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REPORT 79-33

LIGHTWEIGHT AGGREGATES:
PROPERTIES, APPLICATIONS AND OUTLOOK

H.S. WILSON

MINERALS RESEARCH PROGRAM
MINERAL SCIENCES LABORATORIES

Energy, Mines and
Resources Canada

Énergie, Mines et
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AUGUST 1979

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Catalogue No. M38–13/79-33 Canada: $2.25
ISBN 0-660-10482-2 Other countries: $2.70

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N° de catalogue M38–13/79-33 Canada: $2.25
ISBN 0-660-10482-2 Hors Canada: $2.70

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LIGHTWEIGHT AGGREGATES:
PROPERTIES, APPLICATIONS AND OUTLOOK

by

H.S. Wilson*

ABSTRACT

Lightweight aggregates are produced in many countries from clay, shale, slate, fly ash and blast furnace slag. These aggregates can all be used in lightweight structural concrete.

The clays, shales and slates are most often processed in rotary kilns in which it is necessary that the material bloat as a result of simultaneous formation of glass and gas. This method of manufacture is used in seven locations in Canada.

Another process, not used in Canada, is one in which the raw material with solid fuel added is sintered to a clinker which is subsequently crushed to aggregate size. Fly ash is also converted into lightweight aggregate by this process in several other countries. Colliery shale, which already contains a fuel, is processed in the same manner in various locations in Europe and its use is being investigated at CANMET.

Various methods have been used to expand, or foam, blast furnace slag. The sole Canadian producer developed a process that produces a pelletized expanded slag and also virtually eliminates the release of sulphurous gases associated with other processes.

The lightweight aggregates are used mainly in concrete masonry units and to a lesser extent in structural concrete. Such concretes are 20 to 30% lower in density than normal concrete, and it is this property that is its greatest asset. The strength properties and durability are comparable and the thermal resistance is about double that of normal concrete; its long-term creep is frequently somewhat higher and the modulus of elasticity lower.

Lightweight masonry units and structural concrete have been used in virtually every application in which normal concrete is used. The largest amount of lightweight structural concrete is used in floor slabs, but entire structures up to 52 stories (217.6 m) high have been constructed of lightweight concrete. It has also been used cast in place and precast for bridge decks and beams, domes and roofs, wall panels, ships and pipes.

With continually increasing fuel and other production costs, the manufacturers using rotary kilns and sintering machines will have to make their processes more efficient if the products are to remain economically competitive.

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AGREGATS LEGERS:
PROPRIETES, APPLICATIONS ET PERSPECTIVES

par

H.S. Wilson*

RESUME

Dans plusieurs pays, les agrégats légers sont produits à partir d'argile, de schiste argileux, d'ardoise, de cendre volante et de laitier de haut fourneau. Ces agrégats peuvent tous être employés dans la fabrication de béton structural léger.

Les argiles, les ardoises et les schistes argileux sont habituellement transformés dans des fours rotatifs dans lesquels le matériau doit gonfler à la suite de la formation simultanée de verre et de gaz. Cette méthode de fabrication est employée à sept endroits au Canada.

Un autre procédé qui n'est pas employé au Canada consiste dans la transformation par frittage du matériau brut ajouté d'un carburant solide en un clinker qui est ensuite concassé en agrégats. La cendre volante est aussi convertie en agrégats légers selon ce procédé dans plusieurs autres pays. La schiste houillière qui contient déjà un carburant est traitée de la même manière à plusieurs endroits en Europe et son usage est à l'étude par le CANMET.

Diverses méthodes ont été employées pour dilater ou mousser les laitiers de haut fourneau. Le seul producteur canadien a mis au point un procédé par lequel on produit un laitier dilaté sous forme de boulettes ainsi qu'on élimine en toute fin pratique le dégagement de gaz sulfureux commun aux autres procédés.

Les agrégats légers sont principalement employés pour les articles de maçonnerie en béton et, moins fréquemment, dans le béton de structure. De tels bétons ont une densité 20 à 30% plus basse que les bétons réguliers ce qui constitue leur meilleur attrait. Les propriétés de résistance et de durabilité sont comparables et la résistance thermique est de deux fois celle des bétons réguliers. Leur fluage à long-terme est fréquemment plus élevé et leur module d'élasticité plus bas.

Les articles de maçonnerie légers et le béton structural léger ont été employés dans pratiquement toutes les applications qui normalement utilisent le béton régulier. La majeure partie du béton structural léger est employée pour les dalles de plancher, mais des immeubles complets pouvant atteindre 52 étages (217.6 m) ont été fabriqués de béton léger. Il est aussi utilisé soit à l'état préfabriqué ou soit lorsque mis en place sur chantier pour des applications diverses telles que tabliers et poutres de pont, dômes, toitures, panneaux de mur, tuyaux, bateaux et navires.

Comme les coûts du carburant et de production ne cessent d'augmenter, les manufacturiers qui utilisent les fours rotatifs et les appareils de frittage devront améliorer le rendement de leurs procédés s'ils désirent que leurs produits demeurent compétitifs.

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INTRODUCTION

Lightweight aggregates used in construction are produced from a wide variety of materials: shale, clay, slate, blast furnace slag, fly ash, pumice, diatomite, perlite and vermiculite. The properties of these aggregates differ greatly, e.g., densities vary between 30 and 900 kg/m^3. As only the aggregates produced from shale, clay, slate, blast furnaces slag and fly ash possess sufficient strength for structural concrete, only these materials will be discussed. The other lightweight aggregates are used in non-load bearing and insulating applications and are beyond the scope of this report.

The benefit of lightweight aggregate in concrete has been recognized as far back as Roman days. In more recent times, industrial cinders were used as lightweight aggregate in the ubiquitous cinderblocks, particularly immediately after the Second World War when construction was booming. Cinders usually contain unburned fuel and sulphur compounds, all of which are detrimental to concrete. By 1950 the supply of cinders was decreasing as industries began to convert from solid fuels to oil and gas, and more concern was shown for quality of the concrete blocks.

The first manufacturerd lightweight aggregate in Canada was produced at Cooksville (now Mississauga), Ont. in 1927. It was produced from a shale by a rotary-kiln process patented in the United States in 1917. The second such plant was built in 1953 in Calgary, Alta. During the next ten years, growth of the industry was rapid and since the mid 1960's annual production has fluctuated between 550,000 and 740,000 m^3; in 1977 it was 576,600 m^3 (1). Currently there are seven producing plants in Canada, three using shale and four clay. Processing at all these plants is done in rotary kilns.

In 1947, production of expanded blast furnace slag began on a limited scale at Sydney, N.S. A second and larger facility was put into operation at Hamilton, Ont. in 1954. The original plant was shut down in 1968 and since then only the plant in Hamilton has been in production.

LIGHTWEIGHT AGGREGATES FROM CLAY, SHALE, SLATE, AND OTHER MATERIALS

The "common" clays, shales and slates are most abundant materials available for making lightweight aggregates. They differ considerably in physiochemical properties because of different mineralogical compositions and physical structure. They have all been formed from the decomposition of silicate rocks, the products frequently having been transported, classified and re-deposited by water, ice or wind. These deposits may subsequently be altered by geochemical or pyrochemical reactions. They all contain a proportion of clay minerals and a variety of other minerals. According to Krumbein and Pettijohn, a clay is composed of particles at least 50% of which are smaller than 4 µm (2). A silt is composed of particles more than 50% of which are between 26 and 4 µm. Indurated clay and silt form claystone and siltstone. If the clay were bedded upon induration, it forms a shale. Slates are metamorphosed argillaceous rocks which nearly always develop strong parallel cleavage.

BLOATING PHENOMENON

The original and still most common method of producing a lightweight aggregate from a clay, shale or slate is in a rotary kiln. In this method the raw material is heated to incipient fusion, usually between 1100 and 1200°C. At this stage, a glass has formed and filled the pores of the particles. While the material is in the pyroplastic state, a gas is formed by dissociation of and by reactions between constituents and, being trapped by the glass, causes expansion or bloating of the particles of the material. The glass formed must be of such viscosity as to entrap the gas and also prevent agglomeration of the particles in the kiln.

