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Blended Cements in North America — A Review*

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Abstract

This paper traces the history of the use of blended cements in Canada and the USA and describes briefly the various supplementary cementing materials which have been, and are being, used to produce blended cements. A rationale is given as to why the blended cements in North America constitute only a very insignificant amount of the total cement production. Reference is made to the current ASTM and CSA standards on the subject and the properties of blended silica fume cements being produced in Canada are discussed. Also, the blended cements made with controlled particle-size distribution, which are still in the development stage, are described briefly.

Keywords: Blended cements, fly ash, slag and silica fume, high volume fly ash concrete, chemical requirements, fresh concrete properties, mechanical properties, shrinkage, durability.

INTRODUCTION

During the late 1970s and early 1980s, the cement industry worldwide underwent major changes in corporate ownership, marketing and distribution, with cement becoming an international commodity. The European companies not only control more than 80% of the Canadian and North American cement production, it is not unusual to see Spanish and Greek cements being imported into Canada and the USA. The Canadian, Mexican and the USA cement production in 1989 was 12, 22 and 72×10^6 t, respectively, in comparison with the total world cement production of 1121×10^6 t. Not surprisingly, China was the leading cement producer with an annual production at 207×10^6 t, indicating the maturity of the cement industry in the developed countries.[1] When compared with the total cement production in Canada and the USA, the production of blended cements is minuscule.

This paper traces the history of blended cement in North America, and describes the blended amounts currently available. Also, rationale is offered as to why the industry in North America has opted for separate batching of supplementary cementing at concrete batch plants rather than for the production of blended cements in a cement manufacturing facility.

SUPPLEMENTARY CEMENTING MATERIALS FOR POTENTIAL USE IN BLENDED CEMENTS AND THEIR AVAILABILITY IN NORTH AMERICA

Mexico leads in the production of blended cements in North America with about 60% of the production being blended cements incorporating natural pozzolans. The plants producing blended cements are located throughout the country.

Even though very little blended cement is being produced in Canada and the USA, there are sufficient good quality fly ashes and slags available in these countries and a brief mention of these materials, together with that of silica fume, should be of interest because of their potential use in blended cements.

Fly ash

About 4×10^6 t of fly ash are available in Canada, most of this is classified as ASTM Class F (low-calcium) fly ash. Apart from Ontario, where the

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fly ash sources are within reasonable distance of large population centres and construction activity, the bulk of available fly ash is far removed from construction activity. This is especially so in the Maritime provinces. At present, less than 10% of fly ash is being used in concrete as a separately-batched material at concrete batch plants.

In the US, the fly ash available for use in concrete is about 60×10^6 t. In the eastern US, the fly ash available is classified as ASTM Class F (low-calcium). Significant amounts of ASTM Class C (high-calcium) are available in the western US. Once again, less than 10% of the fly ash is being used in concrete as replacement for cement.

In Mexico, no significant quantity of fly ash is available, and whatever quantity that is available is very poor quality and is not being used in the cement and concrete industries.

Recent development of high-volume fly ash concrete at CANMET, and the serious environmental regulations being imposed by the regulatory agencies, are expected to contribute to the increased use of fly ash in Canada and the USA in years to come.

High-volume fly ash concrete

Briefly, this concrete contains a large volume of ASTM Class F fly ash (about 56–58 wt% cementitious material). The water–cementitious-material ratio is maintained at about 0·32 and high slumps are obtained by using large dosages of a superplasticizer. The concrete thus produced has adequate early-age strength, high later-age strength and excellent durability.[2]

The typical mixture proportions and properties of high-volume fly ash concrete are as follows:

Mixture proportions	*Batch quantities*
ASTM Type I cement	150 kg m^{-3}
Fly ash	210 kg m^{-3}
Water	115 kg m^{-3}
Coarse aggregate (19 mm max)	1275 kg m^{-3}
Fine aggregate	620 kg m^{-3}
Air-entraining admixture	720 ml m^{-3}
Superplasticizer	4·0 l m^{-3}
Properties of fresh concrete	
Slump	200 mm
Unit weight	2375 kg m^{-3}
Air content	5 ± 1%

Mechanical properties		
Compressive strength	1 day:	8 MPa
	7 days:	18 MPa
	28 days:	30 MPa
	56 days:	35 MPa
	91 days:	42 MPa
Flexural strength	28 days:	5 MPa
Splitting-tensile strength	28 days:	3 MPa
Modulus of elasticity	28 days:	34 GPa

Berry *et al.*[3] undertook basic research to explain the high-performance of high-volume fly ash concrete and their explanation is reproduced below:

> 'Overall, in the high-volume fly ash system, physical and chemical factors combine at all ages to densify and bind the paste. In the early stages, the physical effect of space filling and the chemical contribution of the formation of ettringite or related sulphoaluminate production are important factors in strength development. In the longer term, hydration reactions dominate as silico-aluminate binders are generated by reactions involving fly ash. The following observations indicate that chemical mechanisms are involved in late-age strength development in the Portland cement–fly ash paste:
>
> (i) Levels of bound water substantially in excess of those consistent with the hydration of Portland cement are present in the fly ash paste at ages beyond 28 d. This is taken to indicate the formation of silanol groups in the fly ash glass components.
> (ii) The pore water solutions at curing ages beyond 1 d have high concentrations of sodium, potassium and hydroxyl ions. These conditions are ideally suited to hydrolytic attack on fly ash glasses to produce silanol and related species.
> (iii) There is considerable evidence for a dynamic mass transfer of Na and K between solid and solution phases. This would be consistent with ion-exchange mechanisms occurring at silanol and siloxane sites in partly hydrolyzed fly ash glasses, or in gels precipitated from siloxane oligomers.
>
> It is suggested that a mechanism similar to the alkali-activation of alumino-silicates originally proposed by Purdon in 1940 is active in

the fly ash pastes with the pore water acting as a vehicle for transfer of alkali ions from cement or fly ash into the fly ash glasses. Many glass types are known to be hydrolyzed by strongly alkaline solutions with the formation of hydroxylated polymeric gels containing silica, ionic $Si\text{–}O^- \ldots Na^+$, or Al–OH groups. Similar reaction products have been found in previous work where fly ash was subjected to acidic hydrolysis.

Though the early attack on the fly ash glasses may derive from pore solutions of high Na and K content, it is probable that exchange with Ca^{2+} ions may subsequently proceed with the precipitation of C–S–H gel-like materials. These secondary processes may be responsible for the apparent decline in bound water content and the indicated gel-shrinkage responsible for the increase in pore volume at late ages.

While this investigation has indicated the importance of one or more chemical mechanisms in the reaction of fly ash in Portland cement systems, it has also raised many questions about the role of alkali ions in the pozzolanic process. Further work is needed to elucidate the complex reaction sequences and processes that are undoubtedly involved. [sic.]'

Granulated blast-furnace slags

In Canada, granulated/pelletized blast-furnace slags are available only in Ontario, and current production is about 100 000 t in northern Ontario and about 250 000 t in southern Ontario. Most of the slag from northern Ontario is being used for cementitious mine backfill in the Sudbury basin, whereas the pelletized slag from near Toronto is being used as a separately batched ingredient at concrete batch plants.

Mexico used to produce relatively small amounts of blended cements incorporating granulated slag, however, recently, the environmental concerns resulted in closing of the blast-furnace operation in Monterrey, which in turn eliminated the availability of granulated blast-furnace slag.

In the US the current granulated slag production is about 1×10^6 t and most of this is from the Sparrows point facility located near Baltimore, Maryland. Two new plants are nearing completion, one in West Virginia and the other near Chicago. This will almost double the availability of slag to about 2×10^6 t. Most of the blast furnace slag is being used as a separately batched ingredient at concrete batch plants.

Similar to the high-volume fly ash concrete, CANMET has developed structural concrete with high-volumes of ground granulated blast-furnace slag, which has excellent strength both at one day old, and at later ages.[4] Typical mixture proportions, properties of fresh concrete and mechanical properties of high-volume slag concrete are given below.

Mixture proportions		*Batch quantities*
ASTM Type I Cement		121 kg m^{-3}
Blast-furnace slag		181 kg m^{-3}
Water		109 kg m^{-3}
Coarse aggregate (19 mm max)		1137 kg m^{-3}
Fine aggregate		757 kg m^{-3}
Air-entraining admixture		113 ml m^{-3}
Superplasticizer		5·2 kg m^{-3}
Properties of fresh concrete		
Slump		200 mm
Unit weight		2305 kg m^{-3}
Air content		5·6%
Mechanical properties		
Compressive strength	1 day:	4·3 MPa
	7 days:	25·6 MPa
	28 days:	45·6 MPa
	91 days:	49·9 MPa
Flexural strength	7 days:	7·0 MPa
Young's modulus (*E*)	28 days:	42·3 GPa
Resistance to chloride-ion penetration		325 C

Silica fume

The sources of silica fume in Canada are located in Quebec, with a total production of about 15 000 t year^{-1}. As mentioned elsewhere, most of the fume is being used to produce silica fume blended cements.

No silica fume is available in Mexico.

In the US, silica fume production is about 100 000 t annually. Various forms of silica fume, such as slurry or in a compacted form are being used as cement replacement or to produce concrete of very low permeability for use in bridge decks and parking structures.

HISTORICAL BACKGROUND ON THE USE OF BLENDED CEMENTS IN THE USA

According to Mather,[5] the history of blended Portland/slag cement goes back to 1900, when the

Corp. of Engineers investigated the manufacture and properties of slag (pozzolan) cement. It was concluded that '...The cement was well adapted for use in sea water... and in the interior of heavy masses of masonry or concrete'. However, it was only in the early 50s that Portland blast-furnace slag cement was manufactured commercially in the USA by several US cement companies. This was later discontinued, probably due to marketing concerns and corporate strategy.

