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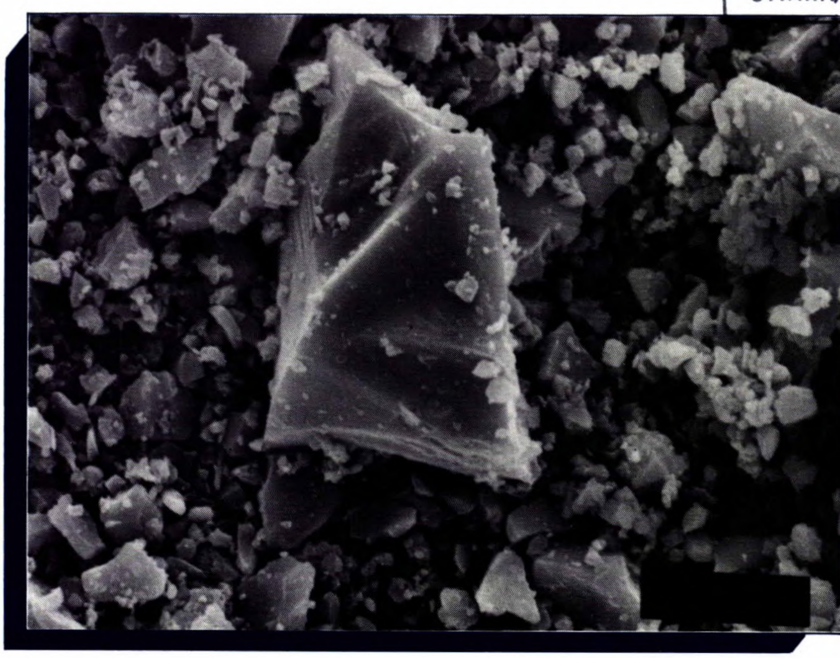
COMPILATION OF ABSTRACTS OF PAPERS FROM RECENT INTERNATIONAL CONFERENCES AND SYMPOSIA ON FERROUS AND NON-FERROUS SLAGS IN CONCRETE

E. Douglas and V.M. Malhotra
MINERAL PROCESSING LABORATORY



MINERAL SCIENCES LABORATORIES
SPECIAL PUBLICATION 88-13E

COVER PHOTO

Microphotograph showing the morphology of granulated blast–furnace slag ground to 6000 cm^2/g.

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May 1988

Available in Canada through

Associated Bookstores
and other booksellers

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Ottawa, Canada K1A 0S9

Catalogue No. M38-15/88-13E
ISBN 0-660-13124-2

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E. Douglas* and V.M. Malhotra**

Synopsis

This report is a compilation of abstracts of papers from recent international conferences and symposia on the use of ferrous and non-ferrous slags in concrete. The conferences covered include those held in Europe, North America and South America between 1980 and 1988. Papers for this report were selected on the basis of their direct relevance to the use of slags in concrete. The abstracts are given in chronological order and include keywords.

COMPILATION DE RÉSUMÉS DE COMMUNICATIONS PRÉSENTÉES LORS DE CONFÉRENCES ET SYMPOSIUMS INTERNATIONAUX RÉCENTS SUR LES LAITIERS FERREUX ET NON FERREUX DANS LE BÉTON

E. Douglas* et V.M. Malhotra**

Résumé

Ce rapport est le résultat d'une compilation des résumés de communications présentées lors de conférences et de symposiums récents sur l'utilisation des laitiers ferreux et non ferreux dans le béton. Les conférences couvertes comprennent celles qui ont eu lieu en Europe, en Amérique du Nord et en Amérique du Sud entre 1980 et 1988. Les communications mentionnées dans ce rapport ont été choisies en fonction de leur pertinence pour ce qui est de l'utilisation des laitiers dans le béton. Les résumés sont présentés par ordre chronologique. Les mots clés sont indiqués.

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KEYWORDS

abrasion; abrasion resistance; accelerated tests; acid resistance; adiabatic conditions; admixtures; aggregate; aggregate gradation; air-cooled slag; air-entraining agents; air-entrainment; alkali-activation; alkali-aggregate expansion; alkali-aggregate reactions; alkalis; alkali-silica reactions; Australia; autoclave expansion; backfilling; basic oxygen-blown converter steel slag; basic oxygen steel slags; batching; bending strength; binders (material); blast-furnace slag cement; blast-furnace slags; bleeding (concrete); blended cements; blending; BOF slag; Britain; calcium hydroxides; Canada; carbonation; cement; cement content; cementitious materials; cement pastes; Cemsave System; cesium; chemical analysis; chemical moduli; chloride ion penetration; chloride permeability; chlorides; clinker mineralogy; compressive creep; compressive strength; concrete; concrete durability; cooling; copper; copper slags; corrosion; corrosion resistance; creep; crystallization; curing; de-icing chemicals; diffusion; drying shrinkage; durability; early strength development; erosion; evaluation; expansion; exposure; F-cement; FGD gypsum; field tests; fine aggregates; fineness; Finland, flash set; flexural strength; fly ash; formwork; freezing and thawing; freeze-thaw; freeze-thaw durability; frost resistance; glass content; granulated blast-furnace slag; granulating; granulation; granulated/pelletized slags; grinding; grinding (comminution); ground granulated blast-furnace slag; ground pelletized slag; heat of hydration; high-strength concretes; hydration; hydraulic activity; hydration processes; hydraulicity; in situ strength; iron; Japan; lead (metal); lightweight aggregate; lightweight concrete; low porosity; manufacturing; marine atmospheres; marine environment; mass concrete; mechanical properties; mercury porosimetry; micro-concrete; microcracking; microstructure; mineralogy; mines backfill; mines (excavations); mixing; mix proportioning; modulus; modulus of elasticity; mortar; mortars (material); mortar strength; natural pozzolans; nickel; nickel slags; non-evaporable water; nonferrous slags; open-hearth slag; pelletized blast-furnace slag; pelletized slag; pellets; performance; permeability; placeability; plasticizers; pore size distribution; porosimetry; porosity; portland blast-furnace cement concrete; portland cement replacements; portland cements; portland slag cements; pozzolan; pozzolan cements; pozzolanic activity; pozzolanic properties; pre-blended cements; precast; precast concrete; preparation; ready-mixed concrete; refractive index; regression analysis; reinforced concrete; review; sands; seawater; setting times; shrinkage; silica; silica flour; slag; slag activity; slag activity index; slag cements; slag granulation processes; slump loss; slurries; sodium chloride; sorption; soundness; specifications; standards; statistical analysis; steam curing; strength; sulphate; sulphate attack; sulphate content; sulphate resistance; sulphate-resisting cements; superplasticizer; supersulphated cement; supplementary cementing materials; surface hardness; surface scaling; temperature; temperature effects; temperature rise (in concrete); tensile strength; tertiary blends; tests; thermal cracking; thermogravimetry; three-part blends; variability; vitrified slags; volumetric stability; water; water cement ratio; water-reducing agents; weathering; wetting and drying tests; work practices; workability X-ray diffraction;.

CONTENTS

INTRODUCTION

In the past seven years a number of conferences and symposia have been conducted on the use of supplementary cementing materials in portland cement concrete. The most notable have been the following:

- Seventh International Congress on the Chemistry of Cement, Paris, France, 1980.
- Fifth International Symposium on Concrete Technology, Nuevo Leon, Mexico, March 1981.
- International Conference on Slags and Blended Cements, Mons, Belgium, September 1981.
- Symposium on Fly Ash Incorporation in Hydrated Cement Systems, Materials Research Society, Boston, Massachusetts, U.S.A., November 1981.
- International Conference on Slag and Blended Cements, University of Alabama, Birmingham, Alabama, U.S.A., February 1982.
- EPRI Workshop on Research and Development Needs for Use of Fly Ash in Cement and Concrete, Palo Alto, California, U.S.A., March 3–5, 1982. (Proceedings EPRI Report, CS–2616–SR, September 1982.)
- Sixth International Symposium on Fly Ash Utilization, Reno, Nevada, U.S.A., March 1982.
- International Symposium on the Use of PFA in Concrete, University of Leeds, England, April 14–16, 1982.
- First CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By–Products in Concrete, Montebello, Quebec, Canada, July 31 – August 5, 1983. (Published as ACI Special Publication SP–79, American Concrete Institute, Detroit, Michigan, U.S.A., edited by V.M. Malhotra.)
- Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete, Madrid, Spain, April 21–25, 1986. (Published as ACI Special Publication SP–91, American Concrete Institute, Detroit, Michigan, U.S.A., edited by V.M. Malhotra.)
- Eighth International Congress on the Chemistry of Cement, Rio de Janeiro, Brazil, September 22–27, 1986.
- International Workshop on Granulated Blast–Furnace Slag in Concrete, Toronto, Ontario, Canada, October 22–23, 1987.

Recent compilations of abstracts of selected papers from these sources, relating to the use of fly ash and condensed silica fume in concrete, have been prepared by CANMET. This document is an extension of those compilations and presents abstracts relating to the use of ferrous and non–ferrous slags in concrete. The abstracts have been compiled in this form because the proceedings of some of the above conferences and symposia are not easily available to the general reader.