Many studies have been made over the past 30 years on the effect of material composition and heating conditions on the bloating properties. Riley, White, and Utley et al. delineated similar chemical limits within which the composition of bloating materials occurred (Fig. 1) (3-5). They

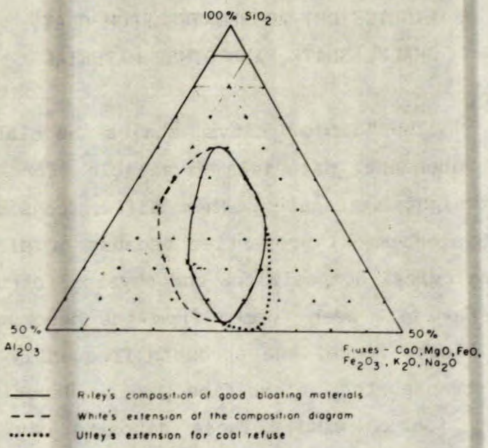


Fig. 1 - Compositional limits of bloating clays

concluded that materials with compositions within these limits would, on being heated, produce a glassy phase of sufficient viscosity. Other investigations by Pavlov, Blyumen, Vrublevskii, Kromer, Sandrolini and Palmonari, and Maniatis and Tite also studied the effect of composition on the glass-phase formation (6-11). Clay mineral crystals are composed of tetrahedral layers of (Si, Al)-O and octahedral layers of (Al,Mg,Fe)-(O,OH) (12). Kaolinites, composed of one tetrahedral and one octahedral layer in the ratio of 1:1 do not contribute to bloating, because a liquid phase does not develop below 1400°C. The micas, illite, montmorillonite and vermiculite, composed of two tetrahedral layers and one octahedral layer or a ratio of 2:1, form a liquid phase between 950° and 1050°C. These latter clay minerals possess a great capacity for cation exchange and may contain iron, alkalis and alkaline earth elements which reduce the temperature of liquid formation. Studies showed that silica and alumina increase the viscosity of a glass, whereas the fluxes decrease viscosity (7). The alkali elements Na_2O and K_2O lengthen the bloating-temperature range, whereas the alkaline earth elements CaO and MgO shorten the bloating-temperature range. Iron in the ferrous state reduces the glass-forming temperature. A reducing atmosphere promotes the formation of ferrous iron from the ferric state.

From studies made by Everhart et al., Hill and Crook, Chopra et al., Kolesnikov, Houseman and Koenig, and Wilson, the bloating gases are one or a combination of: water from the clay minerals, oxygen from the reduction of ferric oxide, carbon dioxide or carbon monoxide from the dissociation of carbonate minerals, and sulphur dioxide or trioxide from the dissociation of gypsum and the oxidation of iron sulphide minerals (13-18). Figure 2 shows the interior of a piece of bloated shale.

ROTARY-KILN METHOD OF PRODUCTION

To prepare a material as feed to a rotary kiln, frequently only crushing and screening to about minus 25 mm are necessary (19). Because the effect of firing a clay or shale is dependent on time as well as on temperature, the smaller particles are more effected in a rotary kiln than are the coarser particles. By the time the coarser particles have been brought to the bloating condition, the finer particles may have received too much heat and begun to agglomerate. It may be necessary for instance, to remove the minus 6 mm material from the kiln feed. In an extreme case the material may have to be separated into two or more size fractions and each processed separately.

If the particles are discharged from the kiln discreetly, they have a somewhat rounded form and a hard coating. If they agglomerate, the re-

Fig. 2 - Cellular interior of bloated shale, x 4

sultant material would have to be crushed to obtain the desired sizing and would be angular and harsh and the more porous interior of the particles would be exposed. If agglomeration becomes excessive, rings or logs could form and could cause the kiln to be shut down until the obstructions can be removed.

If a clay is too soft to withstand handling and travels through the kiln, or if an excess of too fine material is obtained through crushing, or if two or more materials require blending to alter the properties of the individual materials, some means of pelletizing would be used. The two most popular types of equipment used are the disc pelletizer and the extrusion machine. In the disc pelletizer, dry material and water are added simultaneously to a revolving inclined shallow disc. By adjusting the angle, the rotational speed, and the points where the material and water are added, the size of the pellets can be controlled. In an extrusion machine, dry material and water are mixed in a pug mill and are extruded through a metal die incorporating a large number of holes or through a wire screen. The streams of clay issuing from the machine either break off under their own weight or are cut to the desired length.

In a process used in several European countries, a gas-producing compound is added to a clay before being pelletized to increase the bloating beyond what would occur normally (20).

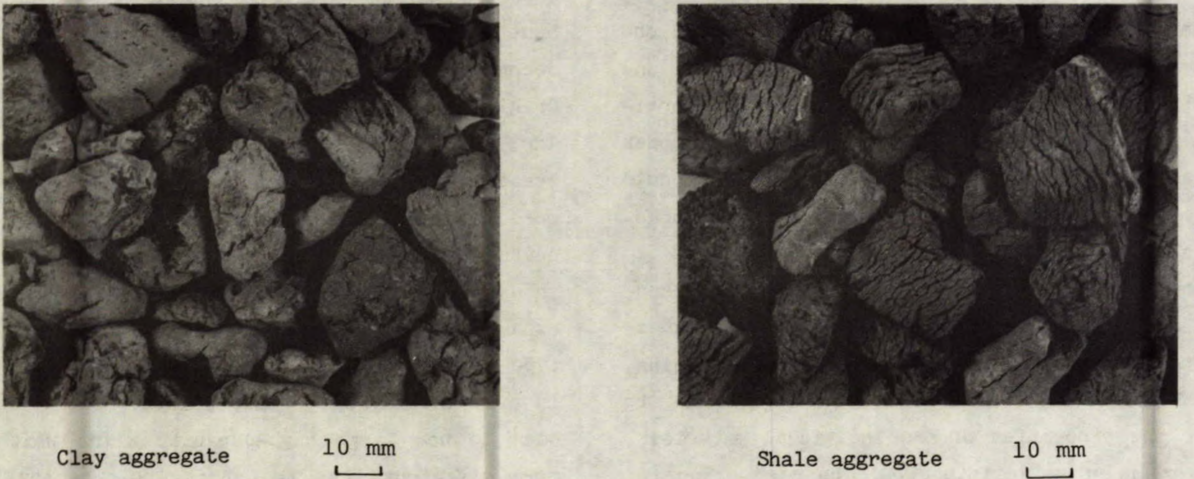
The rotary kilns used in this industry are between 20 and 75 m long and between 2 and 4 m in diameter. Most are of the same diameter throughout its length; others have a larger diameter for about 20 to 30% of the length at the discharge end. This is to retard travel of the material in the zone of highest temperature, and to achieve better bloating. In at least one plant in the United States, the kiln is of larger diameter at both the feed and the discharge ends. In its simplest form, a rotary kiln is only about 15% efficient. In recent years this low efficiency has become an ever-increasing problem as the cost of fuel has continued to increase. Various modifications such as baffles, lifters and dams have been installed in some kilns to improve the transfer of heat. Product coolers, with the heat recovered being introduced into the kiln as secondary air, have been used for many years. Originally, the rotary cooler was the most popular, but grate coolers, and planetary coolers attached to the shell of the kiln have been found more efficient. In recent years, the feed preheater has received much attention in the cement industry. This apparatus uses heat in the gases exhausted from the kiln to preheat the feed. This type of installation is costly and, at present, is used in only one or two plants. The trend has been to use large high-capacity kilns which are more efficient than the short low-capacity kilns that were in use in many locations 25 years ago. The heat required in the more efficient kilns is about 2.3 MJ/kg.

The product from the kiln is screened or when necessary is crushed to the desired size and graded for particular applications. Figure 3 illustrates typical lightweight aggregates produced from clay, shale and slate.

SINTERING METHOD OF PRODUCTION

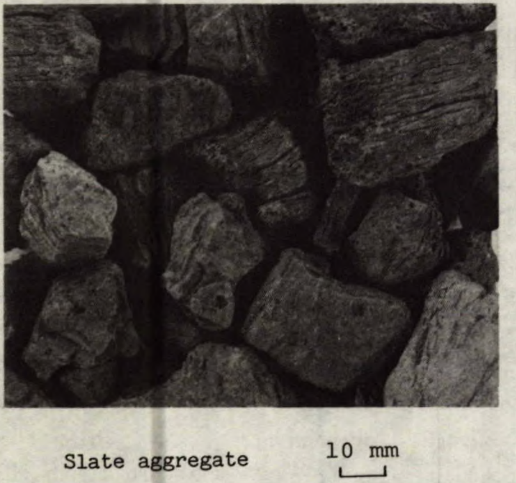
The sintering process is another method used in Europe and the United States to produce lightweight aggregate from clay or shale.

