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Markets for Fly Ash in Canada

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MARKETS FOR FLY ASH IN CANADA

BY

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1. FLY ASH AS A RESOURCE MATERIAL

The present annual world consumption of coal in electric power plants is approximately 2 400 million tonnes, with a consequent production of 250 to 300 million tonnes of ash. It has been predicted that consumption will increase to 6 500 million tonnes by the year 2000, and production to over 700 million tonnes of ash. This represents a growth of well over 100 per cent in 16 years. Ash disposal is therefore a matter of urgent concern from the environmental conservation perspective and represents a major cost to electrical power producers.

Since the early 1970s there has been growing recognition that fly ash and other industrial wastes can replace or supplement materials that require substantial energy to manufacture. Consequently, there has arisen an increasing body of literature and practical experience on the use of ash in varying applications.

This document presents an overview of potential markets for coal ash from a Canadian perspective. Most of the uses discussed are not new. Some, however, are new to Canada, still others are in early stages of development and some are already established.

1.1 <u>Fly Ash - Its Origin</u>

When coal is burned in electrical generating plants, the organic material provides fuel and is converted to combustion gases. The inorganic, non-combustible material remains as a solid ash. In modern thermal generating stations, coal is injected into the boiler as an airborne suspension of fine particles (pulverized fuel). In the combustion process, two types of ash are produced. The first is bottom ash or boiler slag - a combination of heavier ash particulates, and molten slag that forms on the internal surfaces of the boiler. The second is fly ash - a fine particulate, light material that is carried out of the boiler in the flue gases. Typically, 80 per cent of the ash formed in a modern boiler is fly ash, and the remaining 20 per cent is bottom ash.

To prevent atmospheric pollution, collection devices are used to remove as much as 99.9 per cent of the fly ash prior to discharge of the flue gas.

The most common methods of collecting fly ash are:

- wet scrubbers;
- mechanical collectors;
- fabric filters;
- electrostatic precipitators.

The type of particulate control equipment used influences the grain-size distribution of the ash collected. Due to their greater efficiency, electrostatic precipitators normally collect fly ash having a finer size-gradation than that collected by cyclones.

Fly ash removed from the flue gas stream by a wet collector is sluiced directly to a pond for dewatering or disposal. If the ash has been collected by fabric filters, electrostatic precipitators or mechanical collectors, it must be transported either to a temporary storage silo or an ash sluicing area.

The chemical, physical and engineering properties of a particular fly ash may result from:

- the type and geological origin of the coal;
- the extent and type of coal preparation;
- the design, type and operation of a power plant boiler unit;
- the collection, handling and disposal methods employed.

Coal ash, consequently, displays a high degree of variability in its properties. Not only do ash properties vary from one power plant to another, they vary from one boiler to another at a particular plant, and within an individual boiler at different times.

1.2 The Chemistry of Fly Ash

The chemical composition of ash is primarily a function of the composition of the feed coal. The major components of coal are carbon, hydrogen, oxygen, nitrogen and sulphur. These elements typically account for 70 to 90 per cent of the total, and are present in varying quantities. The major elements form gaseous combustion products that are mainly discharged with the flue gases, and have little influence on ash composition. Most minor components and the sand, clay and shale associated with coals are incombustible and form the solid residues that comprise ash.

Over 85 per cent of most fly ashes comprise chemical compounds and glasses formed from SiO_2, Al_2O_3, Fe_2O_3, CaO and MgO. Unburned coal collects with the fly ash, the amount of which is determined by the rate of combustion, air-fuel ratio and degree of coal pulverization. Bottom ashes and slags are generally of similar chemical composition, but contain less glassy material.

The amount of ash generated by a boiler depends on the inorganic content of the coal, which ranges from three to 30 per cent. Higher grades of coal generally produce less ash than lower grades. A number of systems are used for classifying or ranking of coals, each of which define different coal grades. The most important are:

- anthracite;
- bituminous;
- subbituminous;
- lignite.

Anthracite is not normally used for thermal generation in Canadian power plants.

From the perspective of ash utilization, it is convenient to consider two classes of fly ash:

> Type 'F' fly ash, derived from burning bituminous coals (or anthracite), frequently distinguished by its relatively high iron content and relatively low calcium oxide content.
>
> Type 'C' fly ash is derived from burning subbituminous or lignite coals and distinguished by its 'basic' nature, characterized by the presence of elevated levels of calcium oxide. Type 'C' ash frequently reacts with water to form solid cement-like concretions.

The chemical properties of coal ashes make them useful as raw materials in a number of secondary process industries. Some typical examples of applications that depend upon the chemical properties are:

- the manufacture of Portland cement;
- the manufacture of mineral wool;
- the manufacture of ceramic and clay products;
- the extraction of major and trace elemental values such as Al, Fe and Ge;
- the manufacture of ferro-silicon.

1.3 The Physical Nature of Fly Ash

The majority of fly ash particles are spherical and range in diameter from 0.5 to 150 microns. The typical form of these particles is shown in Figure 1. Spherical particles, some of which are hollow, predominate over the entire size range. The crystalline growths seen clearly on the large particle in Figure 1 are also typical and are presumed to have formed through the deposition of materials from combustion gases as cooling occurs.

Bottom ashes are generally of much larger particle size and very irregular shape. Figure 2 shows size distributions for both types of ash in comparison with those of typical silty sand, clay, graded sand and gravel.

The specific gravity of fly ash varies widely from one particle to another, ranging from less than 1.0 for hollow particles (termed cenospheres or floaters) to greater than three for magnetic spinels. The differences in specific gravity, particle size and magnetic properties have been used to provide a basis for beneficiation of ash into its components.

Figure 1. Electron Micrograph of Fly Ash
(Magnification x 60 000)