In preparing these abstracts, papers were selected on the basis of their direct relevance to the practical application of slags to concrete construction. The reader is urged to consult the original proceedings of these meetings for further consideration of the subject and to review the many papers on research and other aspects of the topic not directly applicable to concrete construction.

This compilation is part of a CANMET project on the use of waste materials as supplements to portland cement.

ABSTRACTS OF PAPERS

Seventh International Congress on the Chemistry of Cement
Paris, France, 1980

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1. Baragano, J.R. and Rey, P. "The study of a non traditional pozzolan: copper slags," Vol. 2, III, pp. 37–42.

The slags obtained in copper metallurgy are vitreous, hard, compact, abrasive, of fine granulometry, and are composed principally of fayalite (Fe_2SiO_4) and iron oxides in their crystallized phase.

Different assay methods show that the slags possess pozzolanic properties. The formation of fine, deficiently crystallized C–S–H with alveolar and vermiculate structure and the possible existence of a C_4FH_x type of hydrated calcium ferrite when reacted with calcium hydroxide, $Ca(OH)_2$, was shown in X–ray diffraction (XRD), differential thermal analysis (DTA) and scanning electron microscope (SEM) techniques.

Cements prepared with these slags have similar characteristics to those of portland and pozzolanic cements with advantages in workability. The hardening curves show certain inertia in the increase in strength over short periods but with considerable later advantage, though the initial strengths improve well due to activation by alkaline sulphates. Their behaviour in the presence of atmospheric agents, in freeze–thaw cycles and in alkali–silica reactions is noteworthy.

In the protection of reinforcements, when the mortars do not contain any chemical additives, the behaviour of the slag cements is similar to that of portland super–cements and is superior to these when $CaCl_2$ is present with normal steels, especially when 45% slags are used in their manufacture.

The durability tests with solutions of $MgSO_4$, $CaSO_4.2H_20$ and Na_2SO_4 give results that are better than those obtained with pure portland and pozzolanic cements. They are particularly stable to effects of seawater.

Thus, copper slags are especially suitable for the manufacture of addition and pozzolanic cements and those that are resistant to external agents. Experience with industrial cements and concrete manufactured with them supports this statement.

Keywords: *alkali–silica reactions; copper slags; durability; freezing and thawing; pozzolanic properties; strength; workability.*

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2. Laneuville, J. "The hardening of nickel slags," Vol. 2, III, pp. 52–57.

The chemical composition of non–ferrous slags produced in Canada from nickel and copper smelters is mostly iron oxide and silica, with minor amounts of calcium oxide. This composition is quite distinct from steel blast–furnace slags (BFS), which are usually used in blended cements. The pozzolanic properties of finely ground nickel slags have been investigated in comparison with fly ash and ground quartz by means of the Pozzolanic Activity Test, ASTM C 595. A good relationship exists between the lime mortar strengths of the materials investigated and their HCl–soluble SiO_2 plus Al_2O_3 contents after seven days of curing.

The hardening properties of granulated nickel slag, in blends of slag and cement, have been investigated in ASTM C 109 modified mortars, cured at 23°C for periods extending to one year or autoclaved at 2 MPa. The contribution of slag to concrete strength is negligible at early ages, but is equivalent to that of cement at later ages, say 90 days to one year, provided that the slag content of the binder does not exceed 45%.

For mortars made with various slag/cement ratios, hydrated for 7, 28 and 90 days at 23°C and dried at 105°C, the combined water was calculated from thermogravimetric curves and loss at 1000°C. A fair relationship was found between the mortar strengths and the combined water contents. The proportions and nature of hydration products were found to vary with slag/cement ratios. Comparative micrographs of cement paste and cement–slag paste, hydrated for two months, have been obtained with an SEM, analyses of selected areas were made with an X–ray energy dispersive spectrometer.

Keywords: *copper slags; fly ash; mortars; nickel slags; non–ferrous slags; pozzolanic activity; strength.*

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3. George, C.M. and Sorrentino, F.P. "Valorization of basic oxygen steel slags," Vol. 2, III, pp. 140–144.

The problems of dimensional instability due to a high and variable free lime content in basic oxygen process slags as well as their lack of hydraulic activity have been overcome by the use of a new slag forming agent. This synthetic material, combining CaO, MgO, Al_2O_3 and iron oxide in specific proportions, when added to the converter during refining, leads to final slags with a consistently low free lime content and useful hydraulic properties, without prejudice to the conversion of iron into steel. This paper deals briefly with the preparation of such slags and then reports on the study of their mineralogy and hydraulic behaviour.

Keywords: *basic oxygen steel slags; hydraulic activity; mineralogy; preparation.*

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4. Hawthorn, F., Demoulian, E., Gourdin, P. and Vernet, C. "Blast furnace slags and clinkers mutual influences," Vol. 2, III, pp. 145.

The authors studied mixes containing 80% blast–furnace vitrified slag and 20% clinker with additions of gypsum, prepared with combinations two by two of seven clinkers and three BFS ground to two different degrees of fineness, representative of French production. They showed, with the help of the analysis of variance, the preponderance of type and fineness of slags in the performance of these cements. The clinker mineralogy has more influence on the normally ground than on the finely ground slag. The evolution curve of compressive strength of these mixes is generally different from that of portland cement made with the same clinkers. The influence of sulphate content and of a slight increase in clinker content was also examined.

Keywords: *blast–furnace slags; blended cements; clinker mineralogy; compressive strength; concrete; fineness; sulphate content.*

Fifth International Symposium on Concrete Technology
Nuevo Leon, Mexico, March 1981

(Available from Department of Civil Engineering, University of Nuevo Leon, Monterrey, Mexico.)

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5. Mather, B. "Blends of cementitious materials for concrete to be exposed to sea water," pp. 291–310.

With the increasing cost of energy and hence of energy–intensive products such as portland cement clinker, increased attention is properly being given to the use of blends of portland cement with other materials for purely economic considerations. Where exposed to seawater, concrete must be resistant to wetting and drying and to moderate sulphate attack. Also, it must usually be of low permeability to protect the reinforcement material from corrosion. Both available laboratory data and field experience indicate that blends of portland cement and pozzolan or portland cement and pulverized, quenched iron BFS have benefits for seawater exposure, in addition to their reduced cost, which should make them initially attractive. With these relations in mind, the factors relevant to the use of materials and the properties of concrete affected by exposure to seawater are reviewed.

Keywords: *blast–furnace slags; blended cements; concrete; durability; permeability; pozzolans; seawater; sulphate attack.*

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6. Mills, R.H. "Assay of blast furnace slag," pp. 85–116.

Pelletized BFS may be used as an aggregate or may be finely ground and used as a partial substitute for portland cement. For equivalent workability, specified strength, durability and volumetric stability, the quantities of cementitious material depend on target strength, water demand and the relationship between strength and water/binder ratio. Performance of the BFS component of a blended cement is expressed as a non–dimensional efficiency factor derived from the equivalent mass of portland cement.

Keywords: *blast–furnace slag; concrete; durability; strength; volumetric stability; workability.*

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7. Malhotra, V.M. "Strength and freeze–thaw characteristics of concrete incorporating granulated blast–furnace slag," pp. 159–184.

Portland cement is a highly energy intensive material requiring 6570 MJ/t of product, representing 42% of the total plant production cost. Attempts are thus being made to find materials that are less energy intensive to partially replace cement in concrete. Considerable potential has been shown by slag, the non–metallic product normally discarded when making pig iron in the blast furnace. This report gives the results of laboratory investigations to determine the strength and freeze–thaw durability characteristics of concrete incorporating granulated iron BFS.

A series of 32 mixes of 0.062 m^3 was made, with water/(cement + slag) ratios ranging from 0.30 to 0.65, and with the percentage of slag used as a partial replacement for normal portland cement ranging from 25 to 65% by weight. All mixtures were air entrained and some incorporated a superplasticizer in addition to an air–entraining agent. A number of 100 x 200–mm cylinders were cast for testing in compression and splitting tension at ages up to one year. Test prisms, 90 x 100 x 400 mm, were also cast to determine flexural strength and freeze–thaw durability.

Test data showed that the dosage required for the agent to entrain a given amount of air increased markedly with increased slag content, whereas there were indications that the percentage of the superplasticizer needed to obtain a slump of 200 mm was lower for concrete incorporating slag than for control concrete. Visual examination of the fresh concrete and slump test determinations did not show any increased workability of concrete incorporating slag; on the contrary, there was evidence of higher water demand for concrete mixes having a lower water/(cement + slag) ratio.

Regardless of the water/(cement + slag) ratio, there was a wide gap between the strength of the control concrete and that of concrete incorporating slag, with the former being greater. The difference in strength narrowed between 7 and 91 days depending on the water/(cement + slag) ratio; beyond 91 days, the difference widened again. The above strength development pattern was more marked for concrete with water/(cement + slag) ratios of 0.30 and 0.38.