PRESENT SITUATION IN THE USA AND CANADA

According to the information available to the authors, presently there is only one cement plant in the USA which is producing blended cements, and that is only in a limited quantity. The Dundee Cement Company, located in Dundee, Michigan, markets fly ash blended cement (20% ASTM Class F fly ash; 80% normal Portland cement) meeting the requirements of IP cements of the ASTM Standard C595, which covers the use of blended cements in the USA. The production, which started in 1972, ranges from 50 000 to 200 000 t annually.

In the market place this cement competes with ASTM Type II cement, a moderately sulphate-resistant cement.

Fly ash or slag blended cements have not been manufactured in Canada. Silica fume blended cements became available in 1983 and these are described in detail later.

BLENDED CEMENTS VS ADDITIONS AT A BATCH PLANT

Unlike Europe and Russia, in Canada and the USA the slags/fly ash blended cements have not found much acceptance. Instead, the granulated BF slag or fly ash is added as a separate ingredient at a concrete batch plant. The rationale is that this allows the concrete producer to supply concrete incorporating different percentages of slag or fly ash. For example, in Canada and in the northern USA, slag percentage in concrete is limited to about 20% in the winter months, because of the very low early-age strength of the slag/Portland cement system at low temperatures. This percentage is generally increased to about 35% in the summer when ambient temperatures are of the order of 25–30°C. The only exception to the above is the appearance of silica fume blended cements. The rationale advanced is that silica fume, because of its extreme fineness, is difficult to transport and handle, and creates environmental problems, though these are being overcome by the production of compacted silica fume.

In addition, until recently, cement producers have been reluctant to produce blended cements because they had sufficient kiln capacity to meet the demands. Also, there were no environmental imperatives to do so.

SPECIFICATIONS FOR BLENDED CEMENTS

Both ASTM and CSA have published specifications for blended cements. ASTM C595 covers the specifications for blended cements in the USA and CSA Standard CAN3-A362 covers the use of blended cement in Canada.[6,7] The relevant portions of these specifications and standards are reproduced below together with the definition of blended cements, as given by ASTM C219.

Definition of blended hydraulic cements

ASTM C219 defines blended hydraulic cement as follows:[8]

> 'A hydraulic cement consisting of two or more inorganic constituents (at least one of which is not Portland cement or Portland cement clinker) which separately or in combination contribute to the strength gaining properties of the cement (made with or without other constituents, processing additions and functional, additions) by intergrinding or other blending [sic]'.

ASTM C595: Standard specifications for blended hydraulic cements

The type of blended cements covered by this specification are as follows.

Classification

(1) *Portland blast-furnace slag cement* — one type with three optional provisions is covered as follows:

- (a) *Type IS* — Portland blast-furnace slag cement for use in general concrete construction.
- (b) Moderate sulfate resistance, air entraining, moderate heat of hydration, or any combination, may be specified

by adding the suffixes (MS), (A) or (MH).

(2) *Portland-pozzolan cement* — two types, each with three optional provisions, are covered, as follows:

(a) *Type IP* — Portland-pozzolan cement for use in general concrete construction.
(b) Moderate sulfate resistance, air entrainment, moderate heat of hydration, or any combination, may be specified by adding the suffixes (MS), (A) or (MH).
(c) *Type P* — Portland-pozzolan cement for use in concrete construction where high strengths at early ages are not required.
(d) Moderate sulfate resistance, air entrainment, low heat of hydration, or any combination, may be specified by adding the suffixes (MS), (A) or (LH).

(3) *Slag cement* — one type is covered as follows:
(a) *Type S* — slag cement for use in combination with Portland cement in making concrete and in combination with hydrated lime in making masonry mortar.
(b) Air entrainment may be specified by adding the suffix (A).

(4) *Pozzolan-modified Portland cement* — one type is covered as follows:
(a) *Type I(PM)* — pozzolan-modified Portland cement for use in general concrete construction.
(b) Moderate sulfate resistance, air entrainment, moderate heat of hydration, or any combination, may be specified by adding the suffixes (MS), (A) or (MH).
(c) Pozzolan-modified Portland cement should not be used when special characteristics attributable to the larger quantities of pozzolan in Portland-pozzolan cement are desired.

(5) *Slag-modified Portland cement* — one type is covered as follows:
(a) *Type I(SM)* — slag-modified Portland cement for use in general concrete construction.
(b) Moderate sulfate resistance, air entrainment, moderate heat of hydration, or any combination, may be specified by adding the suffixes (MS), (A) or (MH).
(c) Slag-modified Portland cement should not be used when special characteristics attributable to the larger quantities of slag in Portland blast-furnace slag cements are desired.

(6) A given weight of blended cement has a larger absolute volume than the same weight of Portland cement. This should be taken into consideration in purchasing cements and in proportioning concrete mixtures.

Chemical requirements

The chemical requirements for the blended cements are given in Table 1.

Physical requirements

The physical requirements for the blended cements are given in Table 2.