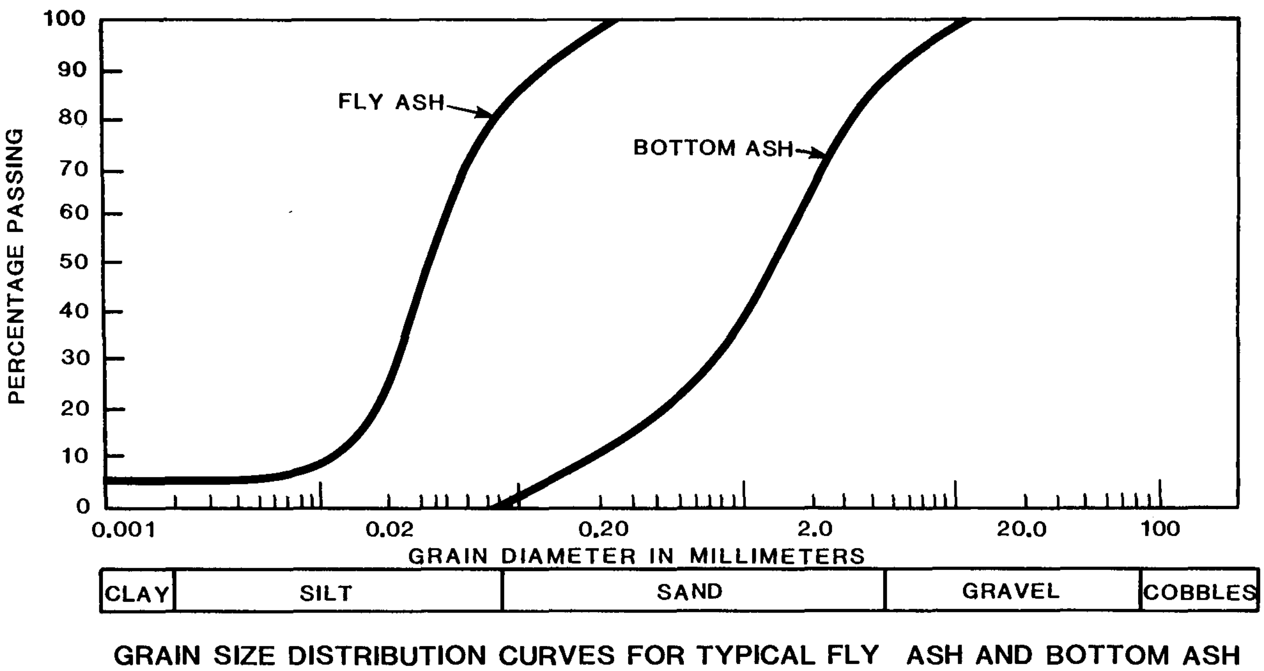

Figure 2: Grain Size Distribution of Fly Ash and Bottom Ash Particles Compared with Sand and Gravel Aggregates.

The physical properties of fly and bottom ashes are exploited in such applications as:

- filler for plastics and rubber products;
- land and structural fill;
- absorbents for oil spills;
- water treatment.

1.4 Fly Ash as an Engineering Material

In common with volcanic ashes, certain diatomaceous earths and artificially heat-treated minerals (such as clays or shales), ashes from the combustion of coal are frequently pozzolanic. A pozzolan is a material that reacts at ordinary temperatures with calcium oxide (lime) and water to form stable insoluble compounds possessing cementing properties.

The term pozzolan is derived from the historical use of red volcanic tuff from the Pozzoli or Pozzuoli (in Latin: Puteoli) region near the Bay of Naples. Its use, mixed with lime, as a construction cement was described both by Vitruvius and by Pliny. As both the Romans and Greeks were aware of the cementitious properties of lime and volcanic ash mixtures, the use of pozzolanic ashes is probably the oldest known means of forming truly hydraulic cements.

Although it is likely that all coal ashes, if finely divided, will exhibit some pozzolanic activity, only fly ash (pulverized fuel ash) is sufficiently reactive to be considered a practicable pozzolan in the form collected from thermal power plants. There is no single characteristic or simple combination of characteristics that determines the utility of fly ashes as pozzolans. There is, however, general agreement that many types of fly ash are pozzolanic and that their degree of pozzolanic activity relates to the chemical composition and fineness of the component particles.

The pozzolanic property of fly ash forms the basis for a number of uses that are exploited on a large scale. In this context the ashes are used as:

- stabilizing agents for soils;
- components of soil cement with lime or cement;
- components for stabilizing toxic or hazardous solid and liquid wastes;
- reactive constituents in numerous non-Portland cements;
- components of Portland-pozzolan cements;
- supplementary cementing materials added, with Portland cement, in the manufacture of concrete and concrete products;
- components of grouts, mortars and backfilling cements;
- components of oil-well cements.

2. COAL ASH IN CANADA

2.1 Sources

Approximately 75 per cent of coal consumed in Canada is used for thermal power generation.

Historically, the proportion of Canadian electrical power generated from coal has been less than in most other industrialized nations. This is because most Canadian electricity is generated from oil burning or hydroelectric sources. The per capita generation of coal ash in Canada is consequently lower than in many equally developed countries (Table 1).

TABLE 1

APPROXIMATE ANNUAL PER CAPITA PRODUCTION OF COAL ASH

Country	Ash Production Per Capita (Tonnes per year) (1977-1980)
Australia	0.38
Federal Republic of Germany (West)	0.24
U.K.	0.22
U.S.A.	0.24
U.S.S.R.	0.27
Canada	0.16

In 1982, Canadian utilities operated 22 coal-fired thermal generating stations with a total capacity of approximately 17 300 MW (see Table 2). In 1982, thermal power generation in Canada consumed about 33.7 x 10^6 tonnes of coal and produced about 3.5 x 10^6 tonnes of ash (1.2 x 10^6 tonnes of bottom ash; 2.3 x 10^6 tonnes of fly ash). The location of Canadian coal-burning generating stations is shown in Figure 3.

TABLE 2

COAL-FIRED THERMAL POWER STATIONS IN CANADA, 1982

Utilities	Station	Capacity (kw)	Coal Consumption (tonnes)
(numbers refer to locations on Figure 3)			
Nova Scotia			
1. Nova Scotia Power Corporation	Seaboard	111 000	74 221
2. Nova Scotia Power Corporation	Maccan	25 000	5 558
Nova Scotia Power Corporation	Trenton	210 000	400 864
3. Nova Scotia Power Corporation	Lingan	300 000	819 551
New Brunswick			
4. New Brunswick Electric Power Commission	Dalhousie	200 000	323 202
5. New Brunswick Electric Power Commission	Grand Lake	85 000	224 436
Ontario			
6. Ontario Hydro	R.L. Hearn	1 222 500	191 560
7. Ontario Hydro	Lakeview	2 422 500	1 841 763
8. Ontario Hydro	Nanticoke	4 022 500	6 137 234
9. Ontario Hydro	J. Clark Keith	271 500	203 112
10. Ontario Hydro	Lambton	2 022 500	3 283 160
11. Ontario Hydro	Thunder Bay	277 300	826 996
Manitoba			
12. Manitoba Hydro	Selkirk	155 800	21 259
13. Manitoba Hydro	Brandon	237 000	163 045
Saskatchewan			
14. Saskatchewan Power Corporation	Estevan	70 000	339 230
15. Saskatchewan Power Corporation	Boundary Dam	875 000	3 838 259
16. Saskatchewan Power Corporation	Queen Elizabeth	232 000	40 363
17. Saskatchewan Power Corporation	Poplar River	300 000	1 679 278
Alberta			
18. Alberta Power Limited	Drumheller	15 000	1 924 580
29. Alberta Power Limited	Battle River	737 000	2 452 143
20. TransAlta Utilities Corp.	Wabamum	582 000	1 840 022
21. TransAlta Utilities Corp.	Sundance	2 100 000	8 339 531
22. Alberta Power Limited	H.R. Milner	150 000	610 190

Source: Aylsworth, J. "Coal and Coke - 1982" Canadian Minerals Yearbook - 1982, Energy Mines and Resources Canada, Ottawa, 1984.

By 1986, a further three Canadian generating stations, at Atikokan (Ontario), Keephills and Sheerness (Alberta), are expected to enter production. This should increase the total industry generating capacity (derived from coal-burning) by 5.8 per cent to over 18 300 MW.

Projected coal consumption and fly ash production data for Canadian sources to 1986 are summarized in Table 3.