The flexural strength of concrete with water/(cement + slag) ratios of 0.46 and 0.56 was comparable to, or greater than, the corresponding strength of the control concrete. The reverse was true for concrete with a water/(cement + slag) ratio of 0.38 for both air entrained, and air entrained and superplasticized concretes; at 65% slag replacement, there was a drop in strength of about 20% compared with the control concrete. The 14–day flexural strength of concrete ranged from 4.2 to 6.0 MPa for a water/(cement + slag) ratio of 0.56.

Durability studies indicated that regardless of the water/(cement + slag) ratio and whether the concrete was air entrained or air entrained and superplasticized, the test prisms performed satisfactorily in freeze–thaw tests (ASTM C 666, Procedure B) except for mixtures with a high water/(cement + slag) ratio and 65% slag content.

Keywords: *air entrainment; blast–furnace slag; concrete; freeze–thaw; strength; superplasticizer; workability.*

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8. Scanlon, J.M. "Mixture proportioning of concrete containing natural pozzolans, fly ashes, and slags for use in seawater," pp. 323–367.

Many concrete technologists are concerned with the resistance of concrete containing natural pozzolans, fly ashes and slags to deterioration by seawater. Concrete containing these materials can be made just as strong and durable as concrete containing only portland cement. Procedures for proportioning concretes to assure adequate quality, durability and placeability are discussed. The water/cement ratio is emphasized and how to recompute effective water/cement ratios by volume when using natural pozzolans, fly ashes and slags is reviewed. Densities of the materials involved contribute to mixture proportioning problems, but because of the energy used in producing portland cement, we need to develop the technology for using some of the less energy–consumptive waste materials.

Keywords: *concrete; durability; fly ash; mix proportioning; placeability; pozzolan; seawater; slag.*

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9. Munn, R.L. and Ryan, W.G. "Concretes in Australia containing fly ashes and/or slags: their properties and performance in aggressive environments," pp. 368–392.

Very significant use of both bituminous fly ashes and BFS has been made in Australian concretes since the first recorded use of air-cooled BFS in 1923. During the last 16 years, concretes containing fly ashes and ground granulated slags as partial cementitious components have been used in up to 80% of the concrete produced in major areas of eastern Australia. Some concretes have used a tertiary blend of fly ash, ground granulated slag and portland cement, with considerable success. The locations of the plants producing slags and fly ash are such that a unique opportunity exists to study the long-term performance of concretes containing these materials in the marine environment.

Data have been collected from laboratory investigations into compressive strength development, shrinkage and creep, and freeze–thaw resistance of a wide range of concretes using slags and fly ash. Core samples have been taken from concrete in long-term service, tested for compressive strength and examined by SEM. Field surveys have been made on the durability of concretes containing slags and fly ashes. Australian studies into durability of concrete structures have indicated that effects of salt spray on buildings has been greatly underestimated. Provided concretes are given adequate curing and compaction, pozzolanic binders play an important role in improving durability of concrete for buildings and marine structures. It is concluded that with appropriate mix design, concretes containing slags and fly ashes can match the properties of conventional concretes in all respects.

Keywords: *creep; fly ash; freeze–thaw; marine environment; shrinkage; strength; tertiary blends.*

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10. Villarreal, R.R. "Effect of a superplasticizer additive on concrete made with two blended portland cements, blast furnace slag and natural pozzolan," pp. 611–639.

This paper presents the results of a comparative study of some properties of mortars and of concretes made with portland cement clinker interground with BFS cement and natural pozzolan cement. To these were added a formaldehyde naphthalene sulphonate superplasticizer. Compressive strengths of mortars were determined according to the ASTM standards with the same flow and the same content of cement for different amounts of admixture. To maintain these conditions, the quantity of water was reduced, which caused a reduction in the water/cement ratio and consequently the compressive strength increased.

Setting times of mortars were determined, according to the ASTM Standard C 403, using the two types of pozzolanic cements and the natural pozzolan cement with admixture and without it, and at two temperatures, 25 and 38°C. At 25°C, with the superplasticizer, the initial and final setting times were increased with all cements. At 38°C, the setting times were accelerated in mortars for the three types of cements, with or without the admixture. Increases in compressive, flexural and splitting tension strength, and in Youngs' modulus of elasticity were observed.

The slump loss of superplasticized concretes maintained at 18°C was more rapid for concretes made with NPPC than for those made with natural pozzolan cement but was less for BFS cement. Slump loss cement increased at the higher temperature; the concrete with NPPC was the most affected.

Keywords: *concrete; modulus; mortars; natural pozzolans; setting times; slag; slump loss; strength; superplasticizer; temperature effects.*

International Conference on Slags and Blended Cements
Mons, Belgium, September 1981

NOTE: The abstracts of papers for this conference were taken from preprinted material. They are neither consecutively page-numbered, nor are there any identifying paper numbers. Thus, no page identification can be given for the abstracts presented in this document. Some of the papers from this conference have been published in various issues of "Silicates Industriels," commencing in 1981.

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11. Wainwright, P.J. and Reeves, C.M. "A review of some recent U.K. data on the strength/maturity relationships of slag cement concretes."

It is generally understood and accepted that portland blast–furnace cement (PBFC) concretes develop strength more slowly than comparable ordinary portland cement concretes and that the lower the ratio of portland cement to the ground granulated blast–furnace slag (GGBFS) component, the slower the rate of hardening. However, the rate of strength development of PBFC concrete is, like that of portland cement concrete, influenced by the temperature at which hydration commences and continues, whether the temperature is imposed by some external means, e.g., steam–curing, or is induced within the concrete by the exothermic hydration processes.

It is not uncommon practice to assume PBFC/portland cement strength relationships from data obtained under British Standard 1881: Part 3: 1970 test specimen curing conditions (around 20°C). This practice is unwise because the result can be unduly conservative – for example, when establishing a formwork striking program – or it can be unduly optimistic, in the case of high GGBFS–content PBFC concrete placed and cured at low temperatures.

This paper reviews some laboratory and site data obtained on PBFC concretes produced by the Cemsave System (which is the U.K. production of PBFC concrete by blending GGBFS with portland cement aggregates and water in the concrete mixer); the data are considered principally from the concept of maturity in °C hours (to a base of −10°C) as applied to British Standard CP 110: Part 1: 1972 formwork striking tables.

Keywords: *blast–furnace slag cement; Britain; Cemsave System; concrete; formwork; standards; steam curing; strength; temperature.*

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12. Reeves, C.M. "The use of ground granulated blast furnace slag for within–mixer production of slag cement concretes: a review of U.K. experience."

Laboratory and field trials into the feasibility of introducing GGBFS with portland cement, aggregates and water in the concrete mixer began in Scunthorpe in the 1960s. The first recorded site trial was the successful construction of a scrap billet run–out table in a Scunthorpe steelworks in 1962, and the first major contract took place in 1964/65. The latter was a traditional application of PBFC concrete, i.e., it was chosen for heat of hydration advantage in mass concrete construction of the Wet Sleddale dam; some 20 000 t of Scunthorpe GGBFS were used. The trials continued intermittently throughout the decade and resulted in the introduction of the Cemsave System (production of PBFC concrete within–mixer blending) to the U.K. building and construction markets in 1969.

The first contract on which the Cemsave System was used extensively as an alternative to ordinary PBFC concrete began in that year. In construction of the Anchor steelworks for the British Steel Company, some 70 000 t of Cemsave were used in 500 000 m^3 of concrete. It is now well established and is providing the economic and technical advantages of PBFC concrete to a growing market.

This paper reviews the development of the Cemsave System.

Keywords: *blast–furnace slag cement; Britain; Cemsave System; mass concrete.*

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13. George, C.M. and Sorrentino, F.P. "New concrete based on oxygen steel slag containing alumina."

The use of an aluminous slagging flux in the BOF process produces a slag that, when used in concrete, confers excellent mechanical properties. These properties are shown to be due to the development of particularly strong chemical bonding between the slag aggregate and the cement paste phase in the concrete. Results are reported using monodimensional aggregates of various types in conjunction with portland cement and with aluminous cement, the concrete being cured under a variety of conditions.

Keywords: *BOF slag; concrete; mechanical properties; review.*

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14. Jones, P.R. and Reeves, C.M. "Progress in the use of ground granulated blast furnace slag by the U.K. ready mixed concrete industry."

GGBFS has been manufactured and sold in the U.K. under the trade name Cemsave for 10 years or so; it is supplied for blending with portland cement, aggregates and water in the concrete mixer, to produce PBFC concrete. Until comparatively recent times the market for Cemsave could be easily divided into three principal categories:

a. limited use mainly for building contracts supplied by ready–mixed concrete (RMC) plants close to the manufacturing centre at Scunthorpe;

b. for economy in materials' cost in civil engineering contracts mainly involving large volumes of concrete – usually in excess of 20 000 m^3;

c. for technical reasons, in contracts where a particular concrete property was required, e.g., reduced thermal movement.

