 640 kg/m ³)				Blended Expanded Slag 1/2 in. to dust : 60 lb/ft ³ (12.5 mm to dust : 960 kg/m ³)			
Mean Temp		Thermal Conductivity		Mean Temp		Thermal Conductivity	
°C	°F	Btu in./hr ft ² deg F	W/mC	°C	°F	Btu in./hr ft ² deg F	W/mC
199.2	92.9	0.77	0.11	217.9	103.3	1.16	0.17
213.6	100.9	0.78	0.11	233.6	112.0	1.25	0.18
248.7	120.4	0.96	0.14	250.5	121.4	1.32	0.19
				255.2	124.0	1.42	0.20

Lewis (74) studied the properties of insulating and structural concretes made with two typical expanded slags produced in the United States. He varied the maximum size of the aggregates and the cement-to-aggregate ratios; with one slag, natural sand was used as the fine aggregate. The insulating concretes had oven-dry unit weights of 82 to 97 lb/ft³ (1310 to 1560 kg/m³) and 28-day compressive strengths of 560 to 1650 psi (3.8 to 11.4 MPa) with cement contents of 370 to 560 lb/yd³ (220 to 330 kg/m³). The structural concretes had oven-dry unit weights of 92 to 103 lb/ft³ (1480 to 1650 kg/m³) and compressive strengths of 2100 to 3780 psi, (14.5 to 26.0 MPa) with cement contents of 700 to 815 lb/yd³ (420 to 480 kg/m³). He found that increasing the maximum size of the aggregate from $\frac{3}{8}$ in. (9.5 mm) to $\frac{3}{4}$ in. (19.0 mm) increased the compressive strength and decreased the unit weight. The coefficient of thermal expansion of the concretes, both with and without natural sand, varied from 4.8 to 5.5×10^{-6} in/in/^oF (8.6 to 9.9×10^{-6} mm/mm/^oC). These values are similar to the values for conventional concretes. The lightweight concretes withstood 300 cycles of freezing and thawing. The drying shrinkages of the concretes were similar to other typical lightweight concretes.

He found that the relationship of oven-dry unit weight and thermal conductivity is approximately a straight line. Aggregate characteristics, cement and air contents, and the use of natural sand have little influence except as they affect the unit weight. Concretes made with four typical expanded slag aggregates, with oven-dry unit weights between 60.0 and 103.4 lb/ft³ (960 and

1660 kg/m³), conductivity (K) varied from 1.50 to 3.19 Btu in./hr ft² deg F (0.216 to 0.459 W/mC).

The National Slag Association (73) found that, in general, the modulus of elasticity of concrete made with expanded slag aggregate, will be higher than that with other types of lightweight aggregates, but lower than that for normal weight concretes.

The properties of expanded slag concrete masonry units, produced in the United States, are also reported by the National Slag Association (75). The properties of masonry units containing Canadian expanded slag, as reported by National Slag Limited, Hamilton, Ontario, are shown in Table 10.

TABLE 10

Properties of Expanded Slag Concrete Masonry Units*

<p><u>Sound Absorption</u></p> <p>4 in. (102 mm) hollow block fine-texture coarse-texture 8 in. (203 mm) solid block</p>	<p><u>Noise Reduction Coefficient**</u></p> <p>0.60 0.50 0.75</p>
<p><u>Sound Transmission</u></p> <p>8 in. (203 mm) hollow block unplastered 1 in. (25 mm) plaster</p>	<p><u>Decibel Loss</u></p> <p>45.0 52.6</p>
<p><u>Thermal Insulation</u></p> <p>90 lb/ft³ (1440 kg/m³) concrete</p>	<p><u>Btu in./hr ft² deg F</u> <u>W/mK</u></p> <p>2.60 0.37</p>
<p><u>Fire Resistance</u></p> <p>4.7 in. (118.4 mm) thickness</p>	<p><u>Rating</u></p> <p>4 hour</p>
<p><u>Modulus of Elasticity</u></p> <p>Block of average compressive strength</p>	<p><u>psi</u> <u>MPa</u></p> <p>1.6 x 10⁶ 1.1 x 10⁴</p>
<p><u>Compressive Strength</u></p>	<p>Meets ASTM specification (Designation C 331-69)</p>
<p><u>Drying Shrinkage</u></p>	<p>Low pressure cured; pre-dried, have low residual shrinkage. High pressure cured: normally less total shrinkage than other lightweight masonry.</p>

* Information supplied by National Slag Ltd.