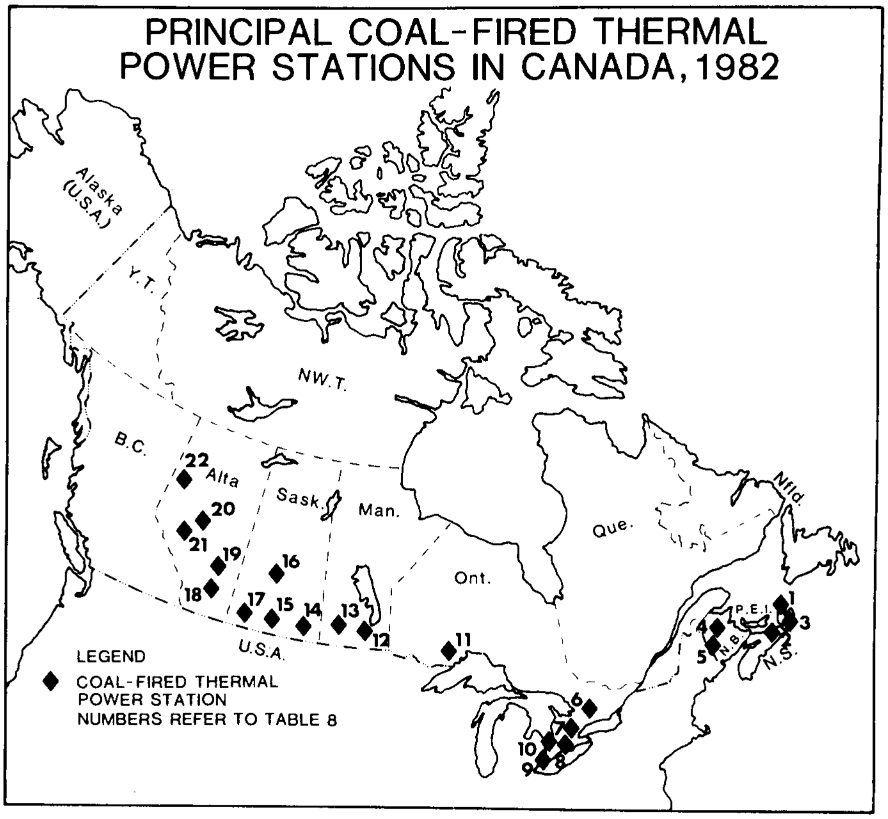

Figure 3: Location of Coal-Fired Electrical Generating Stations in Canada.

Source: Aylsworth, J. "Coal and Coke - 1982" in Canadian Minerals Yearbook - 1982, Energy Mines and Resources Canada, Ottawa, 1984.

TABLE 3

ESTIMATED COAL CONSUMPTION AND TOTAL ASH PRODUCTION BY CANADIAN UTILITIES 1980 - 1986

Coal Consumption (10^6 tonnes/year)

Province	1980	1981	1982	1983	1984	1985	1986
Nova Scotia	1.25	1.27	1.49	1.57	1.90	2.10	(2.10)
New Brunswick	0.51	0.53	(0.53)	(0.53)	(0.53)	(0.53)	(0.53)
Ontario	10.65	12.84	15.65	13.99	10.69	12.44	12.71
Manitoba*	------------- average 0.4 -------------						
Saskatchewan	5.80	6.70	6.90	6.70	(6.70)	(6.70)	(6.70)
Alberta	11.00	11.60	11.90	12.20	13.30	14.60	15.80
Canadian Totals	29.60	33.30	36.50	35.40	33.50	36.80	38.20

Fly Ash (10^3 tonnes/year)

Province	1980	1981	1982	1983	1984	1985	1986
Nova Scotia	90	126	141	153	194	213	(213)
New Brunswick	84	88	(88)	(88)	(88)	(88)	(88)
Ontario	733	842	1060	1046	731	828	860
Manitoba*	(10)	(10)	(10)	(10)	(10)	(10)	(10)
Saskatchewan	146	199	202	199	199	(199)	(199)
Alberta	1010	1070	1070	1130	1250	1380	1600
Canadian Totals	2073	2335	2571	2620	2472	2718	2970

Note: Quantities in parentheses are extrapolations assuming no increase over preceding year(s).

*Manitoba data are not specific due to exceptional variability.

Source: Berry, E.E., Hemmings, R.T. and Burns, J.S. Coal Ash in Canada: Volume 1, Ash as a Potential Resource. Canadian Electrical Association, Contract Report G195, 1983.

2.2 Utilization

The total Canadian utilization of coal ash in 1980 is estimated at approximately 500 000 tonnes (See Table 4). The total used for all purposes other than landfill (disposal) amounted to approximately 15 per cent of production.

Large-scale ash use (for purposes other than landfill) was limited to Alberta (220 000 tonnes or 13 per cent of production) and Ontario (300 000 tonnes or 32 per cent of production). Saskatchewan used about 30 000 tonnes or 6.5 per cent of total production. Some 12 000 tonnes of cyclone ash or 9 per cent of output was used in Nova Scotia.

About 50 per cent of ash marketed for non-landfill uses was used as a cement substitute or replacement. Approximately 27 per cent was used for highway base and some 20 per cent for waste stabilization.

Table 5 was compiled from several literature sources to illustrate patterns of ash utilization in Canada and a number of countries.

Considering world use statistics, structural fill, Portland cement replacement (as a supplementary cementing material), Portland cement addition (blended cement), and road base stabilization accounted for 59 per cent of the more than 31 million tonnes of ash used in 1977.

TABLE 4

ASH UTILIZATION IN CANADA BY PROVINCE*

Province	Total Ash Produced 1980 (Tonnes per year)	Ash Used (Tonnes Per Year)	Purpose	Total Use (1980) (Tonnes Per Year)
Nova Scotia	135 000	12 000	Cyclone ash for blasting and roof grit.	12 000
New Brunswick	105 000	none reported	-	-
Ontario	930 000	40 000	Cement Replacement	226 000 - 376 000
		100 000	Waste Stabilization	
		36 000	Roads	
		50 - 200 000**	Special Projects	
Manitoba	30 000	none reported	-	-
Saskatchewan	460 000	24 000	Concrete	30 000
		6 000	Oil Well	
Alberta	1 713 000	150 000	Cement Replacement	220 000
		70 000***	Special Projects	
TOTALS	3 373 000	488 000 - 638 000		486 000 - 636 000

* Collective data for fly ash, bottom ash, boiler slag and cyclone slag.

** Irregular demand dependent on construction activity.

*** Temporary supply to Revelstoke Dam construction.

Source: Berry, E.E., Hemmings, R.T. and Burns, J.S. Coal Ash in Canada: Volume 1, Ash as a Potential Resource. Canadian Electrical Association, Contract Report G195, 1983.

TABLE 5

PRODUCTION/UTILIZATION STATISTICS FOR COAL ASH: MAJOR ASH USES IN THE WORLD (1977)*

	U.S.A.	Poland	United Kingdom	Fed. Rep. Germany	German Dem. Rep.	Canada	World
Ash Production							
Total ash produced ($x10^3$ tonnes)	61 495	15 000	12 336	15 000	15 000	2 626	278 443
Total ash utilized ($x10^3$ tonnes)	9 079	5 512	5 070	3 413	2 475	711	31 605
% ash production utilized	14.8	36.7	41.1	22.7	16.5	27.1	11.4
End Use	--- (Per cent of utilized ash) ---						
Structural fill	24.3	0.2	44.8	5.8	--	75.9	18.3
Portland cement replacement	15.8	9.1	--	9.1	--	18.3	17.7
Addition to Portland cement	4.1	1.8	0.6	--	24.2	0.3	12.9
Road stabilizer	4.7	38.1	--	--	1.6	--	10.1
Aerated concrete block	--	18.1	32.2	--	1.0	--	5.8
Blasting and roofing grit**	14.9	--	--	7.8	--	--	5.1
Asphalt mineral filler	1.3	--	--	29.3	--	--	3.7
Cement raw material	5.3	--	--	4.6	--	--	3.2
Lightweight aggregate***	2.8	--	6.0	--	9.1	--	2.5
Bricks and ceramics	--	--	--	6.9	3.4	--	1.8
All other uses****	26.9	32.7	16.4	36.6	60.6	5.2	30.1

* Source: Berry, E.E., Hemmings, R.T. and Burns, J.S. Coal Ash in Canada: Volume 1, Ash as a Potential Resource. Canadian Electrical Association, Contract Report G195, 1983.