Some of a. and b. were supplied by RMC plants.

As a result of a revised approach to the potential market, more widespread and general use began to develop about two years ago. The revised approach was based on established confidence in the suitability of the within–mixer production of PBFC concrete for both minor and major construction projects; it has been successful largely because it has been supported and guided by Members and Officers of the British Ready Mixed Concrete Association (BRMCA).

This paper reviews the use of Cemsave through RMC plants since 1968, with particular reference to types of plants, market areas and the BRMCA Code for ready–mixed concrete.

Keywords: *blast–furnace slag cement; Britain; Cemsave; ready–mixed concrete; review.*

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15. Heaton, B.S., Down, F.W. and Emery, J.J. "Blast furnace slag cement in Australia."

Concrete containing a three-part blend of portland cement, GGBFS and fly ash has been used in Australia since 1966; the paper reports the durability and field performance of this material.

Australian BFS have a high alumina content (17–19%), and laboratory studies have shown mortar specimens with a 50% blend of normal portland cement and ground granulated slag to be unstable in 5% sodium sulphate solutions. This blend was found to be inferior to the normal portland cement, C_3A content 8% alone. However, blends with low-heat portland cement, C_3A content 3.8%, were stable, as were normal portland cement fly ash blends.

Laboratory studies have been made of the properties of equal strength, equal workability concrete mixtures containing portland cement alone and blends of portland cement with both ground granulated slag and fly ash individually and jointly. Results of the study indicated regions where each of the cement blends would hold a cost advantage over its competitors. Concrete with cement blends containing ground granulated slag generally exhibited greater drying shrinkage than concrete containing portland cement alone or portland cement with fly ash. This study indicated some interaction between air-cooled BFS as an aggregate and ground granulated slag as a cement blend. This interaction resulted in increased strength when compared with cement blends not containing slag and when compared with igneous rock as an aggregate.

Slags from one blast furnace in Australia may be granulated either by water or by air (National Slag Ltd. of Canada, Pelletizer). This property has made possible the examination of slags of substantially the same chemical composition but subjected to these alternative vitrifying processes. An investigation has shown the differently processed vitrified slags to have identical hydraulic properties; however, the pelletized slag was more easily ground.

Keywords: *aggregate; air-cooled slag; Australia; blast-furnace slag cement; concrete; durability; pelletized slag; sulphate; three-part blends.*

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16. Hooton, R.D. and Emery, J.J. "Strength development predictions for slags."

Based on a study of about 50 BFS, it has been shown that the compressive strengths of mortars containing 70% ground slag/30% normal portland cement as the binder (i.e., Keil Index cubes) can be related to the chemistry (X-ray fluorescence), fineness of grinding (Blaine) and degree of vitrification (XRD) of the slag. Of these three parameters, the chemistry of key oxides and degree of vitrification are the most important. The best correlation has been found for seven-day strengths, particularly as the later age strengths even out between vitrified slags. As early strength development is important in practical applications, the hydraulicity prediction method may be of help during slag selection. However, it still appears that performance criteria (i.e., compressive strength development) are more realistic and should be adopted in specifications.

Keywords: *blast-furnace slag cements; early strength development; hydraulicity; specifications; vitrified slags.*

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17. Hooton, R.D., Emery, J.J. and Low, C.A. "Sulphate resistance of slag cements."

The basic needs that prompted this study were the lack of Canadian standards on the sulphate resistance of slag cements and the fairly recent use of slag cements in Canada. The slag cement studied in detail is manufactured from pelletized BFS and meets CSA 363. There were three main phases in the study: concrete cylinders subjected to sulphate solutions representative of field conditions, accelerated testing of mortar prisms, and cubes subjected in the fresh condition to concentrated sulphate solutions. The testing program and findings are outlined. It was found, for instance, that a 50% slag cement/50% Type 10 (normal) portland cement blend is equivalent in sulphate resistance to a Type 50 (sulphate–resistant) portland cement. The accelerated mortar test procedure was found to be the most reliable test for evaluating a cement's sulphate resistance performance in a relatively short time.

Keywords: *accelerated tests; Canada; mortars; slag cements; standards; sulphate resistance.*

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18. Cannon, R.P. "Measurement of the in situ strength and temperature development of concretes containing portland and portland blast furnace cements."

This paper describes the instrumentation of the in situ strength and temperature development of concrete containing portland cements and PFBC. The PFBC concretes monitored were produced by the within-mixer blending system, i.e., the combination of portland cement with Cemsave, GGBFS, at the concrete mixer.

Compressive strength determinations were undertaken using temperature–matching curing baths linked to the midpoint and the concrete–formwork interface for a series of walls. Further comparative specimens were also cured at a constant temperature of 20°C. The method employed and the operation of the temperature–matching baths is described in detail. Continuous temperature measurements were also undertaken for the above walls, base slabs and suspended slabs of different thicknesses. These data are summarized and supported with further data obtained from other in situ instrumentations of portland and portland blast–furnace cements.

Keywords: *blast–furnace slag cements; Cemsave; in situ strength; temperature.*

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19. Forss, B. "F–cement, a new low–porosity slag cement."

F–cement is a low–porosity cement that was developed in Finland to meet the precasting industry's need for a rapidly hardening, high–strength binder. F–cement is based on the activation of Ca silicates relatively poor in lime, such as slag and fly ashes, by activators giving alkaline reaction. F–cement contains a sulphonated polyelectrolyte as superplasticizer, which makes it possible to obtain concrete of a fluid consistency at very low water/cement ratios. In this way, the porosity can be reduced by 40 to 80 L/m^3 of concrete, so that a dense concrete of high early and final strengths can be obtained. Because of low lime content and great density, the concrete has high corrosion resistance, and its chemical composition makes it completely sulphate resistant.

As the heat of hydration is low, either a warm mix or thermal curing is required to achieve high early strengths. In full–scale tests at about 20 plants, good results have been obtained.

Keywords: *corrosion resistance; F–cement; precast concrete; slag cements; sulphate resistance; superplasticizer.*

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20. Mitrovic, N., Miletic, S. and Moskovljevic, M. "Blended hydraulic cement based on clinker with high alkali content and addition of blast furnace slag."

Production of blended hydraulic cements based on BFS is an energy–saving process compared with the production of pure portland cements. These cements are important for producers of clinker with high alkali content. This paper presents results of investigations of flexural and compressive strengths and shrinkage of micro–concrete based on portland cement with high alkali content and 25, 35, 45, 55 and 70% BFS. The strength obtained was about the same as for pure portland cement with a fineness of 3000 cm^2/g.

Keywords: *alkalis; blast–furnace slag cements; early strength development; fineness; micro–concrete; shrinkage.*

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21. Niell, E. and Bijen, J. "Supersulphated cement: improved properties."

The Dutch Ministry of Public Health and Environmental Protection, in the context of recommendations to be formulated on "The use of alternative materials and/or processes for production of portland cement, clinker or limestone," issued a commission for a preliminary study into the potential applications of supersulphated cement on the basis of BFS and chemical gypsum available in the Netherlands or from neighbouring countries.

This report covers research into the mechanical strength development and the surface hardness. The tests were carried out on sand–cement mortar as well as on concrete. A comparison was made with a type of supersulphated cement that was in the market until recently, and with portland and blast–furnace cement. A review was made of the effects of hardening temperature, relative humidity, degree of grinding of the cement, use of a water–reducing additive and treatment with a curing compound. The conclusion is drawn that one of the cements produced, consisting of 83% mass/mass Dutch BFS, 15% mass/mass fluorgypsum (anhydrite) and 2% mass/mass portland clinker ground to the relatively high specific surface of 500 m^2/kg, is not inferior to blast–furnace cement as regards the properties examined.

Further studies on supersulphated cement were performed on:

a. optimization of the composition;
b. applicability of flue–gas desulphurization gypsum;
c. effect of separate or combined grinding of slags, clinker and anhydrite;
d. effect of long–term carbonation of cement hydration products on the strength and the surface hardness;
e. corrosion of reinforcement steel.

Keywords: *blast–furnace slag cements; carbonation; FGD gypsum; supersulphated cement; surface hardness.*

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22. Shu–shan, S. and Yu–shun, Y. "Study of steel slag cement."

Studies were made on the morphology and chemical and mineralogical composition of steel slags and their influence on the cementing properties of steel slag cement. The strength of steel slag cement depends mainly on the C_3S and C_2S contents of the steel slag. In general, a cement of Grade 325 can be obtained by grinding high basicity ($CaO/SiO_2 + P_2O_5$) open–hearth steel slag, converter steel slag and granulated BFS to which an appropriate amount of activator has been added.

Also studied were the hydration products of steel slag cement. Special features of steel slag cement are described, such as high late strength, low heat of hydration, impermeability, abrasion, corrosion and frost resistance, stability under atmospheric conditions and expansion. Measures are presented for improving the grinding efficiency of steel slag, and the application of steel slag cement in various engineering projects is also described.