**The absorbed fraction of the sound energy incident on a material

Applications

Expanded slag has a variety of uses, the principal use being as aggregate in lightweight concrete where it is used mainly in masonry units, but also, to a lesser degree, in precast shapes and in structural lightweight concrete.

In 1863, blast furnace slag cement was developed in Germany. Granulated slag, which has a very high proportion of glass, develops cementitious properties when pulverized, and normally is blended with portland cement. When the slag content is between 25 and 65 per cent, the blend is portland blast-furnace slag cement. When the slag content is over 65 per cent it is referred to as slag cement (76).

Emery, Kim and Cotsworth (77) utilized the cementing properties of pulverized pelletized slag to develop a stabilized base for highway construction. They found that the strength developed was mainly dependent on the amount and fineness of the minus 200-mesh (minus 75 μ m) fraction of the pulverized slag. A satisfactory stabilized base was composed of 70 per cent crusher-run air cooled slag and 30 per cent pulverized pelletized slag.

A manufacturer of concrete products in southern Ontario is to erect, in 1975, a plant to grind pelletized slag to cement fineness*. This material, which at that fineness has cementitious properties, will be mixed with normal portland cement by the company for use in the manufacture of concrete. Similar plants producing such a blended cement are reportedly in operation in Britain and in South Africa.

*Personal communication

Other uses to which expanded slag can be put include: back-fill around buildings and as floor fill to reduce heat or cold penetration, as a soil conditioner and liming agent, and for insulation in the cores of concrete masonry units.

The following are examples of some structures in which expanded slag has been used in Canada:

The floors of the 42-storey Century 21 building in Hamilton, Ont., were constructed of structural semi-lightweight concrete having compressive strength of 3500 psi (24.2 MPa). Figure 51 is a sketch of the structure.

Approximately 20,000 yd³ (15,000 m³) of fully lightweight concrete were used for fire resistant purposes with the cellular steel sub-floor of the Medical Science Centre at McMaster University, Hamilton, Ont.

The floors of the recent extension of Dofasco's head office building used a semi-lightweight concrete that had been pumped into place; the spherical shape of the pelletized lightweight aggregate lending itself to the pumping method of placement.

Figure 52 is a photograph of the Toronto-Dominion Bank Centre, Toronto, in which 1¹/₄ million expanded slag masonry units were used for the centre core construction and in column fire proofing.

Lightweight expanded slag masonry units are also used in such low-rise buildings as schools and theatres.

Specifications

The following ASTM specifications cover the use of expanded slag aggregate in lightweight concretes and in blended hydraulic cements:

ASTM Designation C 330-75a; "Lightweight Aggregates for Structural Concrete" (59)

ASTM Designation C 331-69; "Lightweight Aggregates for Concrete Masonry Units" (60)

ASTM Designation C 332-66; "Lightweight Aggregates for Insulating Concrete" (61)

ASTM Designation C 595-74; "Blended Hydraulic Cements" (78).

The latter standard gives the chemical and physical requirements for portland blast-furnace slag cements, portland pozzolan cements, and slag cements.

Prices

The 1975 selling price of expanded slag aggregate in Canada was \$4.95 per ton (\$5.46/1000 kg)*. The coarse aggregate has a density at 53 lb/ft³ (850 kg/m³) and the fine aggregate has a density at 67 lb/ft³ (1075 kg/m³)

*Available from National Slag Limited, Hamilton, Ont.