** Boiler and cyclone slag.

*** Bottom ash and sintered ash.

**** Agriculture, fillers, ice control, mineral extraction, mineral wool, grout, etc.

3. FLY ASH AS A CONSTRUCTION MATERIAL

Fly ash can be used as fill in land reclamation or development. In combination with other materials or through placement in a carefully engineered fill, fly ash can be a very useful construction material for:

- road bases and sub-bases;
- hard shoulders;
- site and access roads;
- sidewalk bases;
- bridge seatings;
- building floors and foundations;
- highway embankments.

3.1 Land Reclamation

As the value of land close to urban centres increases and as public demand for the preservation of farm and recreational land, environmental protection and renovation grows, there is a growing requirement for the reclamation of land. In most cases reclamation involves the restoration, to a useable state, of land that has been subjected to such surface disturbances as mining or waste disposal. Typical projects have been the restoration of abandoned mines, quarries or municipal waste dumps.

Frequently the land to be reclaimed is located either in areas where natural fill is not accessible or where environmental regulations limit the supply of suitable fill materials. In such cases, fly ash or mixtures of fly and bottom ash have been widely used to raise the land to a desired grade prior to applying soil cover and seeding vegetation.

Where more valuable uses cannot be found, such controlled disposal is a suitable means of restoring otherwise unusable land.

Ontario Hydro has been a leader in using ash to reclaim land close to urban centres in southern Ontario. Over the past 25 years, more than 3.5 million tonnes of ash have been used to reclaim property in the Mississauga and Etobicoke areas. The following projects have used ash from sources in Ontario.

Oakridge Park, Mississauga

Between 1968 and 1970, more than 450 000 tonnes of coal ash were used to reclaim an abandoned gravel pit which had been turned into a garbage dump. The site, located close to a suburban development, is now used as a public park (See Figure 4).

Birchwood Park, Mississauga

Originally an abandoned gravel pit, Birchwood Park was reclaimed during 1970 to 1973 using ash from the Lakeview Generating Station.

Booth Quarry, Etobicoke

From 1976 to 1980, almost 700 000 tonnes of ash were used to reclaim a disused shale quarry in the Borough of Etobicoke. An unsightly piece of property was improved and contoured for use as municipal parkland.

Figure 4: Oakridge Park, Mississauga - Land Reclaimed by Using Coal Ash.

Domtar Quarry, Mississauga

Recovery of land occupied by a shale quarry operated by Domtar is a use of Ontario Hydro ash that will probably continue for 10 to 15 years and consume about 2 million tonnes of ash. The quantity of ash to be used and the final contours of the finished property will depend to some extent on future energy demands placed on the Lakeview and R.L. Hearn generating stations. It is expected that the land will be used for a variety of applications, including residential and commercial development.

The primary advantage of using coal ash to reclaim land is that it can be designed as load-bearing fill.

After complete rehabilitation, such areas are suitable for the construction of roads, services, residences and public, commercial or industrial complexes. While this fill concept provides a desirable end-use, certain design criteria and operating standards are required to protect the environment. When ash is used this way, particular attention must be given to drainage, potential dust and water pollution problems and the load-bearing capabilities of the finished fill.

3.2 Fly Ash as a Structural Material

Applications discussed in the previous section were concerned with the use of fly ash as fill material where the principal purpose is to provide a stable base for the application of soil and vegetative cover. Fly ash is not limited to this application. It has been shown that most ash can be successfully stabilized or compacted, either alone or with other materials, to become a construction material capable of supporting highways and buildings.

The most important properties of structural fill materials are strength, durability and dimensional stability. Durability is the capacity of a material to retain its strength and integrity in service, particularly under cyclic freezing and thawing and prevailing moisture conditions. Dimensional stability is the extent to which a material resists excessive shrinkage and swelling with changing temperature and moisture conditions. Strength and stiffness can be attained through structural design, once appropriate test measurements are made on the available materials. If, however, the materials are not durable or are dimensionally unstable, structures will either disintegrate with time or severely crack, regardless of the method or care used in the design.

It is often difficult to categorize the roles that ash plays in construction applications. Ash may be the sole material, it may be used to regulate the the properties of silty soil, or it may be mixed with lime, cement, soil or aggregate to form a stabilized or compacted mass. In general, the use of ash as construction material can be considered for:

- soil stabilization;
- structural fill;
- stabilized base.

3.2.1 Soil Stabilization

Often a non-cohesive soil has insufficient load-bearing capacity for the construction of roads or buildings. Whenever this is the case, the load-bearing capacity may be increased through stabilization.

In some cases, fly ash can be used alone. More frequently it is used in conjunction with lime or Portland cement. Lime/fly ash mixtures reduce plasticity and shrinkage, and improve the drainage of many soils. In addition they may produce a cementitious matrix which further increases a soil's strength and durability.

The function of ash in stabilized soil is to act as a pozzolan or component of a soil-cement. In some instances, however, its granular nature also modifies plasticity.

3.2.2 Structural Fill

In terms of soil-mechanics, fly ash falls into the same material category as sandy silt. Ash density varies widely from source to source over a range of 1 900 to 3 000 kg/m^3. Bulk densities also vary greatly: compacted dry density is usually in the range of 1 120 to 1 440 kg/m^3, which is much less than most common fill materials. Optimum compaction is found at 18 to 30 per cent moisture for most ashes. Specimens of ash compacted with more than optimum moisture content show decreased undrained shear strength. The permeability of compacted ash ranges from 5×10^{-5} to 5×10^{-7} cm/sec.

Light weight and good shear strength make fly ash an excellent embankment material, particularly over weak or compressible soils. Many fly ashes have shear strength characteristics which render them ideal for light load-bearing fills such as highway embankments. In Scotland, more than 600 000 tonnes of fly ash were used to construct high embankments on the M9 Motorway, solely because its lightness made it more suitable than traditional fill materials such as colliery spoil or heavy clay.

One of the most frequently reported applications is as fill behind abutments and other concrete structures. The main advantages here are claimed to be:

- low active pressure (resulting from high shear strength);
- low density;
- pozzolanic properties;
- negligible ash settlement because of pozzolanic properties;
- less settlement below the ash because of its light weight.

In Europe, fly ash is widely used as load-bearing structural fill. Because of its lightness and self-hardening properties it may be used to form "rafts" for building over poor ground.

The major problems associated with compacted ash fills are erosion and liquefaction. Internal erosion by movement of ground waters may be controlled by properly designed drainage. External erosion due to wind or rain is controlled with vegetative or other cover material.

Other reported problems are: a) that some fly ashes are frost-susceptible and require cover or stabilization, and b) sulphate in some ashes may be sufficiently soluble that precautions are required where ash is placed next to concrete. The most common precaution is the use of bituminous coating on the concrete.

A number of large-scale applications of ash as structural fill have been reported in Canada over recent years.

In 1978, 125 000 tonnes of lagoon ash from the J. Clark Keith Generating Station were used to construct the core of the E.C. Row-Walker Road overpass in Windsor, Ontario. The lightness of the ash and its proximity to the job site were the major reasons why it was selected. The success of the project led, in 1980-81, to the use of 250 000 tonnes of fly ash from the Lambton Generating Station to construct an approach ramp to Highway 402 and Front Street in Sarnia, Ontario. Other projects have followed, and ash is now established as a structural fill material for many forms of highway construction in southern and southwestern Ontario.