This process was developed shortly after the turn of the century and has been used extensively in the metallic ore processing industry. In 1949, it was first adapted for lightweight aggregates (21). The raw material, mixed with up to 10% solid fuel, is placed as a permeable bed on a travelling-grate sintering machine. Fuel at the surface of the bed is ignited by an external heat source, and as the bed moves along the machine, an induced draft draws the horizontal zone of ignition progressively down through the bed, until the fuel is completely burned and the material has sintered to a clinker. According to Leitner, most clays or shales will sinter at a rate of 12.3 to 18.1 m^3/m^2 of grate area 24 h (22). A wider range of materials may be sintered than may be processed successfully in a rotary kiln. In the sintering process the material need not bloat; the particles fuse together and the interstices between the particles become voids in the aggregate when the sinter is crushed.



Clay aggregate 10 mm

Shale aggregate 10 mm



Slate aggregate 10 mm

Fig. 3 - Lightweight aggregates produced in rotary kilns from clay, shale and slate

A clay or shale raw material is crushed to about 9 mm and is mixed with the fuel and agglomerated with water in a drum or disc pelletizer. It is not a true pelletizing operation as for the feed to a rotary kiln, but an agglomeration of fine-sized particles to form coarser particles of about 1 to 9 mm. The wet material is placed directly on the sintering machine. A number of factors affect the rate of sintering and the properties of the resultant lightweight aggregate. These factors include: fusibility of the raw material, size and quantity of fuel, amount of water added, size range of the agglomerated material, depth of sintering bed, and rate at which air is drawn through the bed (draft). This process has an efficiency about the same as the most efficient rotary-kiln plant. It also has the flexibility of stopping and starting without the extended period required to preheat a rotary kiln before it can be utilized. The sintered aggregate produced by crushing the sinter cake, is irregular in shape and has a rough, porous surface.

SINTERING OF OTHER MATERIALS

Another material which has been sintered successfully for a number of years in Britain and to some degree in the United States is fly ash, or pulverized fuel ash (PFA) as it is known in Britain. It is the finely divided ash precipitated from the flue gases in coal-fired electrical generating stations.

To be satisfactory, it must be uniform in composition, particularly its carbon content. Consequently, the source should be a base-load station, where power demand is constant rather than a peak-load station where demand fluctuates. In the latter, carbon content of the fly ash varies with steam generation. It should not contain more than about 5% carbon. Pretreatment may be necessary to adjust composition or grain size of the particles through blending of fly ashes or by extraction of components such as iron. The fly ash is then pelletized in a disc pelletizer, the size of the resultant pellets being controlled, normally between 6 and 12 mm. Sintering of the pellets is similar to that for clay or shale, with the exception that the fly ash pellets do not normally fuse but remain discrete. Mechanical handling of the pellets following sintering separates any that may become attached.

Two plants in Britain sinter colliery shale for lightweight aggregate. One plant in Scotland uses shale from the dumps, known as bings, at a former coal mine. The material is washed to recover coal still contained in it. The washed shale contains sufficient fuel to be sintered in the conventional manner. A plant in England sinters a blend of colliery shale and fly ash (PFA). Both of these installations produce sinter cake that is crushed to produce aggregates of angular shape. The sintering of colliery shales from British Columbia and Nova Scotia is currently being studied by CANMET (23). Figure 4 shows examples of sintered shale and fly ash.

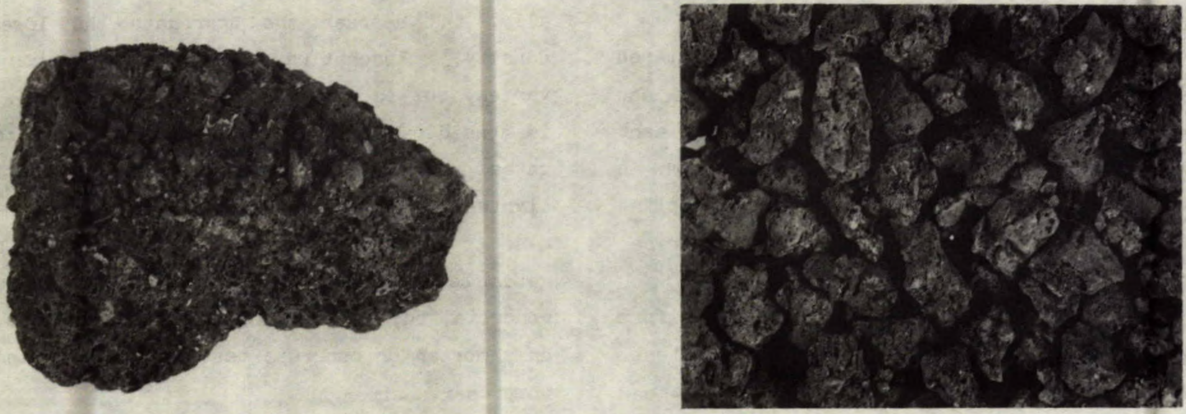
PROPERTIES

The lightweight aggregates produced in North America have densities of between 600 and 1100 kg/m^3, depending on the degree of bloating or cellulation and the size of aggregate. Generally, the coarser the aggregate the lower the density. Absorption of the aggregates also varies, but is generally between 5 and 20%. This is considerably higher than that of normal aggregates and is of importance in proportioning lightweight concrete mixes. Endeavours have been made to correlate the crushing strength of aggregates to the compressive strength of lightweight concrete, but the relationship is tenuous at best; only mortar or concrete tests will truly indicate compressive strength.

The aggregate in lightweight concrete masonry units is usually all lightweight. Such concretes in which the aggregate is minus 9 mm will have densities of between 1300 and 1700 kg/m^3; and compressive strength will vary between 10 and 20 MPa, and with selected aggregates and high cement content, it will be as high as 31 MPa. Hollow masonry units 200 x 200 x 400 mm, of 50% solid material and 50% core space would weigh between 11.0 and 13.6 kg and will have compressive strengths of between 4.1 and 8.8 MPa on the gross area of the unit. Similar high-strength units of 75% solid material would weigh about 17 kg.

Structural lightweight concrete is usually semi-lightweight in that the coarse aggregate is lightweight and all or part of the fine aggregate is normal weight. This semi-lightweight structural concrete incorporating lightweight aggregate sized 19.0 to 4.75 mm and natural sand of minus 4.75 mm will have densities of between 1760 and 2000 kg/m^3 and will have 28-day compressive strengths up to 35 MPa and in many cases up to 40 MPa. Concrete strength will depend on strength of the lightweight aggregate as well as on the mix proportions. Invariably, a lightweight concrete will require a slightly higher cement content than would a normal concrete of comparable compressive strength.

The splitting-tensile strength of lightweight structural concrete is comparable with that of normal concrete of equal compressive strength if continuously moist cured, but if the lightweight concrete is dry cured, the splitting-tensile strength will be about 25% lower. The same generalization holds true for flexural strength, although the strength of dry cured lightweight



Sintered shale 10 mm

Sintered shale aggregate 10 mm

Sintered fly ash aggregate 10 mm

Fig. 4 - Lightweight aggregates produced by sintering shale and fly ash

concrete may be as much as 40% lower than that normal-weight concrete (24).

Shideler evaluated eight lightweight aggregates produced in the United States and compared them with one normal concrete (25). He found that the modulus of elasticity of the lightweight concretes was from 53 to 82% of the modulus of the normal concrete of 2.36×10^4 MPa at 28 days, and from 44 to 63% of the modulus of the normal concrete of 3.45×10^4 MPa at six months. Nominally, the static modulus can be determined within 15 to 20% by the formula:

$$E_c = W^{1.5}\ 0.043\ \sqrt{f'_c}\ \text{(from 26)}$$

E_c = static modulus of elasticity, MPa

W = air-dry weight of concrete, kg/m^3

$f'c$ = compressive strength of concrete at time of test, MPa

The drying shrinkage of lightweight concretes varies considerably, generally increasing with compressive strength. The creep of lightweight concretes also varies widely at low strengths; the creep decreasing with increasing strength.