Table 1. Chemical requirements (ASTM C595)

Cement type	*I(SM), I(SM)-A, IS, IS-A*	*S.SA*	*I(PM), I(PM)-A, P, PA, IP, IP-A*
Magnesium oxide (MgO), max (%)	—	—	5·0
Sulfur reported as sulfate (SO_3), max (%†)	3·0	4·0	4·0
Sulfide sulfur (S), max (%)	2·0	2·0	—
Insoluble residue, max (%)	1·0	1·0	—
Loss on ignition, max (%)	3·0	4·0	5·0
Water-soluble alkali, max (%)	—	0·03‡	—

†When it has been demonstrated by Test Method C563 that the optimum SO_3 exceeds a value 0·5% less than the specification limit, an additional amount of SO_3 is permissible provided that when the cement with the additional calcium sulfate is tested by Test Method C265, the calcium sulfate in the hydrated mortar at 24 ± 1/4 h, expressed as SO_3, does not exceed 0·50 g litre^{-1}. When the manufacturer supplies cement under this provision, he will, upon request, supply supporting data to the purchaser.
‡Applicable only when the cement is specified to be nonstaining to limestone. The amount and nature of the staining material in limestone varies with the stone. The alkali in any cement may, therefore, induce markedly different staining on different types of stone, even though the stone may have come apparently from the same source. The amount of alkali permitted by the specification should not cause staining unless stone high in staining material has been used, or unless insufficient means have been used to prevent infiltration of water into the masonry.

Table 2. Physical requirements (ASTM C595)

Cement type	*I(SM), IS, I(PM), IP*	*I(SM)-A, IS-A, I(PM)-A, IP-A*	*IS(MS), IP(MS)*	*IS-A(MS), IP-A(MS)*	*S*	*SA*	*P*	*PA*
Fineness†								
Autoclave expansion, max (%)‡	0·50	0·50	0·50	0·50	0·50	0·50	0·50	0·50
Autoclave contraction, max (%)	0·20	0·20	0·20	0·20	0·20	0·20	0·20	0·20
Time of setting, Vicat test:§								
set (min), not less than	45	45	45	45	45	45	45	45
set (h), not more than	7	7	7	7	7	7	7	7
Air content of mortar (Method C185), (vol. %)	12 max	19 ± 3	12 max	19 ± 3	12 max	19 ± 3	12 max	19 ± 3
Compressive strength (min), psi (MPa):								
three days	1800 (12·4)	1450 (9·9)	1500 (10·3)	1200 (8·3)	—	—	—	—
seven days	2800 (19·5)	2250 (15·5)	2500 (17·2)	2000 (13·8)	600 (4·1)	500 (3·4)	1500 (10·3)	1250 (8·6)
28 days	3500 (24·1)	2800 (19·3)	3500 (24·1)	2800 (19·3)	1500 (10·3)	1250 (8·6)	3000 (20·7)	2500 (17·2)
Heat of hydration:¶								
seven days, max, cal g^{-1}	70	70	70	70	—	—	60	60
(kJ kg^{-1})	(293)	(293)	(293)	(293)	—	—	(251)	(251)
28 days, max, cal g^{-1}	80	80	80	80			70	70
(kJ kg^{-1})	(335)	(335)	(335)	(335)			(293)	(293)
Water requirement, max (wt% of cement)	—	—	—	—	—	—	64	56
Drying shrinkage, max (%)	—	—	—	—	—	—	0·15	0·15
Mortar expansion:″								
at age of 14 days, max (%)	0·020	0·020	0·020	0·020	0·020	0·020	0·020	0·020
at age of eight weeks, max (%)	0·060	0·060	0·060	0·060	0·060	0·060	0·060	0·060
Sulfate resistance:								
expansion at 180 days, max (%)			0·10	0·10				

†Both amounts retained when wet sieved on a 45 μm (No. 325) sieve and specific surface by air permeability apparatus (cm^2 g^{-1}) shall be reported on all mill test reports requested under 14·4.
‡The specimens shall remain firm and hard and show no signs of distortion, cracking, checking, pitting, or disintegration when subjected to the autoclave expansion test.
§Time of setting refers to initial setting time in Method C191.
¶Applicable only when moderate (MH) or low (LH) heat of hydration is specified, in which case the strength requirements shall be 80% of the values shown in the table.
″The test for mortar expansion is an optional requirement to be applied only at the purchaser's request and should not be requested unless the cement will be used with alkali-reactive aggregate.

Table 3. Chemical requirements (CSA CAN3-A362)

Property	*Type*					
	10	*10S*	*10SM*	*10F*	*10FM*	*10SF*
	Maximum (%)					
Sulfur trioxide	3·0†	3·0†	3·0†	3·0†	3·0†	3·0†
Sulphide sulphur	—	2·0	1·0	—	—	—
Insoluble residue	1·0	1·0	1·0	—	—	—
Loss on ignition	3·0	3·0	3·0	6·0	4·5	3·5
Magnesium oxide	—	—	—	5·0	5·0	5·0

†This limit may be exceeded provided that the cement exhibits expansion not in excess of 0·020% at 14 days when tested in accordance with Clause 7.5.5. of CSA Standard CAN/CSA-A5.

CSA CAN3-A362: Blended hydraulic cements

The blended cements covered by the above specifications are classified as follows:

Classification

Portland blast-furnace slag cement, Type 10S — a product consisting of Portland cement and finely ground, granulated blast-furnace slag in which the slag is between 25 and 70% of the total mass and to which no processing additions have been made except as provided in Clause 3.1 of the above standard.