Fly ash has been used as structural fill in highway sub-base construction in Saskatchewan. In 1976 and 1977, a three-km test section of Highway 18, close to Estevan, was constructed on a sub-base composed of lagoon ash from the Boundary Dam Generating Plant of the Saskatchewan Power Corporation. Construction of the test highway required approximately 30 000 tonnes of lagoon ash which were transported with bottom-dump trucks and compacted with pneumatic-tired rollers.

After 12 months of service, only four transverse cracks were evident. No pushing or showing between the lagoon ash and asphaltic concrete had occurred. Erosion had occurred on the sideslopes caused by water running off pavement onto the exposed lagoon ash. The results obtained in the test section led to a decision to use lagoon ash as a sub-base for the routine construction of a 25-km section of Highway 47, immediately north of Estevan.

3.2.3 Stabilized Base

There is a narrow line of distinction between soil stabilization using ash and stabilization of the ash itself to become a base or foundation material. In the latter case, ash plays the role of both soil (i.e. inert aggregate) and pozzolan (i.e. one component of a cemented system).

The most common application in a stabilized system lies in the construction of bases and sub-bases for highway pavements where a lime/fly ash/aggregate mixture is used to replace cement.

Lime/fly ash/aggregate (LFA) mixtures are blends of aggregate, lime, fly ash and water. When properly proportioned and compacted, such mixes produce a dense mass. For a given set of component materials, the lime to fly ash ratio and the ratio of lime plus fly ash to the aggregate fraction can be varied.

The aggregate is usually a well-graded stone, sand, gravel or slag and should be free of any substances that interfere with the desired chemical reaction between the ash and the lime. In some instances other waste materials such as coal refuse, boiler slag or bottom ash have been used as aggregate in LFA mixtures.

Fly ash alone can be stabilized with either cement or lime and used as base or sub-base course material. The pozzolanic reaction between lime and fly ash can be produced in a number of ways. In lime-stabilization, lime is added directly to the fly ash, moisture is introduced, and the mixture is compacted. In cement stabilization, cement is added to the fly ash in lieu of lime and the cement hydrates on contact with moisture, producing its own cementitious compounds and releasing certain amounts of lime which react with the fly ash in a pozzolanic manner. Certain types of fly ash contain substantial quantities of free lime which react upon the addition of moisture to produce cemetitious compounds without the addition of lime or cement. The latter process is known as self-hardening.

Fly ashes stabilized with lime or cement or with inherent self-hardening properties have shear strength parameters that increase with time. The compressibility of most fly ash is similar to that of cohesive soils, although stabilized or self-hardening ashes are less compressible, particularly if allowed to cure prior to loading.

Because fly ash is composed mainly of particles in the silt-sized range, it is potentially susceptible to frost heaving. It has been shown in a number of applications, however, that when ash is stabilized with an adequate cement content, the resulting mixes are not generally frost susceptible.

Uncertainty over the frost susceptibility of stabilized fly ash systems has largely prevented their use in Canadian public highway construction, although some systems have been used on private roads owned by power utilities. It is expected that the success experienced in these applications may ultimately lead to wider-scale use in Canada.

4. FLY ASH IN CEMENT AND CONCRETE PRODUCTS

The cement and concrete industry has traditionally provided a substantial market for fly ash in Canada and around the world. In comparison with other large-volume applications, fly ash commands a relatively high value as a supplement to or substitute for Portland cement. Cement and concrete products are divided into the following categories:

- blended cements, masonry cements;
- ready-mixed concrete or other cement/water/aggregate mixes cast in place at a construction site;
- pre-cast concrete products;
- thermally cured cement and concrete products, e.g. block, brick and pipe;
- grouts and backfills;
- oil well cements.

In each of these applications, ash functions as a supplementary cement and contributes substantially to the strength and durability of the finished product.

4.1 Blended Cements and Supplementary Cementing Materials

Concrete, in which the binder is composed of Portland cement and fly ash, may be produced in one of three ways:

- a prepared blended cement;
- Portland cement and a supplementary cementing material added at the concrete mixer as separately dry-batched components; or
- a water slurry of the supplementary cementing material introduced at the concrete mixer.

Whether added as a blended cement or a supplementary cementing material, fly ash affects all aspects of concrete properties.

As an element of the concrete mass, fly ash is partly a fine aggregate and partly a cementitious component. It influences the rheological properties of the plastic concrete, the strength, finish, porosity and durability of the hardened mass, and the cost and energy consumed in manufacturing the final product. Table 6 summarizes the effects of fly ash on plastic concrete; Table 7 summarizes the effects of fly ash on the properties of hardened concrete.

As of this writing, no substantial quantities of blended cements containing fly ash have been sold in Canada, though most Canadian producers have shown interest in such products. The use of fly ash as a supplementary cementing material is well established in all classes of concrete, from low-performance backfill to high-strength structural applications. The following are notable uses of ash in various types of concrete for application in a broad range of construction circumstances.

4.2 Mass Concrete

Early users found that the inclusion of 20 to 40 per cent of fly ash could effectively control the temperature rise and associated cracking that sometimes occur in massive concrete structures such as dams and foundations.

One of the first Canadian applications was in the construction of the Squaw Rapids Hydro Station on the Saskatchewan River. The Squaw Rapids dam required 76 500 m^3 of concrete, of which fly ash was used to provide 20 per cent of the cementitious component. All concrete for the Gardiner Dam (Coteau Creek) hydro project on the South Saskatchewan River contains fly ash. Up to 20 000 tonnes of fly ash will be used in the 268 685 m^3 of concrete to be poured for the Nipawin Hydro Station, on the Saskatchewan River, the first phase of which is complete.

TABLE 6

SUMMARY OF THE PRINCIPAL EFFECTS OF FLY ASH ON THE PROPERTIES OF PLASTIC CONCRETE

Property	Effects
Water Requirement	Concrete mixes containing good quality fly ash will normally require less water for a given slump than that containing only Portland cement. Poor quality ashes will increase water demand.
Air Content	The amount of air-entraining admixture required to obtain optimum air content frequently increases appreciably when fly ash is used in the concrete. The admixture requirement is a function of the carbon content of the ash.
Workability	Good quality fly ashes will normally improve the workability of concretes of equal strength and slump.
Bleeding and Segregation	Fly ash reduces bleeding and segregation of concrete. It is particularly advantageous when used in concrete mixes normally deficient in fines.
Temperature Rise	The hydration of Portland cement is accompanied by an evolution of heat which causes a temperature rise in the concrete. The resulting thermal gradients produced in mass concrete structures may lead to cracking. It is generally accepted that the use of fly ash to partly replace Portland cement is an effective means of avoiding this problem. This has led to the widespread use of fly ash in mass concrete structures such as dams.
Finishing	Quality fly ashes usually improve the finishing properties of concrete.
Pumping	Many fly ashes improve concrete pumpability.