Keywords: *abrasion; blast–furnace slag; concrete; corrosion; erosion; frost resistance; grinding; open–hearth slag; permeability.*

23. Wang, Y. and Lin, D. "The steel slag blended cement."

Basic oxygen–blown converter steel slag has hydraulicity and can be used as an active additive to portland cement clinker to make blended cement.

In this paper, results of chemical analysis and tests of physical and mechanical properties and additive quantities of steel slag on the blended cement are presented. Using XRD, DTA and SEM, the hydration procedure, hydration products and the long–term stability of the blended cement were studied.

Keywords: *basic oxygen–blown converter steel slag; blended cements; hydraulicity.*

International Conference on Slag and Blended Cements
Birmingham, Alabama, U.S.A., February 1982

(Published by the School of Engineering, University of Alabama.)

NOTE: The papers in the proceedings of this conference are neither consecutively page–numbered, nor are there any identifying paper numbers. Thus, no page identification can be given for the abstracts presented in this document.

24. Pierson, C.U. "Blended cement – the importance of uniformity."

The uniformity of concrete is generally more affected by placement practices or variation in aggregates than by variation of the portland cement component.

We can compound this problem by the use of other hydraulic components as a replacement for portland cement if we do not exercise quality control associated with the additional component, equivalent to that of the portland cement produced in the same plant.

This paper discusses the origins of variability in slags, methods to improve uniformity of slags, the effects of fineness of the portland cement component, storage and the effects of admixtures.

Keywords: *admixtures; blended cements; fineness; slags; variability.*

25. Muller, K. "Hoesch/AJO slag granulation system."

This paper presents a detailed description of the Hoesch/AJO slag granulation process for preparing granulated BFS for use in blended cements.

Keywords: *blended cements; granulation; slags.*

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26. Monteyne, G. "Sidmar's blast furnace slag."

This paper presents a comparison of different slag granulation systems used at the Sidmar blast–furnace plant. Characteristics of older systems are discussed in comparison with the INBA systems.

Keywords: *review; slag granulation processes.*

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27. Emery, J.J. "Applications of pelletized slag."

The pelletizing process and rapidly developing range of applications, particularly slag cement manufacture (intergrinding or separate grinding) and lightweight aggregate use in structural and masonry concrete, are described. The basic action of the pelletizer with its spinning drum is to take a pyroplastic expanding slag and chill it quickly in the dispersed form with air and water, by throwing the slag into the air so that spherical pellets are formed. Process and product advantages of pelletized slag have been recognized on an international level with 35 machines active in nine countries. By controlling the process, a more crystalline pellet can be produced for aggregate applications, or a vitrified (glassy) pellet for cementitious applications. The major current aggregate use of pelletized slag is in lightweight concrete blocks. Structural concrete applications have generally been in semi–lightweight mixes. Use in slag cement manufacture is increasing as the significant technical and energy advantages are being exploited in intergrinding and separate grinding plants. The pelletizing process and its features are described before focussing on the product and its uses.

Keywords: *lightweight aggregate; lightweight concrete; review; slag granulation processes.*

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28. Forss, B. "F–cement, a low–porosity slag cement for the precasting industry."

This paper describes the development and properties of a low–porosity slag cement for use in the manufacture of precast concrete. Full–scale tests carried out in Finland comprising its use in columns, piles, floor slabs, wall elements and other structures are described.

Keywords: *F–cement; Finland; low porosity; precast; slag cement.*

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29. Fieser, A.H. "Slag and slag cement practices in Japan."

A historical review of slag use worldwide is presented. Slag production and slag cement utilization practices in Japan are discussed in detail. The properties of typical Japanese slag cements are presented and the types of use to which they have been applied are discussed. BFS cement, produced primarily by a separate grinding process, has received good acceptance in Japan. Advantages claimed for the BFS cement include higher strength, lower heat of hydration, less water permeability, better resistance to chemicals and seawater and better workability. Research into improved slag recovery processes and applications continues in Japan, and we may expect to see further significant developments in the future.

Keywords: *heat of hydration; Japan; permeability; review; seawater; slag; strength; workability.*

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30. Skalny, J. and Brophy, J.E. "Hydration of portland and blended cements."

Principles of water–cement interactions leading to the development of mechanical properties of concrete are reviewed. Special emphasis is given to the basic hydration processes, the cementitious structure formation and their relationship to the development of mechanical properties of concrete. Differences between hydration of portland and blended cements are highlighted.

Keywords: *blended cements; hydration processes; mechanical properties.*

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31. Roy, D.M. and Idorn, G.M. "Development of structure and properties of blast furnace slag cements."

The characteristics of hydration of blends of ordinary portland cement and BFS (in the range of 50% content of slag) are discussed, concerning both the early stages of hydration with considerable temperature rise, corresponding to the curing phase for concrete, and supplementary long–term hydration, such as during the performance stage for concrete. The kinetics of the hydration process are described and special phenomena of hydration of the slag fraction in the blends are traced to the glassy structure of the slag, in contrast to the behaviour of the predominantly crystalline portland cement phases. The particular effects of alkalis in the slag and in the cement are stipulated on the basis of a literature review. The beneficial effects of cements with BFS on the chemical resistance of concrete are outlined with reference to a forthcoming paper on this subject.

Keywords: *blended cements; blast–furnace slag; hydration processes; mechanical properties; temperature rise.*

First CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete Montebello, Quebec, Canada, July and August 1983

(Edited by V.M. Malhotra, ACI Special Publication SP-79.)

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32. Meusel, J.W. and Rose, J.H. "Production of granulated blast furnace slag at Sparrows Point, and the workability and strength potential of concrete incorporating the slag," Vol. 2, pp. 867-890.

A new plant for producing ground water-granulated BFS has been constructed at Sparrows Point, Maryland. The facility was specially designed to water granulate 800 000 t per year of BFS produced by one of the largest and most modern blast furnaces in the world. Molten slag is alternatively supplied to one of four granulators. Granulated slag is collected in an agitating tank where vapours are condensed and from which slag slurry is pumped to a dewatering filter bed. Granulation water is cleaned, cooled and recycled for the next furnace tap and slag granulation. The entire granulation system is environmentally clean, with no discharge of water or gases. After the slag is dewatered, it is removed from the filter beds and is transported to stockpiles at the grinding and processing plant. Slag recovered from stockpiles is dried in a fluid bed dryer and is fed to two 16.5 x 4.6-m, 6000-HP grinding mills for finish grinding. Ground slag is stored in two 20 000-t concrete silos from which the ground slag is loaded into barges and ships for shipment to bulk distribution terminals along the east coast of the United States.

Data are presented on the use of separately ground water-granulated BFS and its physical properties in portland cement concrete. It is shown that when granulated slags are used in proportions of 30 to 50% of the total cementitious material, improved qualities are found in both plastic and hardened properties of the concrete. The data confirm that granulated slag used as a separate cementitious material exhibits marketing potential in today's construction industry.

Keywords: *blast-furnace slag; compressive strength; concretes; granulating; manufacturing; portland cements; water/cement ratio; workability.*

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33. Malhotra, V.M. "Strength and durability characteristics of concrete incorporating a pelletized blast furnace slag," Vol. 2, pp. 891-921.

This report gives the results of laboratory investigations to determine the strength and freeze-thaw durability characteristics of concrete incorporating pelletized iron BFS from a Canadian source. A series of 32 mixtures of 0.062 m^3 was made with water/(cement + slag) ratios ranging from 0.30 to 0.65. The percentage of slag used as a partial replacement for normal portland cement ranged from 25 to 65% by weight. All mixtures were air entrained and some incorporated a superplasticizer in addition to an air-entraining agent. A number of 102 x 203-mm cylinders were cast for testing in compression and splitting tension at ages up to one year. Test prisms, 89 x 102 x 406 mm, were also cast to determine flexural strength and freeze-thaw durability.

Regardless of the water/(cement + slag) ratio, the strength of the control concrete was generally higher than that of the concrete incorporating slag. The difference in strength narrowed between 7 and 91 days depending on the water/(cement + slag) ratio; beyond 91 days, the difference widened again. The above strength development pattern was more marked for concrete with water/(cement + slag) ratios of 0.30 and 0.38.

The 14–day flexural strength of concrete ranged from 4.2 to 6.0 MPa for a water/(cement + slag) ratio of 0.56. The flexural strength of concrete with water/(cement + slag) ratios of 0.46 and 0.56 was comparable to, or greater than, the corresponding strength of the control concrete. The reverse was true for concrete with a water/(cement + slag) ratio of 0.38 for both air–entrained, and air–entrained and superplasticized concretes; at 65% slag replacement, there was a drop in strength of about 20% compared with the control concrete.

Durability studies indicated that regardless of the water/(cement + slag) ratio and whether the concrete was air entrained or air entrained and superplasticized, the test prisms performed satisfactorily in freeze–thaw tests (ASTM C 666, Procedure B) with minor exceptions.