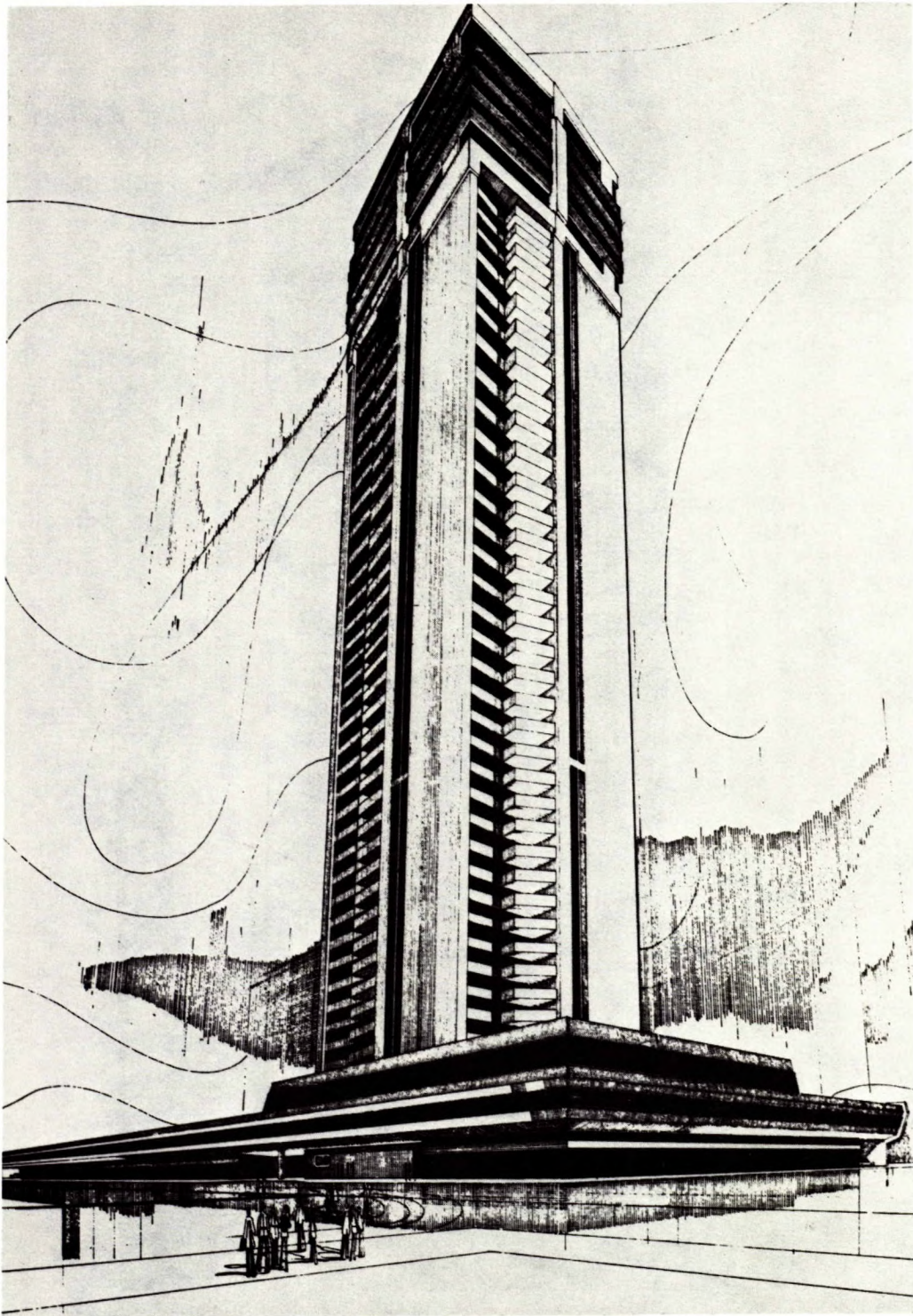


Figure 51. Century 21 Building, Hamilton



Figure 52. Toronto-Dominion Bank Centre, Toronto

OUTLOOK

In several areas of Canada, the reserves of locally available, normal-weight aggregates are rapidly dwindling. In the future, more of the normal-weight aggregates will have to be shipped greater distances to the market. Until the lightweight aggregate plants also have to move, this will result in some economic advantage to the lightweight aggregates, because most plants are now located adjacent to the major markets. Conversely, because of the increasing costs of fuels, the production costs of the lightweight aggregates will increase at a faster rate than will the production costs of normal-weight aggregates.

With the greater awareness of the necessity of insulation in buildings of all kinds, the lightweight aggregate producer should be able to market an aggregate that has lower unit weight and better thermal insulation properties. This has been the practice in Europe for many years. In many situations the production of low weight, high thermal insulating aggregate would necessitate the use of additives to alter the bloating properties of the raw material. In the case of expanded slag, altering production techniques and controls could possibly alter the properties of the aggregate.

The production of lightweight aggregates must become more of a science and less of an art, which to a large degree has been the case up until now. The design and selection of equipment, production techniques, and controls must result in the most economic process possible, and, if practical, the product should be tailored to give the consumer the properties he requires.

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