TABLE 7

SUMMARY OF THE PRINCIPAL EFFECTS OF FLY ASH ON THE PROPERTIES OF HARDENED CONCRETE

Property	Effects
Strength	Portland cement and fly ash both contribute to the strength of concrete, but at different rates. Concretes containing fly ash may develop strength more slowly than those containing an equal quantity of cement as the only binder. When cementing material content is the only variable, equal strength at early ages can only be obtained when the amount of combined cementing material is greater than when Portland cement alone is used. Lean concrete benefits more from the use of fly ash than rich concrete. The optimum amounts of cement and fly ash for any specific mix are determined by the relative cost of materials and the required properties of concrete, and should be established by trial mixes.
Freeze-Thaw Resistance	Fly ash does not influence the freeze-thaw resistance of concrete, provided that: (a) the concrete is adequately air-entrained; and (b) sufficient strength has developed before the onset of freezing.
Permeability	Fly ash reduces the permeability of concrete even when the cement content of the paste is relatively low. This reduces permeability of concrete at early ages.
Drying Shrinkage	The effect of specification fly ash on the drying shrinkage of concrete is generally small. As with concrete not containing fly ash, shrinkage is a function of the water content of the fresh concrete.
Alkali-Aggregate Reactivity	Alkali-aggregate activity of both alkali-silica and alkali-carbonate types can cause excessive expansion of concrete. Some fly ashes are effective in controlling alkali-silica reactions, but not alkali-carbonate reactions.

Hydroelectric power projects in British Columbia have also been major consumers of fly ash, provided mainly from power plants in Alberta. Pozzolans were first used in such projects during construction of the Peace River (Bennett) Dam at Hudson Hope. These were natural pozzolans such as diatomaceous earth and shale dust, however they paved the way for subsequent use of fly ash initially at 'Site One', then at the Seven Mile Dam, and most recently at the large Revelstoke Dam.

The first extensive use of ash in mass concrete structures by Ontario Hydro was in 1960 at Otter Rapids, where 20 per cent of the cementing material in the structural concrete was replaced. After 11 years, inspection of the concrete showed a comparable condition to that of a similar dam built at the same time but without the use of fly ash. The structure with fly ash, however, exhibited less cracking. Most of the mass concrete and much of the structural concrete in subsequent Ontario Hydro hydraulic structures have included some fly ash.

The ability of fly ash to control the rate of temperature rise in mass concrete has been exploited in structures other than dams. A notable example is the use of ash concrete in several 'mattress' pours in the Vancouver area, especially those in the foundations of the Alberta Wheat Pool grain elevators on the Vancouver waterfront. This project was under construction in 1977 and required almost 4 600 m^3 of concrete. Fly ash provided 38 per cent of the cementitious component.

4.3 Marine Concrete

Deterioration of concrete due to attack by sulphate-containing groundwaters or sea water is a very important factor in determining the durability of many structures. Increased activity in offshore waters and other marine environments has lead to widespread use of concrete in such structures as drilling platforms, piers, harbours and concrete storage tanks. Fly ash has proved a useful addition to marine concrete and is known for its value both in reducing the permeability of concrete and increasing its resistance to sulphate and other forms of chemical attack.

Some interesting examples of this application are the recently constructed concrete caissons used to form an artificial Arctic island that Dome Petroleum Limited will use for oil and gas exploration. Four caissons, each 11.5 m high, 15 m wide and 69 m long, were constructed. A total of 880 m^3 of semi-lightweight, high strength (40 MPa) concrete was used in the construction. Approximately 16 per cent of the cementitious material was fly ash. A detailed description of this construction was published in Concrete International, March 1982 (Volume 4, No. 3, pp 57-59).

4.4 Structural Concrete

The use of fly ash in structural concrete is now well established in parts of Canada. In Ontario, Saskatchewan, Alberta and British Columbia much of the ready-mixed concrete supplied to the general construction market contains 5 to 15 per cent. This type of concrete is used to construct basements, walls and columns.

Fly ash is increasingly employed in the manufacture of high-strength concrete. It is now accepted that good quality fly ash is an asset in the production of high-strength concrete, as long-term strength gains cannot be economically attained through other means. A notable example is the use of fly ash in high-strength concrete support columns of the Royal Bank Plaza in Toronto (Figure 5), where compressive strengths up to 75 MPa were attained. Whereas high strength was essential in this project, fly ash was also used to control temperature rise.

4.5 Controlled Density Fill

Cement-stabilized fill, also called controlled density fill, uses Portland cement, blended cement, fly ash and fine aggregates as pumpable backfill around pipes, foundations, shoring, piling and tunnels. The finished product reaches strengths of 0.5 to 10 MPa, depending on the application and selected mix design. The principal property of this material is its capability of flowing without segregation into areas that are difficult to access with more conventional materials. Figure 6 shows a typical example of its placement as fill around concrete foundation structures.

4.6 Cementitious Grouts

Grouting, the process of injecting a slurry of cementitious materials to fill voids, is used to seal construction joints in dams, repair cracks in concrete, make water-tight structures, stabilize rock during construction of tunnels and dams, fill old mine workings, and strengthen old brick and masonry structures.

Grouts commonly comprise neat cement paste with or without the addition of a fluidizing agent. Fine sand, ground slag or fly ash are occasionally added.

Figure 5: The Royal Bank Plaza, Toronto - Where Fly Ash was used in High-Strength Structural Concrete.

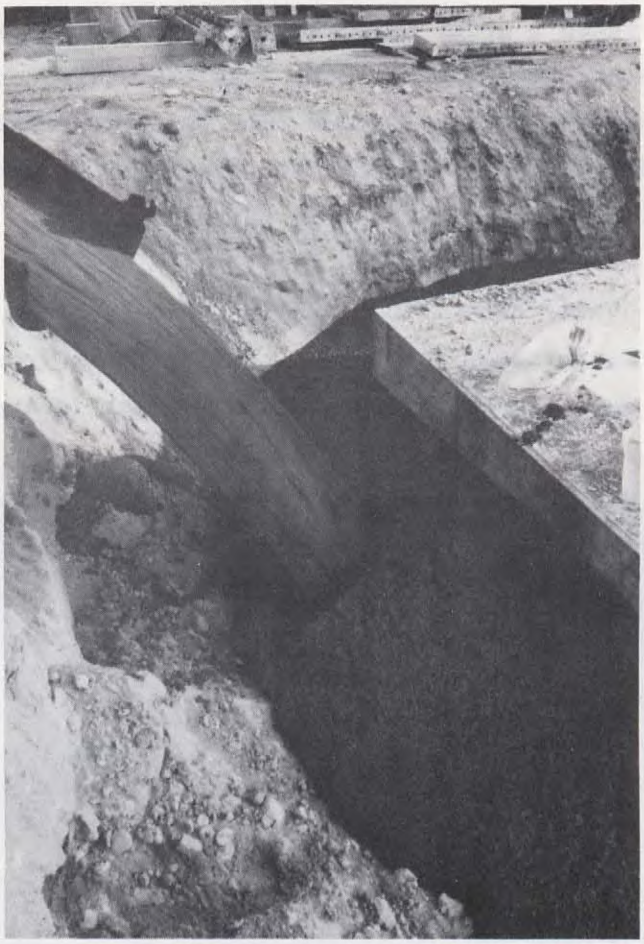

Figure 6: Placing Controlled-density Fill during the Construction of Foundations. (Courtesy of Ontario Hydro)

The most important property of a grout is its ability to flow freely. When a grout is selected for a particular application, the size of the particles making up its solid constituent determines the smallest voids into which it can be successfully injected. The particle size and shape of fly ashes render them especially suitable for use in many grouts.

As with other cementitious applications, pozzolanic activity is an important factor in the use of fly ash in grouts. Relative density may also be important where weight is a consideration.