Durability depends on the particular lightweight aggregate used, and usually improves with compressive strength. As with normal concrete, air entrainment is most desirable. Some lightweight concretes will withstand more than 1000 cycles of freezing and thawing, whereas some have failed before 300 cycles have been completed. A study by the author on concretes incorporating five Canadian lightweight aggregates showed they all withstood at least 300 cycles of freezing and thawing (27). One example of extremely durable concrete was the concrete ship Selma, constructed in 1919, and sunk and partially submerged in Galveston Bay, Texas, in 1922 (Figure 5). The concrete originally had a compressive strength of 38.5 MPa. In 1953, 50-mm cubes were cut from sections which had been: (a) alternatively exposed to saltwater and salt-laden air, (b) continuously exposed to saltwater, and (c) continuously exposed to salt-laden air. The strengths of these cubes were converted to 150- by 300-mm cylinder strengths by the factor of 0.85 and were 60.6, 77.2, and 56.0 MPa respectively (28).

Thermal conductivity of lightweight concrete is about half that of normal concrete and is a function of density. Wilson reported that Canadian lightweight concretes having densities of between 1700 and 1900 kg/m^3 had thermal conductivities of between 0.68 and 0.77 W/mK at ambient temperatures, rising to 0.75 and 0.95 W/mK at 300°C (27). Forder showed that lightweight concretes of densities between 500 and 1500 kg/m^{3}in the dry state, had thermal conductivites of between 0.10 and 0.35 W/mK at ambient temperature (29). The moisture content of the concrete is extremely critical; a lightweight concrete of a density of 1000 kg/m^3 has a thermal conductivity of 0.24 W/mK at 1% moisture and 0.32 W/mK at 5%, equivalent to an increase in density of 50%.

Lightweight concrete can be pumped but, because of the porosity of the aggregate, the aggregate must be presoaked. If unsoaked aggregate is used, water from the mix under pressure in the pump, is forced into the pores in the aggregate and workability is reduced to the extent that the concrete cannot be pumped. With some lightweight aggregates, a water spray as the aggregate travels on a conveyor belt is satisfactory to satisfy the absorption. With others, extended spraying of water onto stock-piles of aggregate introduces sufficient water. Mineral

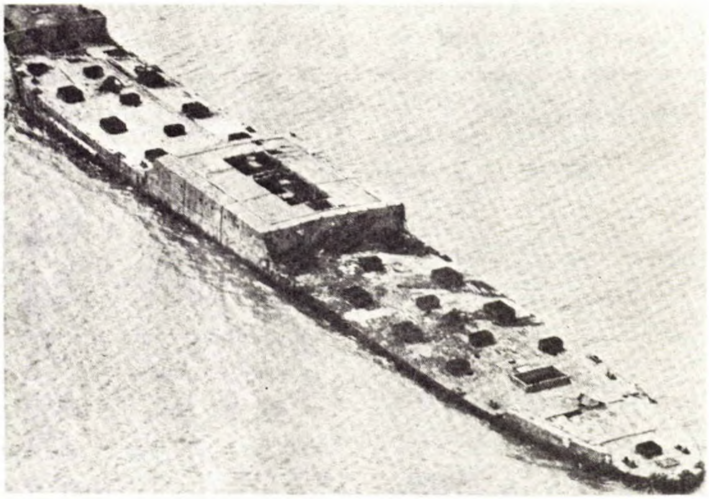


Fig. 5 - Hull of S.S. Selma in Galveston Bay, Texas

or chemical pumping aids have also been beneficial, where presoaking is used. These methods satisfy the normal absorption of from 5 to 20% but they do not saturate the aggregate. Some lightweight aggregates require saturation before the concrete containing them can be pumped.

Two methods have been used to presaturate the aggregate. In the hydrothermal process, the hot aggregate is immersed in water. The higher the temperature of the aggregate the greater the absorption because of the inverse relationship of the volume to the temperature of a mass of gas. As the air in the pores of the aggregate cools, its volume decreases and the water is drawn into the pores. Absorption of more than 50% has been achieved by this method over a soaking period of 30 min. However, Reilly found that strength of the aggregate decreased with temperature of the aggregate at immersion because of microcracks resulting from thermal shock (30).

Vacuum saturation was found to be the more effective method. In this, the aggregate was introduced into a chamber in batches, the air was evacuated, the chamber was flooded with water and the pressure returned to normal. The aggregate should be dry before the process is started. Up to 45% absorption has been achieved in vacuum saturation. Mix proportions and grading of the aggregates are also extremely important in pumping. The fine aggregate should contain 15 to 35% passing the 300-μm screen and 5 to 20% passing the 150-μm screen. The texture and shape of the aggregate also has an effect on pumpability. Lightweight concrete has been pumped successfully up to 122 m vertically.

APPLICATIONS

The lightweight aggregates produced from clays, shales, slates and fly ashes have a variety of applications. Their principal uses are as aggregates in concrete masonry units and in structural concrete. To a limited degree in Canada, and extensively in certain areas of the United States, they have been used in highway pavement. Other uses are in soil conditioning, in low-temperature refractories, in hydroponic propagation of plants, in race track surfacing, in land drainage and as loose insulation. In Britain, they also have been used successfully as vehicle arresters along the shoulders of highways at hazardous locations and also along airport runways. In Canada in 1977, about 72% of the lightweight aggregate produced was consumed in the manufacture of masonry units. Such units may be used for both exterior and interior walls, both above and below grade. They can be of any size from the conventional brick size to the nominal 200 x 200 x 400-mm size. They can have a variety of surface finishes and textures, they can be plane-faced or contoured, painted or faced with other materials, and nails can be driven into them. They are not normally used in load-bearing applications, but are used where density of only 60% of concrete is of considerable advantage. When used below grade in exterior walls, they must be parged and waterproofed.

High-strength lightweight masonry units have found use in engineered masonry construction. In beam and column construction, loads are concentrated in and transmitted to the foundation of the structure through the columns. In the engineered masonry structure, the loads are transmitted to the foundation along the lengths of the bearing walls (31). The structure is, in essence, a series of similar single storey structures built one above another. Although most such structures are rectangular in outline, tri-arc and dodecahedral floor plans have been constructed in this manner (Fig. 6). A major advantage of this type of construction is that the lower floors can be closed in and finished while the upper floors are being constructed, thus speeding construction. The compressive strength of high-strength masonry units should be a minimum of 20.7 MPa, and may be as high as 31.0 MPa. To achieve that strength, cement content and compaction time in the block machine both must be increased. This will result in the standard 200 x 200 x 400-mm unit having a weight of from 0.5 to 1.5 kg more than the normal lightweight unit; absorption will be about 25% lower and the drying shrinkage will be from 0.005 to 0.010% higher.

The following are typical engineered masonry structures built in Canada:

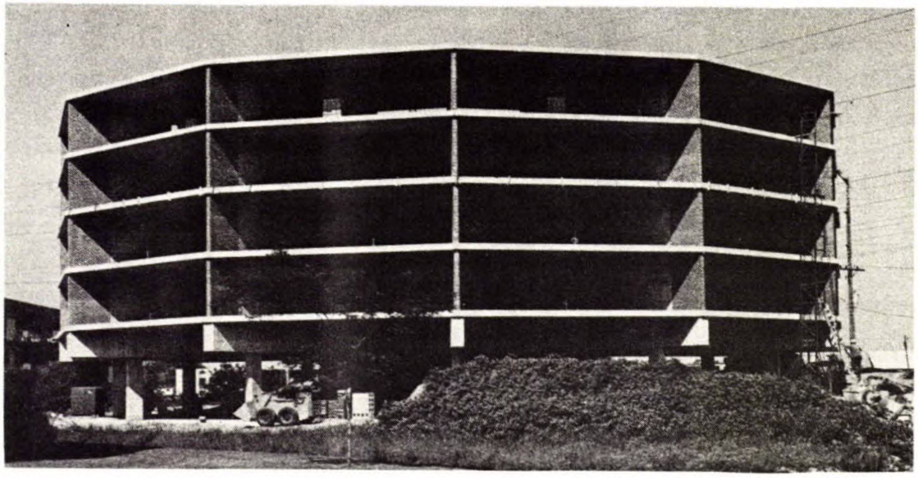


Fig. 6 - Engineered masonry structure of dodecahedral design

- 17-storey Heritage Place apartment tower, Calgary, Alta.; approximately 164,000 lightweight masonry units used in the load-bearing and partition walls for the 137 apartments and three levels of parking and commercial space.
- 6-storey Lilly Rose apartment building in Regina, Sask.; approximately 50,000 lightweight masonry units used for both the load-bearing exterior and partition walls; the large single core of the units filled with lightweight concrete.
- 5150 m^2 St. Benedict Junior High School, Cambridge, Ont; nearly all walls made of load-bearing lightweight masonry units; 110,000 units, the cores of those in the exterior walls were filled with exfoliated vermiculite to further improve thermal insulation.