Keywords: *air–entraining agents; blast–furnace slag; compressive strength; concrete durability; flexural strength; freeze–thaw durability; pellets; plasticizers.*

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34. Virtanen, J. "Freeze–thaw resistance of concrete containing blast–furnace slag, fly ash or condensed silica fume," Vol. 2, pp. 923–942.

The use of GGBFS and fly ash has increased considerably in Finland. Silica fume has not been used in concrete in Finland so far, but research on its properties has been carried out for some years. The use of these materials has been limited because of the lack of knowledge on the durability of concrete containing slag, fly ash or silica. The freeze–thaw resistance of concrete has been evaluated using five different methods. Both air–entrained and non–air–entrained concretes were tested.

Keywords: *air entrainment; blast–furnace slag; concretes; fly ash; freeze–thaw durability; silica.*

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35. Hooton, R.D. and Emery, J.J. "Glass content determination and strength development predictions for vitrified blast furnace slag," Vol. 2, pp. 943–962.

The estimated glass content of a vitrified slag is very sensitive to the method employed. The degree of vitrification (i.e., glass content) of a number of slags has been determined by several optical methods and XRD. Based on this study, the XRD method is considered the most reliable. In this method the glass content is obtained by comparing the peak intensity ratios of a CaF_2 internal standard to the mellilite and merwinite peaks in relation to those found for synthetic materials. The "McMaster Optical Method" involves individual, optical particle analysis under crossed polars and can be correlated to the XRD approach for rapid laboratory use.

As part of this study, it has been shown that the compressive strengths of mortars containing 70% ground slag/30% portland cement as the binder can be related to the chemical composition, fineness of grinding and degree of vitrification by XRD. Of these parameters, key oxide chemistry and degree of vitrification are most important, with the best correlation at seven–day strengths. Since early strength development is important in applications, the hydraulicity prediction method will be of help during slag selection. However, it still appears that performance criteria (i.e., compressive strength development) are more realistic and should be adopted in specifications.

Keywords: *blast–furnace slag; chemical analysis; compressive strength; glass content; pellets; regression analysis; silica flour.*

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36. Pigeon, M. and Regourd, M. "Freezing and thawing durability of three cements with various granulated blast–furnace slag contents," Vol. 2, pp. 979–998.

The freeze–thaw resistance of three cements – containing 100% clinker and 0% slag, 70% clinker and 30% slag, 30% clinker and 70% slag – was studied. Only one clinker (ground to 3165 cm^2/g Blaine) and one granulated BFS (ground to 3920 cm^2/g Blaine) were tested. Six mortar mixes (water/cement ratio = 0.5) with varying air–void characteristics were fabricated from each cement. An air–entraining agent, a water reducer and different fine aggregate gradings were used to produce a range of air–void spacing factor (L) values.

A total of 54 prisms, three of each mix, with dimensions of 70 x 70 x 280 mm, were subjected, after 28 days of moist curing, to 500 freeze–thaw cycles (freezing in air and thawing in water). To assess the degree of deterioration, changes in length, dynamic E and mass were measured. The characteristics of the three hydrated cement pastes were determined by SEM and mercury intrusion porosimetry.

The freeze–thaw durability of all mixes was found to be very good. Only three specimens (made with the cement containing 70% slag) deteriorated significantly, which was caused by the very dense and uniform structure of the hydrated paste and its fine pore texture.

Keywords: *air entrainment; blast–furnace slag; freeze–thaw durability; microstructure; mortars (material); porosity; portland slag cements.*

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37. Nagataki, S., Takada, M. and Sakai, E. "Relation between hydration of slag sand and mechanical properties of concrete," Vol. 2, pp. 1075–1089.

The potential hydraulicity of granulated BFS sand in concrete governs the characteristics of concrete. Physical properties of concrete, particularly the structure of the hydrated layer formed at the surface of the granulated BFS sand, as well as the hydration activity of the granulated BFS sand and the decline in the mechanical properties after drying of concrete, were studied. The physical properties of concrete are influenced by the hydration reaction layers formed around granulated BFS sand particles. The strength reduction during drying may be caused by the embrittlement of the hydration reaction layers or the formation of microcracks.

Keywords: *blast–furnace slag; curing; fine aggregates; hydration; microcracking; pozzolans; tensile strength.*

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38. Roper, H., Kam, F. and Auld, G.J. "Characterization of a copper slag used in mine fill operations," Vol. 2, pp. 1091–1109.

Methods of production, placement and strength requirements of mine fill are briefly described. The chemical composition and details of the mineralogical nature of a particular quenched copper reverberatory furnace slag, successfully used in fill operations at Mount Isa Mine, Queensland, Australia, are discussed.

Experimental work on slag reactivity in the presence of $Ca(OH)_2$ is described, and includes studies on the heat of hydration, non–evaporable water and X–ray intensity variations. The reaction product, which is also observed in the presence of hydrating portland cement, appears to be a 7.34–Angstrom hydrate. Information on hydration characteristics may eventually allow advantageous modifications to be made to the present compositions of fill material.

Keywords: *backfilling; calcium hydroxides; copper; heat of hydration; hydration; mines (excavations); slags; slurries; X–ray diffraction.*

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39. Metso, J., Makinen, S. and Kajaus, E. "Use of blast furnace slag as mining fill," Vol. 2, pp. 1111–1122.

The investigation was carried out by using different amounts of BFS in blended cements. The slag content of the binder varied from 0 to 100% of the weight of the cement. The cement/aggregate ratio in the experiments was 1:15 and the water/(cement + slag) ratio was 5.9. The compressive strength of the mining–fill concrete was determined at the age of 28, 91 and 182 days. The specimens were cured at both +8 and +20°C. The optimum cement content in the binder, when granulated slag was used, was 10% at both temperatures. Using pelletized slag, the optimum cement content of binding agent was 30% at +8°C and 10% +20°C, of the weight of blended cement. At lower temperatures the finer slag gave higher compressive strength results, whereas at 20°C no increase in compressive strength was observed.

Keywords: *backfilling; binders (materials); blast–furnace slag; blended cements; compressive strength; mines (excavations); portland cements.*

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40. Kawamura, M., Torii, K., Hasaba, S., Nicho, N. and Oda, K. "Applicability of basic oxygen furnace slag as a concrete aggregate," Vol. 2, pp. 1123–1141.

Little basic oxygen furnace slag is used as a portland cement concrete aggregate because of its unsoundness in concrete. However, soundness of basic oxygen furnace slag in concrete appears to depend largely on the mineralogical and chemical composition of the slag. Several experiments studing workability, compressive strength and dimensional stability of concrete made with basic oxygen furnace slag were conducted for investigating the possibility of its use as a concrete aggregate. The concrete made with weathered slag showed a much higher slump for a given mix proportion than either natural aggregate concrete or concrete prepared using unweathered slag. The longer the periods during which the slag was placed outdoors, the lower the compressive strength of the slag concrete. The changes in the mineralogical and chemical compositions and the surface texture of basic oxygen furnace slag particles were determined by XRD, DTA, SEM and energy dispersive X–ray analysis (EDXA). The results of these experiments show that reduction in compressive strength and high slumps in the concrete made with the weathered slag aggregates arise from slow hydration of C_2S and C_2F on or near the surface of basic oxygen furnace slag during weathering. It may be concluded that basic oxygen furnace slag can be used as a concrete aggregate if the grading of fine slag aggregates is improved by adding river sand, so as to obtain a workable concrete.

Keywords: *aggregate gradation; aggregates; compressive strength; sands; slags; soundness; weathering; workability; X–ray diffraction.*

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41. Kasami, H., Ikeda, T., Numata, S. and Harada, H. "Pumpability of blast–furnace slag aggregate concrete," Vol. 2, pp. 1143–1164.

Laboratory and field studies were conducted on BFS aggregates to establish nationwide material standards and recommended practices. Absorption of air–cooled BFS kept in water was 2 to 9 times that of natural gravel, whereas that under pressure of 2.0 MPa was 1.2 to 4 times that kept in water. Absorption characteristics of air–cooled BFS under pressure varied depending on its porosity and pore size distribution.

Field studies were conducted on the pumpability of BFS aggregate concretes. Air–entrained concretes containing air–cooled and granulated BFS, and those containing crushed stone and natural sand, were pumped and tested for pumping pressure and properties before and after pumping. Concrete with air–cooled BFS indicated higher pumping pressure than that with crushed stone because of pressure absorption, whereas no significant change was found for granulated BFS concrete. It is concluded that BFS aggregate concrete is pumpable without significant slump loss when such aggregate does not have excessive absorption, and is properly presoaked in water before mixing the concrete.

Keywords: *absorption; aggregates; blast–furnace slag; coarse aggregates; compressive strength; field tests; fine aggregates; porosity; pumped concrete; ready–mixed concrete; slump tests; workability.*

Second CANMET/ACI International Conference on the Use of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete Madrid, Spain, April 1986

(Edited by V.M. Malhotra, ACI Special Publication SP–91.)

42. Paillere, A.M., Raverdy, M. and Grimaldi, G. "Carbonation of concrete with low–calcium fly ash and granulated blast furnace slag: influence of air–entraining agents and freezing–and–thawing cycles," Vol. 1, pp. 541–562.