Fly ash use in grouting is not frequently reported but is a generally accepted practice. An interesting example was the use, in 1980, of fly ash-lime grout to consolidate a railroad bed in St. Catharines, Ontario. Figure 7 shows the equipment used to inject grout into the base of the bed.

4.7 Concrete Products

Precast products such as patio slabs, bricks, blocks, septic tanks, well crocks and pipes are made from concrete, cured in moulds at temperatures ranging from ambient to that of pressurized steam.

In principle, all these products present potential markets for fly ash. Requirements for ash are basically the same as for poured concrete.

A number of Canadian manufacturers of concrete products have used fly ash at one time or another, either as a substitute for part of a Portland cement requirement or, in the case of autoclaved

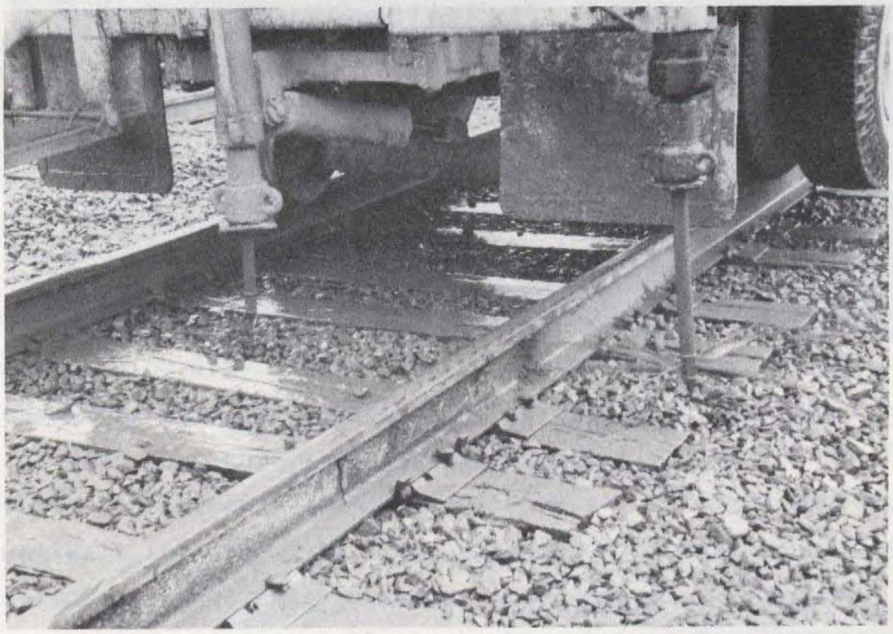

Figure 7: Equipment Used for Injecting Fly Ash Grout into a Railroad Bed. (Courtesy of Ontario Hydro)

and steam-cured products, as a substitute for silica (See Figure 8).

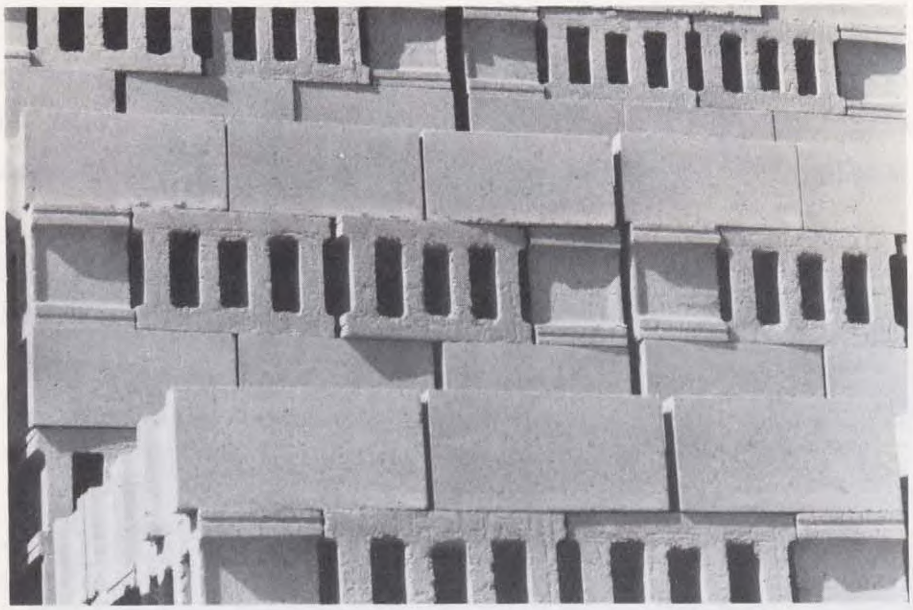

Figure 8: Concrete Blocks Incorporating Fly Ash as a Replacement for Silica.

4.8 Oil Well Cementing

Oil wells are cemented by pumping a cement-water grout to critical points in the annulus around the casing, in the open hole or into a fractured formation. The process was first introduced in the 1920s as a means of protecting oil-producing zones from salt-water flow, of protecting well casings from corrosion, of reducing the dangers of contamination of fresh water strata by oil, gas or salt-water, and of protecting well casings from blowout and collapse under pressure.

In all such down-hole operations, the basic cementing material comprises a slurry of fine particles: no coarse aggregates or sands are used. Oil well cements must withstand temperatures ranging from well below freezing at the surface to close to 370°C in geothermal strata. Pressures recorded in deep hot wells may exceed 138 MPa.

Portland cements have been used for oil wells but are not totally suitable. Slurries of Portland cement and water alone have a narrow range of properties (such as density) that cannot easily be regulated to meet varying requirements. Additional agents are required to give more flexibility to slurry properties. Fly ash was recognized as a suitable admixture and has been widely used since 1949.

A compressive strength of 3.5 MPa is considered more than adequate to support pipe and forms the basis of many regulatory specifications for cementing wells. As with concrete, early strengths obtained with fly ash and Portland cement are lower than with Portland cement alone, however strength development in wells is influenced by time, pressure and temperature. As the pozzolan reacts under pressure and temperature, strength increases and ultimately approaches that of Portland cement.

Cements used in wells must exhibit a long life to down-hole corrosive conditions. The reaction of fly ash with compounds formed in the hydration of cement makes fly ash/Portland cement materials less subject to the leaching action of corrosive waters and maintains low permeability over a longer period. The permeability of set fly ash/Portland cement cured under down-hole conditions is often less than that of the formation across which the cement is being placed.

Ultra-low density cement grouts (1 000 to 1 300 kg/m^3) suitable for oil and gas well cementing have been formulated using high-strength microspheres such as cenospheres with relative densities ranging from 630 to 1 000 kg/m^3.

Both fly ash and cenosphere products derived from fly ash are widely accepted in the Canadian oil and gas industry. Almost one third of all of fly ash from Alberta and 20 per cent of fly ash from Saskatchewan is used for oil and gas cementing. Cenospheres are imported from the United States and England for some special applications.

The use of fly ash by the oil industry is particularly advantageous, as much of the requirement is supplied during the winter months when other construction demands are minimal.

5. CERAMIC PRODUCTS

5.1 Clay Brick

Fly ash has been used for some time in Europe, especially in the eastern regions, as a component in building bricks. Coal ashes were used for this purpose as early as the 17th Century.

The major properties of fly ash exploited in the clay brick industry are:

- its fuel value, imparted by residual carbon content where present;
- its inert nature, which reduces shrinkage;
- the reduced weight it conveys to the product;
- its chemical compatibility with natural clays.