Slag-modified Portland cement, Type 10SM — a product consisting of Portland cement and finely ground, granulated blast-furnace slag in which the slag is less than 25% of the total mass and to which no processing additions have been made except as provided in Clause 3.1.

Portland fly ash cement, Type 10F — a product consisting of Portland cement and fly ash in which the fly ash is between 15 and 40% of the total mass and to which no processing additions have been made except as provided in Clause 3.1.

Fly ash-modified Portland cement, Type 10FM — a product consisting of Portland cement and fly ash in which the fly ash is less than 15% of the total mass and to which no processing additions have been made except as provided in Clause 3.1.

Portland silica fume cement, Type 10SF — a product consisting of Portland cement and silica fume in which the silica fume shall not exceed 10% of the total mass and to which no processing additions have been made except as provided in Clause 3.1.

Note
The blended products defined in Clause 2.2 may be produced by either of the following methods, or a combination of both:

(a) intergrinding Portland cement clinker and granulated blast-furnace slag, fly ash, or silica fume; or
(b) blending Portland cement and finely ground granulated blast-furnace slag, fly ash, or silica fume.

The attainment of an intimate and uniform blend, in the dry state, of two or more types of fine material, is difficult. Consequently, adequate equipment and controls should be provided by the manufacturer.

Chemical requirements
The chemical requirements for the blended cements covered by the above specifications are shown in Table 3.

Physical requirements
The physical requirements covered by the above specifications are shown in Table 4.

Table 4. Physical requirements (CSA CAN3-A362)

Property	*Type*					
	10	*10S*	*10SM*	*10F*	*10FM*	*10SF*
Fineness						
wet-sieved on 45 μm sieve, maximum retained (%)	28·0	24·0	24·0	24·0	24·0	24·0
Soundness†						
maximum expansion (%)‡	1·0	0·8	0·8	0·8	0·8	0·8
Setting time (min)						
min	45	45	45	45	45	45
max	360	480	360	480	360	360
Compressive strength§						
min (MPa) for the following ages at test:						
three days	12·5	9·0	12·0	9·0	12·0	12·0
seven days	18·0	15·0	18·0	15·0	18·0	13·0
28 days	26·5	26·0¶	26·0	26·0¶	26·0	26·0
Heat of hydration						
seven days max, $kJ\ kg^{-1}$″	—	300	—	300	—	—

†See Clause 3.3.2.
‡The specimens shall remain firm and hard and show no signs of distortion, cracking, checking, pitting, or disintegration when subjected to the autoclave test.
§The strength at any age shall be higher than that at the preceding age.
¶When moderate heat of hydration is required, the minimum 28-day strength requirements shall be 80% of the value shown in the table and the 91-day strength shall be a minimum of 26·0 MPa.
″Applicable at the purchaser's option, when moderate heat of hydration is required, the heat of hydration shall be determined in accordance with ASTM Standard C186. Errors in C186 test results can occur when testing blended hydraulic cements, due to the effect of oxidation of sulphides in slags or loss on ignition or due to incomplete solubility of fly ash or silica fumes in nitric acid. The magnitude of these errors is unknown at this time.

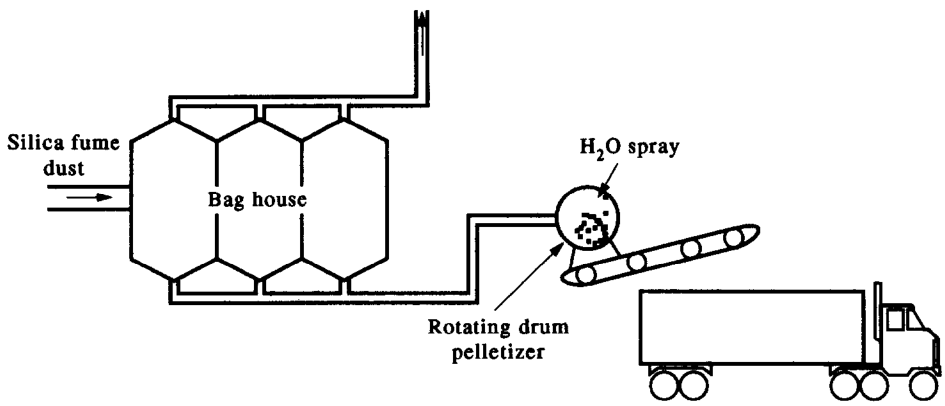

Fig. 1. Pelletizing of silica fume for producing interground blended cement. From Ref. 9.