Carbonation of concrete is increased in the presence of a high percentage of granulated BFS in the cement and is also enhanced after subjecting concrete to freeze–thaw cycles. Air–entraining agents do not modify the carbonation when the concrete containing portland or cements with low–calcium fly ash and granulated BFS (<20%) is subjected to freeze–thaw cycles. Carbonation is increased in the cement containing 84% slag. Uncarbonated concrete resists freezing and thawing better than that carbonated previously.

Keywords: *air–entraining agents; blast–furnace slag; carbonation; concretes; fly ash; freeze–thaw durability; mortars (material); strength.*

43. Wainwright, P.J. and Tolloczko, J.J.A. "Early and later age properties of temperature cycled slag–OPC concretes," Vol. 2, pp. 1293–1321.

The paper presents the results of a laboratory investigation into the effects of subjecting concretes (made from ordinary portland cement and blends of ordinary portland cement and slag) to adiabatic temperature cycles. The adiabatic cycle is similar to that which concrete at the centre of a large mass would undergo during the first few days after placing. Concretes with two different cement contents (330 and 450 kg/m^3) were made with slag replacement levels of 50 and 70% by mass of cementitious material. The properties investigated were adiabatic temperature rise, compressive and tensile strength development and modulus of elasticity. Tests were carried out at ages between one day and six months.

Keywords: *adiabatic conditions; blast–furnace slag; blended cements; cement content; compressive strength; concretes; modulus of elasticity; portland slag cements; temperature rise (in concrete); tensile strength.*

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44. Hwang, C.L. and Lin, C.Y. "Strength development of blended blast furnace slag cement mortars," Vol. 2, pp. 1323–1340.

BFS cooled at different rates were used to study the effect of fineness, mixing method and content of slag on the strength development of blended slag mortar. Test results indicated that the strength development of air–cooled slag was better than expected even though it was less effective than that of water–quenched slag. When the intergrinding method is compared with the separate batching method, the latter needs a longer mixing time to reach a comparable quality. The slump and bleeding were reduced as the amount of slag increased at low water to cementitious mix ratio. Alkali activated the reaction of slag. However, excessive alkali might cause flash setting of the fresh mortar. The diffusion process seemed to govern the cementitious reaction of slag, which, in turn, retarded the hydration of cement. Therefore, the optimum slag content depended upon the age of cement mortar.

Keywords: *alkalis; batching; blast–furnace slag; bleeding (concrete); cooling; diffusion; fineness; flash set; grinding (comminution); mixing; mortars (material); porosity; strength.*

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45. Numata, S., Koide, Y. and Shimobayashi, S. "Properties of ultra–highly pulverized granulated blast furnace slag – portland cement blends," Vol. 2, pp. 1341–1360.

This paper describes a study of the full exploitation of the inherent hydraulic behaviour of granulated BFS. An attempt was made by laboratory tests and by actual concrete practices to improve the properties of conventional slag cements and to develop a high–quality binder.

Granulated BFS, pulverized and classified by an industrial mill (Blaine fineness 850 m^2/kg), was mixed with ordinary portland cement and semi–crushed, granulated BFS sand aggregate with the addition of a high–range, water–reducing admixture. Workability, strength and resistance to freeze–thaw cycles, mechanical abrasion and chemical attacks were determined. Microstructures were measured by SEM, and mercury intrusion and nitrogen adsorption porosimetries.

Major findings of the research include:

a. workable mixtures with ultra–highly pulverized BFS can be obtained with the addition of high–range, water–reducing admixtures and have less bleeding;

b. use of ultra–highly pulverized BFS is effective in obtaining a very dense and uniform structure of the hydrated paste and shows superior characteristics with high–strength concrete having more than 100 MPa, as compared with the straight portland cement high–strength concrete;

c. densification and reduced calcium hydroxide caused by the hydration of slag remarkably improve the resistance to acid and sulphate attack as well as other characters.

Keywords: *abrasion resistance; acid resistance; blast–furnace slag; blended cements; drying shrinkage; freeze–thaw durability; high–strength concretes; plasticizers; porosity; sulphate resistance; water–reducing agents; workability.*

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46. Nakamura, N., Sakai, M., Koibuchi, K. and Iijima, Y. "Properties of high–strength concrete incorporating very finely ground granulated blast furnace slag," Vol. 2, pp. 1361–1380.

This paper describes how some properties of high compressive–strength concrete (60-80 MPa) can be improved by the use of very fine GGBFS as a partial replacement for portland cement. The fineness of very finely ground slag is 715 m^2/kg (Blaine) made from classifying ordinary ground slag (364 m^2/kg Blaine) by the air separator. Concrete mixtures containing very finely ground slag were tested while varying the substitution ratio of slag to total content of cementitious materials (slag plus portland cement) by 10, 40 and 70%. The total cementitious materials were 500 kg/m^3, and the water/cement ratios were 0.30 and 0.325, respectively. Concrete mixtures containing other materials, such as ordinary ground slag and silica fume, were also tested.

The properties of the concrete investigated were compressive strength (at ages of 7, 28, 56 and 91 days), resistance to freezing and thawing, permeability and resistance to chloride penetration. A comparison of these properties was made between very finely ground slag and other materials similarly used. It was found that high compressive strength could be obtained with the improvement of permeability, resistance to chloride penetration, and other properties, even if very finely ground slag was substituted for cement at a replacement level of 70%.

Keywords: *blast–furnace slag; chlorides; compressive strength; freeze–thaw durability; high–strength concretes; permeability; silica.*

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47. Longo, A. and Torrent, R.J. "Methods of addition of blast furnace slag: their effect on the compressive strength of mortars and concretes," Vol. 2, pp. 1381–1400.

The aim of the paper is to determine to what degree the strength of mortar and concrete is affected by the way in which granulated BFS is added. The influence of the following methods of adding the slag on the compressive strength of mortar and concrete was studied experimentally:

a. intergrinding of clinker plus gypsum and slag;
b. separate grinding of clinker plus gypsum and of slag, followed by dry mixing before batching;
c. separate grinding of clinker plus gypsum and of slag and separate batching into the mixer.

The variables considered for this study were slag/(slag + clinker) ratio in the cementitious material (0, 0.342, 0.50 and 0.658), age of test (3, 7, 28, 90, 180 and 360 days) and fineness of cementitious material (330, 360 and 400 m^2/kg). RILEM–CEMBUREAU mortar prisms and cylinders of concrete having 19 mm maximum size of aggregate were tested for strength.

The results were analyzed statistically, and it was found that the differences observed between the various methods were generally non–significant.

Keywords: *blast–furnace slag; blending; compressive strength; concretes; grinding (comminution); mortars (material); statistical analysis.*

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48. Frearson, J.P.H. and Uren, J.M. "Investigations of a ground granulated blast furnace slag containing merwinitic crystallization," Vol. 2, pp. 1401–1421.

A second source of GGBFS has become available in the U.K., from Purfleet in south east England. The Purfleet slag has a slightly higher lime/silica ratio and calcium content than the initial source at Scunthorpe. The slag has a potentially higher rate of hydration because of its chemical composition, but as a consequence can contain up to 30% by volume of merwinitic crystallites included within its glass structure. The presence of these crystallites has been found to increase the reactivity of the slag glass further. SEM studies of concrete containing the slag have confirmed that the glassy particles containing merwinitic crystallites are more reactive than pure glass particles, and that an adequate supply of unreacted glass remains even in mature concrete.

Testing of this merwinitic slag has shown no factors disadvantageous to slag reaction or performance and has confirmed that, when blended in appropriate proportions with portland cement, it can increase sulphate resistance and reduce expansion caused by alkali–silica reaction. The results of the investigations reported are supported by a brief review of published literature, which confirms that slag performance cannot be directly related to absolute glass content.

Keywords: *alkali–aggregate reactions; blast–furnace slag; blended cements; chemical analysis; crystallization; expansion; glass content; sulphate resistance.*

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49. Roy, D.M., Kumar, A. and Rhodes, J.P. "Diffusion of chloride and cesium ions in portland cement pastes and mortars containing blast furnace slag and fly ash," Vol. 2, pp. 1423–1444.

Diffusion of sodium chloride, cesium chloride and simulated seawater solutions across and into cement pastes and mortars blended with granulated BFS has been studied. The temperatures of hydration and diffusion were varied between 23 and 60°C. Phase chemistry, depth profiles of chloride and ion migration measurements across paste membranes were used to follow reaction and diffusion of the salt solutions.

It was observed that cement mortars containing the slag showed lower penetration depths of Cl^- compared with the control portland cement mortars at normal or moderate temperatures. The diffusion of cesium or chloride ions was retarded significantly through the use of slag blending in pastes. The porosity was lower and pore structure was finer in the case of the blended cement, which is considered to be the primary reason for the beneficial effect on diffusion. Phase chemistry studies of blended slag–cement mortars indicated an absence of detrimental reaction products such as gypsum or brucite after exposure, but the presence of Friedel's salt (tetracalcium aluminate dichloride–10–hydrate) was detected. Comparisons are also made with blends with fly ash, which also showed relatively favourable effects. The electronegative nature of portland cement was elucidated by Cs^+ and Cl^- migration in pastes.