The fuel value of carbon in some fly ashes is of particular interest in that this property frequently makes ash unsuitable in other major applications such as the manufacture of cement and concrete products. The exploitation of carbon content could provide alternate employment of ash that cannot be beneficiated to remove carbon.

Fired or calcined clay grog is used in some brick formulations to control shrinkage during drying and firing. Because coal ash has a chemical composition similar to that of clay and because it is a precalcined product, it is an obvious potential replacement for grog or calcined clay.

Extensive laboratory and pilot programs were conducted in Europe and the U.S. in the 1950s and 1960s to establish the technical and economic feasibility of using fly ash as a major constituent in brick production. With the exception of Eastern Europe, however, this work has seldom achieved full-scale production. Research in Britain is revealing that major improvements in properties and the cost of brickmaking can be attained if carefully selected and controlled ash is used.

In the early 1970s, the International Brick and Tile Company of Edmonton established a plant to produce brick, block and tile from fly ash and bottom ash using U.S. technology. This operation was not commercially successful and has since been abandoned. Major problems associated with ash use in the brick industry are concerned with dusting during handling, the lack of natural plasticity of ash, and the presence of soluble salts. Recently published information indicates that the Brampton Brick Company has conducted research into the use of ash in brick products.

5.2. Lightweight Aggregate

Fly ash has been used for many years in Europe, notably in Britain, to manufacture lightweight aggregate, and interest appears to be growing rapidly in the U.S. The Lytag Company of Britain is among the leaders in the field of fly ash aggregate manufacture and currently operates two sinter plants in England.

The manufacture of aggregate from fly ash involves sintering the material at 1 000 to 1 200°C. A prerequisite to any currently applied method of sintering is that the ash be pelletized before firing.

The pelletized ash is converted to lightweight aggregate through firing by shaft kiln, sinter strand or rotary kiln. The most successful Lytag process uses a travelling grate sinter machine.

Fly ash may bring to the lightweight aggregate process the following properties:

- carbon content that may contribute to the fuel demand of the sintering stage;
- chemical composition similar to clays also used;
- the presence of glassey phases that may reduce energy demands of sintering;
- reactivity with water that may contribute to the formation and quality of 'green' pellets.

Major problems associated with ash use in the lightweight aggregate industry are related to lack of uniformity in the composition of some ashes and the presence of soluble salts.

In the early 1970s, Enercon Ltd. of Toronto developed and installed an ash beneficiation plant at the Lakeview Generating

Station. The plant was developed to co-produce lightweight aggregate and pozzolans with concurrent separation of other valuable fractions from the ash. A large pilot facility was constructed in Mississauga, Ontario, but no significant commercial production occurred and the plant was dismantled. Although it failed to attain its commercial objectives, this plant can be considered a pioneering effort in Canada for what is now becoming a growing interest: total resource recovery from ash.

6. NEW AND EXPERIMENTAL OPPORTUNITIES FOR FLY ASH USE

6.1 Mineral Wool and Heat Insulating Materials

Fly ash, bottom ash, boiler slag and so-called modified coal ashes are all potential raw materials for mineral wool manufacture. Accounts of the use of coal ash indicates that, in most instances, an acceptable product was obtained. It is not known, however, whether manufacturers are currently using coal ash for this purpose.

Of primary concern in the manufacture of mineral wool is the attainment of a suitable viscosity in the melt at the lowest possible temperature. This is achieved with fluxing agents. In early attempts to use coal ash, fluxes such as limestone and dolomite were used to adjust the chemical composition. The need for fluxes probably contributed to the poor economics of the approach and the lack of commercialization of the ash-based processes. Recent work by the Coal Research Bureau at West Virginia University has shown that good quality mineral wool may be produced using only raw ash. Results indicate that the conventional chemical criteria for mineral wool melts should be questioned and that more research is needed before ash is eliminated as a possible raw material source.

The thermal history of fly ash gives it refractory properties and good thermal stability. These characteristics have been exploited in a range of materials and products used in heat insulation, e.g. coatings, ceramics, casting aids and heat-resistant building components. In these materials ash may function as a basic raw material, a filler or a pozzolan. The natural thermally insulating properties of cenospheres make them ideally suited for incorporation with heat-resisting compositions.

6.2. Waste Water Treatment

There are many reports of the use of fly ash in treating waste water and sludges. Ash may be used:

- as a flocculant or flocculant aid;
- as a filter medium, filter aid or filter precoat;
- as an absorbent, the high specific surface area and surface chemistry of ash facilitates the absorption of wastes (additional absorptive capacity may also originate in the presence of unburned carbon);
- as a pozzolan in the presence of lime, to stabilize or solidify waste sludges;
- as a neutralizing agent.

This largely undeveloped area of ash use in Canada requires considerable research and development to establish its usefulness.

6.3. The Recovery of Resources from Fly Ash

Historically, there have been a number of attempts to establish fly ash as a source of multiple raw materials for other process industries. A typical flow sheet will provide for the collection of iron and aluminum-rich fractions, carbon, cenospheres and an enriched pozzolan component. Such proposed systems have often failed to reach a production stage because of inadequate technical support or economic factors. Since the mid-1970s, however, a growing interest, spurred by escalating energy costs and concern over declining resource supplies, has resulted in the development of several promising new approaches.

Resource recovery from ash is still very much in the developmental stage. From the perspective of the Canadian marketplace, it is reasonable to assume that the following components could be produced economically from ash:

- magnetic iron concentrate;
- cenospheres;
- fine particulate fillers.

Other products such as carbon, aluminum concentrate, ferro-silicon and trace metals may prove extractable if economic conditions favour development of suitable processes.

Two advantages relate to the selection of magnetic concentrates, cenospheres and filler products likely to reach the market in the near future. The first is that separation methods for these components are relatively simple and well developed and require little processing beyond physical extraction. The second is that existing markets are established for competing products or for ash-derived materials currently supplied from outside of Canada.

The following potential markets for coal ash iron concentrate have been identified:

- "synthetic" magnetite for coal washing;
- iron ore supplement;
- iron salts for sewage coagulation.

Of these three, the use of magnetic iron concentrate as a magnetite substitute for coal beneficiation by heavy medium separation has received the most attention.

In addition to their use by the oil and gas industry (see Section 4.8), a wide and diverse market potential for ash cenospheres exists in other industrial applications. The two major categories are:

- Mineral filler
  The high strength, low weight, chemical inertness and particle size distribution of cenospheres allow them to serve as low-cost substitutes for manufactured glass microsphere and other low-density fillers. A great number of applications are possible when binders such as organic resins or Portland cement are employed. In these applications, cenospheres act both as extenders and materials conferring desirable engineering properties on the finished products.

- Lightweight refractory materials
  Cenospheres can be used as refractory aggregates and be added to refractory cements or sintered without any binders.

In these applications, cenospheres can be considered substitutes for manufactured hollow glass spheres.

Fly ash possesses a number of unique characteristics which render it marketable as a filler or extender. Some of these are:

- that it can be brought to market without penalty of the high energy-related costs required for mining, processing and size-reduction of conventional filler materials;

- that particles of fly ash are uniquely and predominantly spherical, which contributes to improved packing and rheology of the composite and reduced vehicle demand; and

- that particles have high compressive strength and good thermal stability, making them suitable for high production temperatures or when specifications call for high temperature resistance in finished parts.

As economic pressures on petroleum feedstocks escalate, there may be predicted a substantial increase in the use of mineral fillers (including fly ash fractions) in these and related industries as a means of reducing manufacturing costs.