In many European countries and to some degree in North America, prefabricated panels are used in construction. Lightweight masonry units lend themselves ideally to this type of construction, particularly because of their lower density, resulting in lower construction, transportation, and erection costs than would be encountered with normal masonry units.

Winchester showed the saving of energy in the heating of a building of typical cavity-wall construction composed of 100-mm brick, 25-mm cavity and 200-mm masonry units when lightweight masonry units were used, compared with normal masonry units (32). Thermal conductance of the lightweight masonry wall was about 73% that of a similar wall incorporating normal units.

Lightweight structural concrete has been used in a great variety of structures in many countries. Such concrete has been used in nearly all applications in which normal concrete has been used. The principal advantage of using lightweight concrete is its 20 to 30% lower density. It is normally semi-lightweight, in that all or part of the fine aggregate of minus 4.75 mm is natural sand. Its use can result in lower foundation costs, reduction in cross sections of beams and columns, lower reinforcing steel costs, and in case of soil of limited bearing capacity, more storeys may be constructed.

Concretes made with some lightweight aggregates have higher long-term creep properties than do normal concretes. Most lightweight concretes also have a lower modulus of elasticity. Some lightweight concretes may be restricted in application where creep and flexure are important. Virtually every lightweight aggregate can be used in concrete for floor slabs and it is in this application that they are used to the greatest degree. An example of this application is the Lake Point Tower in Chicago, Ill. built in 1968, 71 storeys (195 m) high with a Y-shaped floor plan. The floor slabs from the 2nd to the 70th level and in the garage area were of lightweight cast-in-place concrete with a density of 1730 kg/m^3 and a 7-day compressive strength of 150 x 300-mm cylinders of 22.1-20.1 MPa (33).

Some lightweight concretes can be used in all structural elements of a building, and appreciable savings can result, compared with a structure of normal concrete. The Australia Square, Sydney, Australia, completed in 1967, is a circular tower, 50 storeys (184 m) high by 42.5 m in diameter (Fig. 7). A 13% saving in construction costs was achieved through the use of 31,000 m^3 of lightweight concrete in the beams, columns and the floors above the seventh level. The concrete had an average compressive strength of 34.3 MPa and an average density of 1792 kg/m^3 at 28 days (34).

In many locations, the bearing capacity of the soil determines the height of a high-rise structure. One Shell Plaza, Houston, Texas (1969) is an all-lightweight concrete structure of 52 storeys (218 m). The structure includes a 70 x 52 x 2.5-m lightweight concrete pad, 18 m below grade. The concrete had a density of 1840 kg/m^3. Its 28-day compressive strengths of 150 x 300-mm cylinders was 41.2 MPa for shear walls, columns and mat foundation, and 31.3 MPa for the floor structures. If normal concrete had been used, only a 35-storey structure could have been safely designed (35).

The roofs of the workshops at the Major Straub Barracks Solbad Hall, Austria (1968) are supported by prestressed, precast, lightweight concrete beams with a span of 22.4 m, depths of 1.3 to 1.8 m and webs of various thicknesses. The concrete had a density at 28 days of 1800 kg/m^3 and a compressive strength of 200-mm cubes of 53.9 to 58.8 MPa. The beams each weighed 13.5 tonnes. As they were precast 500 km from the site, there was a corresponding saving in haulage costs because of their low density compared with normal concrete (33).

An interesting precast concrete structure is the Hilton Palacio del Rio Hotel, San Antonio, Texas (1968), (Fig. 8). It is 19 storeys on one side and 21 on the opposite; from the 5th to the 20th floor, it consists of 496 precast lightweight concrete room modules. The modules are 9.95 and 9.04 m long x 3.96 m wide x 2.96 m high; the walls and floors are 130 mm thick and the ceiling 100 mm thick. The concrete had a 28-day density of 1660 kg/m^3 and compressive strength of 150 x 300-mm cylinders of 34.5-27.4 MPa (33).

Cast-in-place lightweight roofs can be of various configurations, such as the dome of the 121.4-m clear span of the Assembly Hall at the University of Illinois, Urbana, Ill. The concrete

Fig. 7 - Australia Square Tower, Sydney, Australia

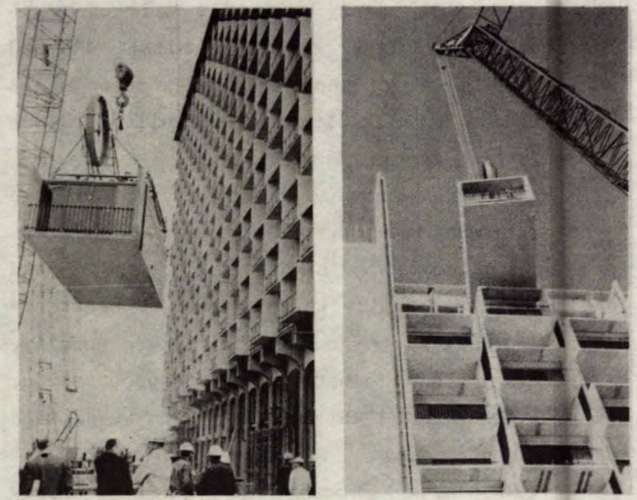


Fig. 8 - Hilton Palacio del Rio Hotel, San Antonio, Texas

had a 28-day density of 1680 kg/m^3 and a compressive strength of 150 x 300 mm—cylinders of 27.4 MPa. The roof over the swimming pools at Hatfield, Hert, Britain, is cruciform in plan and is composed of four hyperbolic parabaloid shells, the overall size of the roof being 56.4 x 50.0 m with a thickness of 76 mm (31).

Many bridges have been built using lightweight concrete in the deck. One of the earlist was the San Francisco - Oakland Bay Bridge (1936). The use of lightweight concrete resulted in a saving in steel of $3 million (36). Lightweight concrete was used in the 64.2-m middle section of the 96.4-m span of the 204.8-m prestressed, cantilevered Dyckerhoff Bridge, Wiesbaden, Federal Republic of Germany.

In Canada in 1977, about 23% of the lightweight aggregate produced was used in precast and cast-in-place structural concrete (1). The National Trust Building in Toronto (1962) is one of the earliest applications of a fully lightweight concrete structure (37). With the exception of the 5th floor, all the concrete in this 22-storey structure is lightweight, 9,900 m^3 structural concrete and 75,000 masonry units for partitions being used. The structural concrete had a 28-day compressive strength of 32.9 MPa and a density of 1840 kg/m^3.

There are numerous examples of lightweight concrete in floor slabs. These include such structures as the 51-storey Manufacturer's Life Centre and the 74-storey Bank of Montreal Building, both in Toronto; the 21-storey Royal Bank of Canada Building in Calgary; and the 45-storey Edmonton House in Edmonton (38,39). In the latter, a reduction in dead weight of 4 x 10^3 Mg and a saving of $45,000 in post-tensioning in the floors resulted from the use of lightweight concrete, compared with normal concrete. More recent structures are Phases 1 and 2 of the Bow Valley Square and the 40-storey Scotia Centre both in Calgary, and the two 40-storey towers of the Harbour Square apartment complex in Toronto (40). The 100-mm thick floors of these two towers, completed in 1974 and 1979, are of concrete having a density of 1840 kg/m^3 and a compressive strength of 27.6 MPa. Each tower, containing about 90.000 m^2 of floor area, incorporated over 25,000 m^3 of lightweight concrete (Fig. 9).

Several bridges have been built or reconstructed in Canada using lightweight concrete. Lightweight concrete was used in the 60 girders and slabs of the modified Y-shaped Heatley Avenue overpass in Vancouver (Fig. 10), and the James MacDonald Bridge in Edmonton. In the former, the girders were between 19.8 and 33.6 m long and 1.1 and 1.3 m deep. The concrete had a dry density of 1730 to 1760 kg/m^3, and with a cement content of 408 kg/m^3 had a 28-day compressive strength of 40.0 MPa (41). When the deck of the Champlain Bridge, spanning the Ottawa River in Ottawa, was replaced in 1972, lightweight concrete was used so that the deck could be made wider.