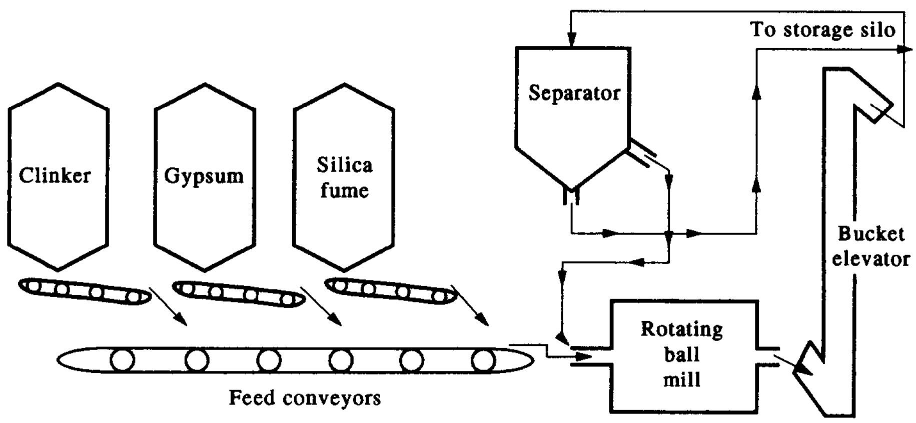

Fig. 2. Intergrinding of silica fume cement. From Ref. 9.

Table 5. Chemical and physical properties of silica fume cements[9]

Parameter	*Units*	*Silica fume*	*CSA cement type 10*	*Type 10SF (interground)*	*Type 10+SF lab blended*
Silica fume content	%	100	0	7·5	7·5
Alkalis	%	—	0·88	0·96	—
C_3A	%	—	11·0	10·2	—
Colour	—	—	36	36	37
Autoclave expansion	%	—	0·01	0·03	−0·01
Sulphate expansion	%	—	0·004	0·002	−0·002
Entrained air	%	—	—	13·2	16·6
Fineness	$m^2 kg^{-1}$	16600†	373‡	526‡	570‡
45 μm (passing)	%	100	86·5	88·8	83·9
LOI	%	1·69	2·66	1·58	2·73
Free lime	%	—	0·60	0·75	0·63
SiO_2	%	94·0	19·93	25·79	25·17
Vicat initial set	min	—	135	105	125
Compressive strength (mortar cubes)					
Three-day	MPa	—	27·3	27·8	26·9
Seven-day	MPa	—	31·9	35·5	33·4
28-day	MPa	—	38·3	46·9	43·1

†By BET method.
‡By Blaine method.

INTERGROUND SILICA FUME BLENDED CEMENT

Interground blended silica fume cement meeting the requirements of CSA Standard CAN-362 Type 105F has been available in Canada since 1983. Presently, there are two cement plants producing the above type of cement: one located in Brookfield, NS and the other at St Constant, Quebec.[9] The production is modest and totals about 80000 t $year^{-1}$ for both plants. The silica fume content of the blend is about 7·5%, which is well below the limit of 10% specified in the Canadian standard.

Because silica fume is very fine (specific surface by BET = 20000 $m^2\ kg^{-1}$ Blaine vs 400 $m^2\ kg^{-1}$ by Blaine method for cement) it is difficult to handle and transport. To overcome this problem, the fume is pelletized by the use of water spray into a rotating drum (Fig. 1). The resulting pellets range in size up to 15 mm. The interground cement is then manufactured from clinker, gypsum and pelletized silica fume, with the three materials being fed into a ball mill in appropriate proportions (Fig. 2).

Table 5 gives comparative data on chemical and physical properties of CSA Type 10 cemen silica fume, interground silica fume (CSA Type 10 SF) and a laboratory blended (CSA Type 10) silica fume. The comparative data on compressive strength of concrete made with the above two cements is given in Table 6.

Table 6. Compressive strength of concrete[9]

Compressive strength, (MPa)	*Type 10SF (interground)*	*Type 10 + SF lab blended*
One-day	36·5	38·3
Seven-day	50·7	56·4
28-day	62·6	64·9

Mix contained 390 kg of cement (including silica fume).

SILICA FUME BLENDED CEMENT (HSF)

In the mid-1980s, St Lawrence Cement Company Ltd commenced research to market blended silica fume cements and this cement, known as HSF cement, was being produced in Quebec City and commercialized in 1989.[10] The current annual production is approximately 70000 t $year^{-1}$. Th blended cement contains 8·5% silica fume.

Tables 7 and 8 give comparative data on the chemical analysis and physical properties of a typical CSA Type 10, normal Portland cement and the silica fume blended HSF cement. The significant differences between the two cements are their fineness and the 24 h compressive strength. Silica fume blended HSF cement has a Blaine fineness of 560 $m^2\ kg^{-1}$, compared to 380 $m^2\ kg^{-1}$ for the Type 10 cement, and the compressive strengths of mortar cubes made with the former cement are significantly higher than those cubes made with the latter cement.