Lightweight precast tilt-up panels have been used successfully for a number of years in low-rise construction. The panels which can be cast on the site can be used in walls 7.5 to 9.0 m in height (Fig. 11). At one installation in Calgary, by using special metal pans which can be tilted up with the panel, the panels were erected within 24 h of being cast (42).

The pumping of lightweight concrete has been done successfully on a number of projects in

Fig. 9 - Harbour Square Apartment Complex, Toronto, Ont.

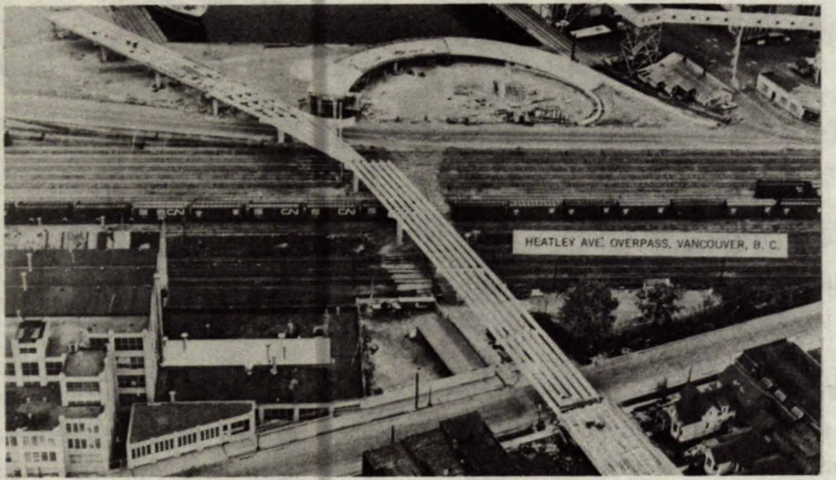


Fig. 10 - Heatley Avenue Overpass, Vancouver, B.C.

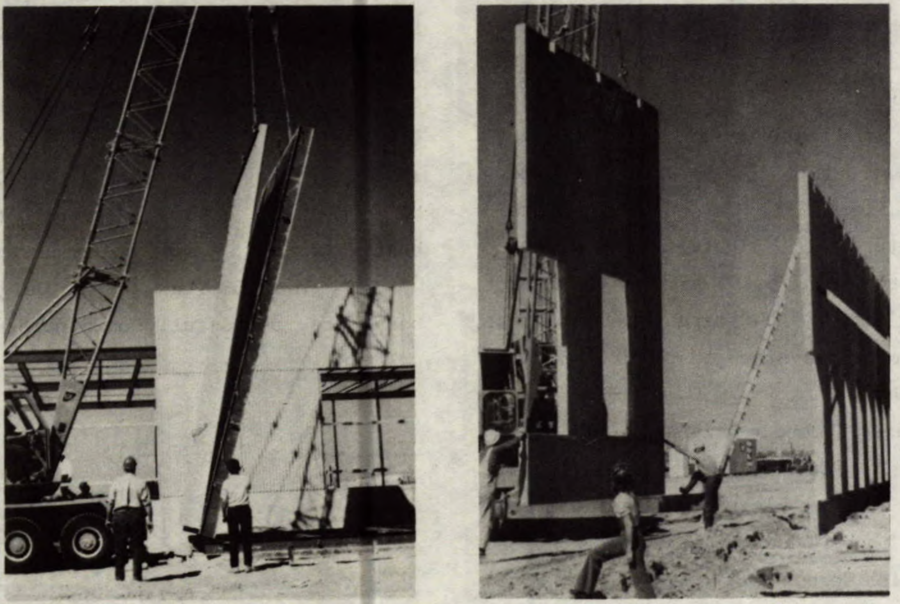


Fig. 11 - Erection of precast panels, Calgary, Alta.

Canada. One such project was the Sandman Inn in Calgary, in which the concrete was pumped 14 storeys.

Lightweight concrete has been used in applications where its appearance as well as its structural properties are important. Examples are the Burlington Central Library in Burlington, Ont., and the administration building of the Royal Botanical Gardens in Hamilton, Ont. (43). In both of these structures the exterior walls were bush-hammered on the exterior surface and sand-blasted on the interior surface.

Minor uses for lightweight aggregates in Canada include ground cover in ornamental garden areas to prevent growth of weeds and to retain moisture in the soil. This application utilizes coarse material between 50 and 20 mm in size. Another use is as a rooting medium in hydroponic propagation of tropical, semi-tropical and domestic plants. The high absorption of the aggregate allows control over the moisture and nutrients in the bed.

SPECIFICATIONS

Various countries have established standards to govern the properties and applications of lightweight aggregates. In Canada, the Canadian Standards Association (CSA) standard CAN3-A23.1-M77 "Concrete Materials and Methods of Concrete Construction" deals with both normal and lightweight aggregates and concretes. The sections dealing with lightweight aggregates have been adopted from the standards of the American Society for Testing and Materials (ASTM). The relevant ASTM standards are:

C330-77 - Lightweight Aggregates for Structural Concrete (44)
C331-77 - Lightweight Aggregates for Concrete Masonry Units (45)
C332-77 - Lightweight Aggregates for Insulating Concrete (46)

The ASTM limits for gradings of lightweight aggregates for structural concrete, for concrete masonry units and for insulating concrete are shown in Tables 1, 2 and 3. The maximum density is shown in Table 4. The relationships between density splitting tensile strength and compressive strength of structural lightweight concrete are shown in Table 5. The relationship between unit weight and thermal conductivity of insulating concrete is shown in Table 6.

LIGHTWEIGHT AGGREGATES FROM BLAST FURNACE SLAG

ASTM defines blast furnace slag as "The non-metallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases, that is developed in a molten condition simultaneously with iron in a blast furnace" (47).

The charge to a blast furnace consists of iron ore, coke, limestone and dolomite. The coke has a dual role: to supply the heat for the metallurgical reactions and to supply the carbon monoxide to reduced the iron in the ore to metallic iron. The limestone and dolomite act as fluxes to assist in the fusion of the ash from the coke and the siliceous and aluminous residue from the ore to form a slag with a composition that will prevent silicon and sulphur from entering the

Table 1 - Grading requirements for lightweight aggregates for structural concrete*

	Percentage (by weight) passing sieves having square openings								
Size designation	25.4 mm	19.0 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	300 µm	150 µm
Fine aggregate:									
4.75 mm to 0	...	...	...	100	85-100	...	40-80	10-35	5-25
Coarse aggregate:									
25.0 to 12.5 mm	95-100	...	0-10	...	...	...	...	...	...
25.0 to 4.75 mm	95-100	...	25-60	...	0-10	...	...	...	...
19.0 to 4.75 mm	100	90-100	...	20-60	0-10	...	...	...	...
12.5 to 4.75 mm	...	100	90-100	40-80	0-20	0-10	...	...	...
9.5 to 2.36 mm	...	...	100	80-100	5-40	0.20	...	...	...
Combined fine and coarse aggregate:									
12.5 mm to 0	...	100	95-100	...	50-80	...	...	5-20	2-15
9.5 mm to 0	...	...	100	90-100	65-90	35-65	...	10-25	5-15

*From ASTM C330-77

Table 2 - Grading requirements for lightweight aggregates for concrete masonry units*

	Percentages (by weight) passing sieves having square openings							
Size designation	19.0 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	300 µm	150 µm
Fine aggregate:								
4.75 mm to 0	...	...	100	85-100	...	40-80	10-35	5-25
Coarse aggregate:								
12.5 to 4.75 mm	100	90-100	40-80	0-20	0-10	...	...	...
9.5 to 2.36 mm	...	100	80-100	5-40	0-20	...	...	...
Combined fine and coarse aggregate:								
12.5 mm to 0	100	95-100	...	50-80	...	...	5-20	2-15
9.5 mm to 0	...	100	90-100	65-90	35-65	...	10-25	5-15

*From ASTM C331-77

Table 3 - Grading requirements for Group II lightweight aggregates for insulating concrete*

	Percentage (by weight) passing sieves having square openings								
Size designation	19.0 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	600 µm	300 µm	150 µm
Fine aggregate:									
4.75 mm to 0	...	...	100	85-100	...	40-80	...	10-35	5-25
Coarse aggregate:									
12.5 to 4.75 mm	100	90-100	40-80	0-20	0-10	...	...	...	...
9.5 to 2.36 mm	...	100	80-100	5-40	0-20	...	...	...	...
4.75 to 2.36 mm	...	...	100	90-100	0-20	...	...	...	...
Combined fine and coarse aggregate:									
12.5 mm to 0	100	95-100	...	50-80	...	...	...	5-20	2-15
9.5 mm to 0	...	100	90-100	65-90	35-65	...	...	10-25	5-15

*From ASTM C332-77a

iron phase. The maximum temperature in a blast furnace is about 1650°C. By that temperature, the components have become fluid; the molten iron settles into the bottom of the furnace and the lighter slag floats on its surface. The slag is tapped from the furnace at intervals as homogenous fluid. As it cools crystallization begins at about 1430°C and the following minerals are formed: the melilite series from akermanite ($2CaO.MgO.2SiO_2$) to gehlinite ($2CaO.Al_2O_3.SiO_2$); anorthite ($CaO.Al_2O_3.2SiO_2$); calcium metasilicate ($CaO.SiO_2$); calcium orthosilicate ($2CaO.SiO_2$); calcium sesquisilicate ($3CaO.2SiO_2$); and calcium, manganese and ferrous sulphides (CaS, MnS, and FeS) (48).

The chemical composition of slag varies between fairly narrow limits as shown in Table 7.

DEVELOPMENT OF SLAG INDUSTRY

It was not until the eighteenth century that practical use was made of slag - cast slag blocks were made in Europe in the early 1700's and were used as paving. Slag was used in a form of cement in Germany in 1822, and as an aggregate in

Table 4 - Maximum unit weight of lightweight aggregate

Size designation	Dry loose unit weight kg/m^3
Fine aggregate	1120
Coarse aggregate	880
Combined fine and coarse aggregate	1040

*From ASTM C330-77

Table 5 - Relationship between weight and strength of structural concrete*

Average unit weight, max kg/m^3	Average 28-day splitting tensile strength, min MPa	Average 28-day compressive strength, min MPa
1840	2.3	28
1760	2.1	21
1680	2.1	17

*From ASTM C330-77

construction by 1870 (49). In the United States it was used for road construction by 1830. In Canada the iron industry began on a continuing basis in 1901 - until about 1920, nearly all the slag produced was used for landfill, from 1920 increasing proportions were used for railway ballast, road construction and as concrete aggregate.

There are three types of slag, the properties of which are controlled by the rate of cooling the molten slag. Slag which is allowed to cool slowly, i.e., up to one week, is air-cooled. When crushed to aggregate size, it has a specific gravity of 2.0 to 2.5 and a dry rodded density of about 1120 to 1360 kg/m^3. This density is between that of normal and lightweight aggregates.

Table 6 - Unit weight and thermal conductivity of insulating concrete*

Maximum average 28-day oven-dry unit weight kg/m^3	Maximum average thermal conductivity, W/mK
800	0.22
1440	0.43

*From ASTM C332-77a

EXPANDED SLAG

It is the expanded or foamed, and the granulated slags that are used as lightweight aggregates. Various methods have been used through the years to expand blast furnace slag. The Brosius and Caldwell machines developed in the early 1930's each incorporated horizontal rotors within a chamber. The addition of controlled quantities of water and the action of the rotors resulted in a cellular expanded slag. The Gallai-Hatchard pit process was developed in Britain in 1943. This was an improvement of an earlier unsuccessful pit method tried in Germany in 1912. The molten slag was dumped onto a bed of sand, incorporating perforated water pipes. The water which turned to steam and was trapped by the blanket of molten slag caused the slag to foam. When cooled, the cellulated slag was crushed to the desired size. Several modifica-

Table 7 - Range of 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%

From Reference 49

tions of this process have been used, including a concrete pit rather than the original sand, and a metal pan which could be tipped when the expanded slag had hardened (51).

The Kinney-Osborne process was developed about 1952 in the United States (52). Steam, air and water are used to expand the molten slag as it comes from the cinder runner at the blast furnace. The slag is disintegrated by a blast of steam or air, the small globules of the slag being expanded by a fine spray of water, after which they agglomerate into clinkers. The agglomerate when cool is crushed to the desired sizes. Many of the expanded-slag producers in the United States use a form of the Gallai-Hatchard process, mainly because the pits can be located a considerable distance from the blast furnace, the slag being transported in large ladles.

GRANULATED SLAG

Granulated slag is produced by chilling the molten slag rapidly, so that few crystals are formed and the product has a very high proportion of glass phase. Granulating frequently is accomplished by using an excess of water to cool the slag. If the slag is broken into small particles, less water is required and the product can be relatively dry because the residual heat in the slag evaporates the water.

A major problem associated with processing slag is the evolution of sulphurous gases. The slag processor at Hamilton overcame this problem in 1968 with the development of a method of producing pelletized slag (53). The slag is initially expanded by a fine water spray on a feed plate. It is then passed over a rapidly revolving drum incorporating fins. The slag is broken into small particles and is propelled through the air into a collecting area. While in the air, the still pyroplastic particles form into spherical pellets through surface tension. They are normally 10 to 1 mm in size. The product has a high proportion of glass and is in essence a granulated slag (45). By regulating the expansion conditions and the speed of the revolving drum the size of the pellets and the proportion of glass can be controlled.

The viscosity and thus the expandability of a slag is dependent on its composition and the temperature at which it is processed. In general, at a particular temperature, the viscosity of a slag will be lower the higher the basicity, basicity being the ratio of (CaO + MgO) to (SiO_2 + Al_2O_3) (55). Feild and Royster, and Rait, M'Millan and Hay found that the viscosity was more dependent on mineralogical composition than on chemical composition (56,57). They found that the orthosilicate ($2CaO.SiO_2$) and the sesquisilicate ($3CaO.2SiO_2$) reduce the viscosity while the anorthite ($CaO.Al_2O_3.2SiO_2$) and the gehlinite ($2CaO.Al_2O_3.SiO_2$) tend to increase the viscosity. Grant and Layton showed that slag will foam well only above 1385°C and that foaming is a result of the formation of hydrogen sulphide from the reaction of the sulphur and water dissolved in the slag (58).

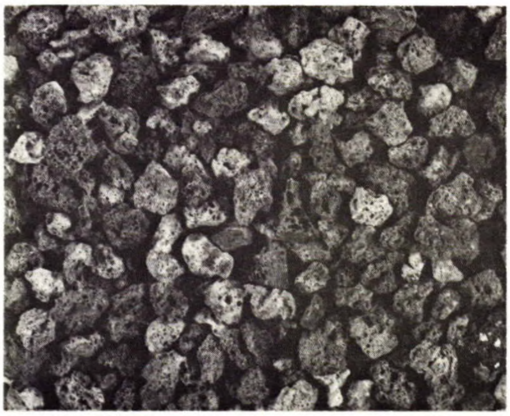
CANADIAN DEVELOPMENTS

Lightweight aggregate was first produced from blast furnace slag at Sydney, N.S., in 1947, using the pit method of expansion. This operation continued until 1968, when it ceased operation. In 1954, a larger plant was put into operation at Hamilton, Ont., and this is now the only producer of expanded slag lightweight aggregate in Canada. Different processes have been used through the years - originally the Kinney-Osborne process, and in 1963 a modification of the Gallai-Hatchand process was adopted, using a specially designed carrier and ladle to transport 27-Mg batches of slag to the pits. In 1968, this company developed and adopted the method of producing the pelletized slag mentioned previously. Figure 12 shows expanded slag produced in a pit and from the pelletizing machine. Figure 13 shows the internal structure of the pelletized slag. The pelletizing process has proven successful and at present, 20 machines have been installed by processors in 11 other countries.