Table 7. Chemical analysis of cements[10]

Component	*CSA Type 10 (%)*	*Type HSF (%)*
SiO_2	20·60	28·00
Al_2O_3	4·30	4·00
Fe_2O_3	1·80	1·60
CaO	62·60	58·00
MgO	2·80	2·80
SO_3	2·80	2·80
Na_2O (equiv.)	0·73	0·75

Table 8. Physical properties of cements

Properties	*CSA Type 10*	*Type HSF*
Initial set	160 min	160 min
Final set	300 min	—
% Finer than 45 μm	90·4	94·0
Blaine fineness	380 $m^2\ kg^{-1}$	560 $m^2\ kg^{-1}$
Soundness		
Autoclave expansion	0·12%	0·08%
Compressive strength on 50 mm cubes		
24 h	—	—
Three days	22·0 MPa	26·0 MPa
Seven days	28·0 MPa	34·0 MPa
28 days	35·0 MPa	48·0 MPa

The comparative data on the mixture proportions and the properties of fresh concrete, made with the control and the HSF cement, are given in Tables 9 and 10. The data on the mechanical properties of the two concretes are shown in Tables 11 and 12. The relative performance of the two types of concrete when subjected to abrasion is shown in Fig. 3.

The significant point to be noted is the high seven- and 98-day strengths of the concrete made with HSF cement.

Table 9. Mixture proportions[10]

Mixture no.	*CSA Cement type*	*Water/ cementitious*	*Cement content (kg m^{-3})*	*Coarse aggregate (kg m^{-3})*	*Fine aggregate (kg m^{-3})*	*AEA (ml m^{-3})*	*HRWR (ml m^{-3})*	*WRA (ml m^{-3})*
A	10	0·45	360	975†	820¶	70	1580	—
B	10	0·30	550	975†	655¶	115	5500	—
C	HSF	0·30	550	975†	650¶	130	5500	—
D	HSF	0·40	425	1124‡	644″	197	5182	1295
E	HSF	0·40	410	1075§	635″	190	4000	1250

†Quarried quartzite.
‡Quarried limestone.
§Screened granite (partially crushed).
¶Natural quartz sand.
″Natural and partially crushed granite sand.

Table 10. Properties of fresh concrete[10]

Mixture no.	*CSA cement type*	*Water/ cementitious*	*Cement content (kg m^{-3})*	*Slump (mm)*	*Air content (%)*	*Mass density (kg m^{-3})*	*Time of set (h:min)*	
							Initial	*Final*
A	10	0·45	360	65	6·6	2285	6:35	8:05
B	10	0·30	550	185	6·2	2330	10:00	11:40
C	HSF	0·30	550	185	6·4	2310	9:40	11:00
D	HSF	0·40	425	190	4·2	2365	—	—
E	HSF	0·40	410	200	6·6	2280	8:54	10:20

Table 11. Properties of hardened concrete: compressive strength and modulus of elasticity[10]

Mixture no.	*CSA cement type*	*Water/ cementitious*	*Cement content (kg m^{-3})*	*Compressive strength*					*Modulus of elasticity (GPa) @ 28 days*
				1 day	*7 days*	*28 days*	*91 days*	*365 days*	
A	10	0·45	360	11·5	37·1	44·3	51·1	58·4	29·7
B	10	0·30	550	43·3	56·5	67·6	74·4	84·6	32·5
C	HSF	0·30	550	31·1	60·0	69·8	74·0	79·6	40·7
D	HSF	0·40	425	31·4	52·2	69·4	76·0	—	43·9
E	HSF	0·40	410	31·7	52·9	63·0	68·2	—	31·7

Table 12. Properties of hardened concrete: flexural strength[10]

Mixture no.	*Cement type*	*Water/ cementitious*	*Cement content (kg m^{-3})*	*Flexural strength*			
				1 day	*7 days*	*28 days*	*91 days*
A	10	0·45	360	2·7	6·0	6·3	7·3
B	10	0·30	550	5·7	8·4	8·8	11·1
C	HSF	0·30	550	4·5	3·6	11·2	11·7
D	HSF	0·40	425	—	—	8·6	10·7
E	HSF	0·40	410	—	—	7·7	10·0

BLENDED CEMENTS MADE WITH CONTROLLED PARTICLE SIZE DISTRIBUTIONS

Those blended cements which incorporate pozzolans or granulated blast-furnace slags usually develop mechanical properties more slowly than comparable Portland cements. This problem can be resolved by the judicious selection of mixture proportions. Helmuth *et al.*[11] have suggested a novel approach to overcome the above problem. This consists of grinding the Portland cements to very high specific areas and then using these cements in the blended systems. When so used, the controlled particle size distribution (CPSD) cements compensate for the relatively slow reactions of fly ashes and granulated slags. Helmuth *et al.*[11] investigated 45 such blended cements made with two different CPSD cements, one normally ground Portland cement, six different powdered mineral admixtures, two water reducing admixtures and one accelerating admixture. Table 13 shows specific surface areas, densities and particle size distributions of the various materials used in the investigation. Cements labelled 128 and 137 are CPSD cements being 95% finer than 23 and 31 μm, respectively.

Tables 14–16 show test data on mixture characteristics, mechanical properties and drying shrinkage of concrete made with normal Portland-blended cements, and blended cements made with CPSD.

Based upon the research, Helmuth *et al.*[11] concluded as follows:

> 'Cement paste, mortar and concretes made with CPSD blended cements have been shown to have properties approximately equal to or superior to those made with normally ground blended cements of the same compositions. The major benefit in the use of controlled particle size distribution blended cements may be to produce concretes with properties, especially at early ages, which are comparable to those obtained with Portland cements. In this way, blended cements may become more readily acceptable to more users. Since the use of blended cements is in itself a major energy savings measure, wider use of higher early strength blended cements could contribute to energy conservation in the United States [sic]'.

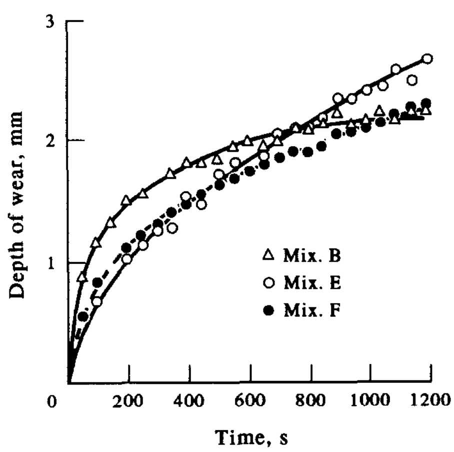

Fig. 3. Abrasion resistance of concrete made with CSA Type 10 and silica fume blended cements (HSF). From reference 10.

Table 13. Specific surface areas, densities and particle size distribution data[11]

Material	*BSS (m^2 kg)*	*Density (g cm^{-3})*	*Cumulative mass % finer than particle size indicated size (μm)*							*95–5% Size range (μm)*
			100	*50*	*20*	*10*	*5*	*2*	*1*	
Portland cement 119†	345	3·15	99	94	60	37	20	8	3	54–1·5
Portland cement 128‡	323	3·15	99	99	90	44	19	5	2	23–1·9
Portland cement 173‡	313	3·15	99	98	71	37	17	5	2	31–1·9
Class C fly ash	418	2·67	99	94	78	55	27	6	1	54–1·9
Class F fly ash	434	2·47	89	87	64	43	21	5	1	100–2·1
Silica fume	5500	2·34	100	99	99	98	96	91	82	3·2–0·1
Ground limestone	810	2·71	99	96	82	66	44	21	9	46–0·7
Ground granulated BFS	449	2·94	98	90	64	44	27	11	4	74–1·1
Classified granulated BFS	112	2·94	86	40	11	5	4	2	1	118–15

†Normally ground Portland cement used to make blended cements used as controls.
‡CPSD Portland cement.

Table 14. Concrete mix characteristics[11]

Cement	W/C	Batch quantities† (lb yd^{-3})				Fines (%)	Slump (in.)†	Entrapped air (%)
		Cement	Water	Aggregate				
				Fine	Coarse			
119P‡	0·50	499	250	1248	2100	37·5	2·9	1·0
137P	0·50	526	262	1214	2072	37·5	2·4	1·0
128P	0·50	536	267	1224	2012	37·5	4·0	0·8
119S‡	0·50	508	254	1367	1957	41·0	3·3	1·5
128S	0·50	499	249	1288	2053	39·0	2·0	1·6

†Metric conversions: 1 lb yd^{-3} = 0·5933 kg m^{-3}; 1 in. = 25·4 mm.
‡Blended cement made with normally ground Portland cement.

Table 15. Mechanical properties of blended cements concrete moist cured at 23°C (73°F)[11]

Cement	Compressive strength (psi)†						Flexural strength (psi)†			Elastic modulus (10^6 psi)†
	1-day	3-day	7-day	28-day	90-day	365-day	3-day	7-day	28-day	28-day
119P‡	1030	2090	3040	4920	6160	7130	450	600	740	4·2
137P	870	2390	3550	4990	6330	6710	480	650	750	4·3
128P	1040	2530	3680	5150	5950	7200	500	700	860	4·5
119S‡	850	2070	3160	5190	5630	7030	440	720	870	4·5
128S	890	2310	3310	4980	5840	6760	500	680	870	4·5

†Metric conversion: 1 psi = 0·0006895 MPa.
‡Blended cement made with normally ground Portland cement.

Table 16. Drying shrinkage of BC concretes[11]

Cement	Mineral admixture	Drying shrinkage (%)					
		One week	Four weeks	Two months	Four months	Eight months	12 months
119P†	Fly ash	0·018	0·035	0·043	0·054	0·058	0·063
137P	Fly ash	0·018	0·039	0·047	0·056	0·061	0·065
128P	Fly ash	0·020	0·041	0·049	0·060	0·064	0·068
119S†	Slag	0·018	0·038	0·045	0·058	0·065	0·066
128S	Slag	0·012	0·029	0·040	0·050	0·059	0·059

†Blended cement made with normally ground Portland cement.

As of now, there is no commercialization of the above type of blended cements.

CONCLUDING REMARKS

In spite of the excellent specifications and standards, the production of blended cements in Canada and the USA is only marginal in comparison with the total cement production. Instead, the North American concrete industry has chosen to use the supplementary cementing materials as separate ingredients at concrete batch plants, and their use is on the rise. Current industrial trends do not indicate any departure from this in the forseeable future. The recent development of high-volume fly ash and high-volume slag concretes and the developmental blended cements with CPSDs will lead to significant increases in the use of supplementary cementing materials in concrete either as a separately batched material or in blended cements.

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