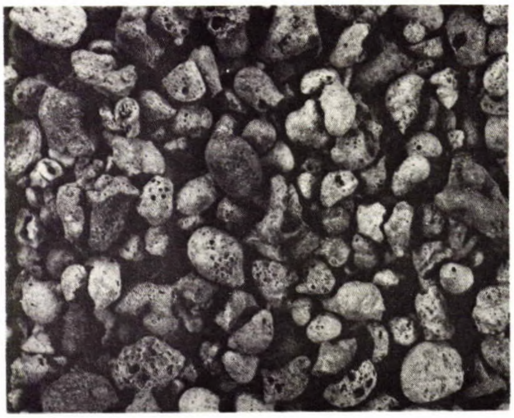
PROPERTIES

The properties of expanded slag lightweight aggregate will depend on the composition and temperature of the molten slag when processed,

Pit expanded slag



Expanded slag aggregate



Pelletized expanded slag aggregate

Fig. 12 - Pit expanded and pelletized expanded slag

and on the method and conditions of expansion. The slag processor does not have any control over the composition or the temperature of the molten slag. These are controlled by the blast furnace operator who is interested primarily in producing iron and the slag is of interest only as its composition affects the iron.

The density of the expanded slag produced in the United States is usually between 560 and 800 kg/m^3 for coarse aggregate sized 12.5 to 4.75 mm, and between 720 and 1040 kg/m^3 for fine aggregate of minus 4.75 mm (59). The pelletized aggregate produced in Canada has a density of 840 kg/m^3 when sized at 8.0 to 2.36 mm, and 1072 kg/m^3 at minus 4.75 mm (60).

Most expanded slag aggregate is used in concrete masonry units. The National Slag Association of Washington, D.C., reports that typical weights of the 200 x 200 x 400-mm units are from 11 to 15 kg; at 50% solids, the density of the concrete is from 1585 to 1760 kg/m^3 (56). Such masonry units have a compressive strength of at least 6.9 MPa on the gross area. Masonry units, containing the pelletized aggregate and 143

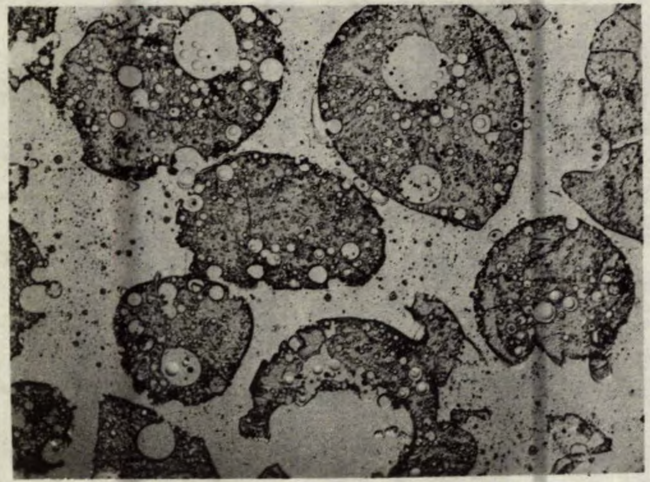


Fig. 13 - Internal structure of pelletized expanded slag

kg/m^3 of cement, have an average compressive strength of 8.3 MPa on the gross area. Table 8 shows other properties of masonry units containing this aggregate.

Lewis prepared structural and insulating concretes from two typical expanded slags (61). The structural concretes containing 415 to 485 kg cement/m^3 had 28-day oven-dry densities of 1480 to 1650 kg/m^3, compressive strengths of 14.5 to 26.0 MPa, and flexural strengths of 3.4 to 5.1 MPa. The insulating concretes with cement contents of 220 to 330 kg/m^3 had 28-day oven-dry densities of 1310 to 1560 kg/m^3, compressive strengths of 3.8 to 11.4 MPa, and flexural strengths of 1.7 to 3.2 MPa. He made thermal conductivity determinations on concretes containing four expanded slag aggregates. With cement contents between 218 and 494 kg/m^3, the concretes had oven-dry densities of 960 to 1660 kg/m^3 and thermal conductivities of 0.22 to 0.46 W/mK. There was a straight-line relationship between density and thermal conductivity.

Table 8 - Properties of expanded slag concrete masonry units*

Sound absorption	Noise reduction coefficient**
102 mm hollow block	
fine-texture	0.60
coarse-texture	0.50
203-mm solid black	0.75
Sound transmission	Decibel loss
208 mm hollow block	
unplastered	45.0
25-mm plaster	52.6
Thermal insulation	W/mK
1440 kg/m^3 concrete	0.37
Fire resistance	Rating
118.4 mm thickness	4 h
Modulus of elasticity	MPa
Block of average compressive strength	1.1 x 10^4
Compressive strength	Meets ASTM specification (Designation C331-77)
Drying shrinkage	Low pressure cured; predried, have low residual shrinkage. High pressure cured: normally less total shrinkage than other lightweight masonry.

* Information supplied by National Slag Ltd., Hamilton, Ont., Canada

**The sorbed fraction of the sound energy incident on material

The pellitized slag produced in Hamilton has cementitious properties when finely pulverized, as do many glassy granulated slags (62). Emery et al. showed that the pelletized slag when pulverized could be used in a stabilized base for road construction using a mixture containing 30% pulverized pelletized slag and 70% air cooled slag (63). It has also been shown experimentally that this pulverized slag, blended with portland cement, can be used in concrete masonry units (60).

APPLICATIONS

Expanded slag lightweight aggregate has been used widely in all applications of concrete masonry units; in the 56-storey Toronto-Dominion Bank Centre, Toronto, 1.25 million units were used for core construction and fire-proofing of the steel columns (Fig. 14).

Fig. 14 - Toronto-Dominion Bank Centre, Toronto, Ontario

It has been used in structural concrete in many locations such as in the floor slabs of the 38-storey Prudential Insurance Company Building, Chicago. The floors of the 42-storey Century 21 Building in Hamilton were of structural concrete, having a compressive strength of 24.2 MPa.

SPECIFICATIONS

The following ASTM specifications cover use of expanded slag aggregate in lightweight concrete:

C330-77 - Lightweight Aggregates for Structural Concrete (44)

C331-77 - Lightweight Aggregates for Concrete Masonry Units (45)

C332-77 - Lightweight Aggregates for Insulating Concrete (46)

OUTLOOK AND CONCLUSIONS

A number of facts effect, and will continue to effect to an even greater degree, the production of lightweight aggregates. These aggregates frequently are in direct competition with gravel and crushed rock, the normal aggregates. In many market areas in Canada the readily available supply of normal aggregate is dwindling and it will have to be shipped in from ever greater distances (64).

The price of fuel has increased dramatically over the past seven years. This factor, in addition to increases in the other components of production costs, have resulted in the average price of the lightweight aggregates, produced in Canada from clay, shale and slag being about double in 1979 what it was in 1972. The cost of heating buildings has, in many areas, increased even more dramatically, and the higher insulation value of lightweight concrete than normal concrete can appreciably reduce the amount of insulation required to meet specifications.

In view of the continued escalation in the cost of natural gas, the fuel used by six of the seven rotary-kiln plants, production costs could reach an uneconomic level unless steps are taken to improve efficiency. The expanded slag industry is not affected nearly as much by the rising cost of natural gas or oil.

There are several alternatives for the rotary kiln producer. Many of the plants in the United States are converting from gas to coal as fuel. This would not be feasible for all the plants in Canada because in some areas coal is more costly than gas.

The alternative to using a lower-cost fuel would be to make the heat exchanger more efficient by using a preheater and kiln internals to transfer more heat from the combustion gases to the material. The possibility of producing a lightweight aggregate from colliery shales, which contain a fuel, is being studied and may prove viable in locations where such material is readily available (23). Fly ash, some of which contains fuel, is another possible raw material that is being sintered successfully in Britain.

One factor which is extremely important and has caused the demise of several lightweight aggregate plants in the United States is environmental protection legislation. All existing and future plants must meet stringent regulations regarding gaseous emissions.

In North America at present there is no market for lightweight masonry having a density of 750 to 900 kg/m^3, a compressive strength of 50-mm cubes of 3.5 MPa, and thermal conductivity at 3% moisture of 0.21 W/mK as is being marketed in Britain. Such concrete presumably could be produced in Canada, but building standards would have to be altered and consumers convinced of the value of such a building material.

There is still some skepticism about the future of lightweight aggregates in North America (65). During the 1980's changes will have to be made in the industry in raising efficiency of the process, in better selection of raw materials, possibly in converting the type of heat exchanger to one such as a fluidized bed calciner, and in altering the properties of the products marketed. The expanded slag industry may also have to make changes in processing methods and the properties of their products to meet market requirements.

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