Keywords: *blast–furnace slag; blended cements; cement pastes; cesium; chlorides; diffusion; fly ash; mortars (material); porosity; seawater; sodium chloride; temperature.*

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50. Litvan, G.G. and Meyer, A. "Carbonation of granulated blast furnace slag cement concrete during twenty years of field exposure," Vol. 2, pp. 1445–1462.

Two experimental houses, one of ordinary portland cement concrete and the other of granulated blast–furnace slag cement (GBFSC) concrete, were built under carefully controlled and documented conditions. After 20 years of exposure, cores were analyzed and significant carbonation to 40 mm in depth was detected by thermogravimetric analysis and the wet chemical method. More significantly, little $Ca(OH)_2$ was found in the GBFSC concrete at all levels, so that any reinforcing steel would have to be considered susceptible to corrosion. According to Hg porosimetry results, the porosity of ordinary portland cement concrete decreased after carbonation but that of GBFSC remained unchanged. In addition, increased permeability of GBFSC concrete with carbonation was indicated by coarsening of the pores, and the tensile strength of the surface region suffered a large decrease.

Keywords: *blast–furnace slag; carbonation; chemical analysis; exposure; field tests; portland cements; portland slag cements; reinforced concrete; tensile strength.*

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51. Ho, D.W.S., Hinczak, I., Conroy, J.J. and Lewis, R.K. "Influence of slag cement on the water sorptivity of concrete," Vol. 2, pp. 1463–1473.

This paper explains the concept of water sorptivity as a measure of concrete quality and discusses the effect of interrupted curing (as distinct from continuous curing) on the quality of concrete. Results of a pilot study on concretes incorporating GGBFS either as a blend or as an intergrind are presented. It was found that the response to interrupted curing varied depending on the constituents of the concrete. Plain concrete (i.e., without chemical or mineral admixtures) with a 28–day strength of 28 MPa showed a very slow response to interrupted curing, but could be improved by the incorporation of slag or by specifying a higher 28–day strength.

Keywords: *blast–furnace slag; concrete durability; curing; portland slag cements; sorption; water; wetting and drying tests.*

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52. Ionescu, I. and Ispas, T. "Properties and durability of some concretes containing binders based on slag and activated ashes," Vol. 2, pp. 1475–1493.

Properties of heavy and lightweight concretes prepared with binders based on slag and activated ashes were studied as follows:

a. fresh concrete;
b. strength of concrete hardened both at normal temperature and by heat treatment;
c. permeability and resistance to freeze–thaw cycling;
d. behaviour of some concrete elements under various working conditions;
e. some technico–economic aspects related to preparation and use of binders and practical conclusions for design and manufacture.

Keywords: *binders (materials); blast–furnace slag; concretes; expansion; fly ash; freeze–thaw durability; mortars (material); pozzolan cements; shrinkage; slag cements; strength.*

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53. Frearson, J.P.H. "Sulphate resistance of combinations of portland cement and ground granulated blast furnace slag," Vol. 2, pp. 1495–1524.

Laboratory test programs have been carried out to assess the sulphate resistance of various portland and portland blast–furnace slag cements and of portland cements blended with GGBFS ("slag"). Slag contents of between 30 and 80% were used. The test method was based upon the German "Flat Prism" test. Tests were carried out on mortars containing ground slag from two sources, on pulverised fuel–ash (pfa – "fly ash"), and on portland blast–furnace cements. Control specimens contained either ordinary or sulphate–resisting portland cements.

Prisms were tested at water/cement ratios ranging from 0.45 to 0.60, using constant cement content mortars. Supplementary tests used water/cement ratios ranging from 0.40 to 0.60 and constant water content mortars. Results are now available for mortars that have been immersed in sodium sulphate solution for periods of up to three years. The results confirm the inferior resistance to sulphate attack of ordinary portland cements and of blends of both ordinary and sulphate–resisting portland cement containing lower slag replacement levels. Sulphate resistance increased as the slag content increased, and the 70% slag content mortars were found to have a superior resistance to those containing sulphate–resisting portland cements alone. The influence of slag content on sulphate resistance was found to be more significant than that of the water/cement ratios in the range examined.

Keywords: *blast–furnace slag; blended cements; expansion; fly ash; mortars (material); portland cements; portland slag cements; sulphate resistance; sulphate–resisting cements.*

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54. Douglas, E., Mainwaring, P.R. and Hemmings, R.T. "Pozzolanic properties of Canadian non–ferrous slags," Vol. 2, pp. 1525–1550.

Copper, nickel and lead slags of Canadian origin have been studied to evaluate the feasibility of their use as partial portland cement replacement in concrete and mine backfill. Pozzolanic activity of the slags was tested in mortars and the corresponding $Ca(OH)_2$ and non–evaporable water contents at the same age were obtained by thermogravimetric analysis. The relationship between pozzolanic activity and glass content, measured by SEM and image analyzer, was assessed as well. It is concluded that non–ferrous slags could be used as partial portland cement replacement in concrete and mine backfill if portland cement and transportation costs justify it.

Keywords: *backfilling; cement content; copper; glass content; lead (metal); mines (excavations); mortars (material); nickel; pozzolans; slags; thermogravimetry.*

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55. Hogan, F.J. and Rose, J.H. "ASTM specification for ground iron blast furnace slag: its development, use and future," Vol. 2, pp. 1551–1576.

In the United States, BFS was first used as a cementitious material in 1896. Since that time its use has followed a course of limited and sporadic success. Recently, however, worldwide attention has been drawn to the technical advantages of GGBFS used as a separate cement to be added at the concrete mixer. Recognizing its potential, the ASTM Subcommittee E38.06.02 developed a specification to cover three grades of ground granulated slag.

This paper discusses the development of the specification and presents round–robin test data leading to the adoption of a test method for evaluating the hydraulic characteristics of slags. Adopted in 1982 as ASTM C 989, the specification has played an important role in market growth, which is approaching one million tonnes annually. Test results from another ASTM cooperative test program demonstrating the usefulness of a rapid (24 hour) hydraulicity test method are also given.

Keywords: *accelerated tests; blast–furnace slag; evaluation; iron; performance; specifications; tests.*

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56. Battagin, A.F. "The use of microscopy for estimating the basicity of slags in slag–cements," Vol. 4, pp. 17–21.

Many countries require or suggest in their specifications for slag–cements the use of chemical moduli calculated from chemical composition of the slags. This paper discusses an attempt to correlate, by means of linear regression analysis, the refractive index of granulated BFS to the most usual chemical moduli employed in the quality control of slags. The investigation of 30 samples of slags from different origins shows a good correlation between the refractive index and

$$\frac{C + M + 1/3A}{S + 2/3A}, \ \frac{C}{S}, \ \frac{C + M}{S}, \ \frac{C + M + A}{S}.$$

The correlation coefficient, *r*, ranges from 0.96 to 0.99. Simultaneously, *r* values of 0.91, 0.80 and 0.87 were obtained in this investigation correlating the refractive index of the slags to the compressive strength of slag cements at 7, 28 and 90 days, respectively.

The method is advantageous not only because of its quickness but also because it may be applied for estimating the moduli of slags in slag–cement samples where the application of chemical method requires previous and laborious separation of the slag.

Keywords: *granulated blast–furnace slag; chemical moduli; compressive strength; refractive index; regression analysis.*

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57. Malolepszy, J. and Petri, M. "High strength slag–alkaline binders," Vol. 4, pp. 108–111.

Two binders were studied that were prepared from BFS with Blaine's surface area of about 3200 cm^2/g and activated by water–glass or Na_2CO_3. Quantities of alkaline additions in both cases were 3% Na_2O in proportion to slag. Sand mortar samples were made with water/solid state ratio of 0.3. Their mechanical properties, compressive strength, bending strength, Young's modulus and scale effect, were determined. Structures were investigated by SEM and mercury porosimetry. It was shown that material made of slag–water glass binder assures high strength, especially compressive strength.

Keywords: *alkali activation; bending strength; blast–furnace slag; compressive strength; porosimetry.*

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58. Bhatty, M.S.Y. "Properties of blended cements made with portland cements, cement kiln dust, fly ash and slag," Vol. 4, pp. 118–127.

Binary, ternary and quaternary blended cements were prepared from one portland cement, three cement kiln dusts, two fly ashes (ASTM Class F and C) and one slag. On the basis of their chemical composition, kiln dusts were classified relatively as (a) low alkali–low chloride–moderate sulphate, (b) low alkali–low chloride–high sulphate, and (c) high alkali–high chloride–low sulphate. The amount of kiln dust used in the blends was fixed at a level of 10% by weight, whereas the amount of fly ash and slag was varied from 10 to 30% and 10 to 40% by weight, respectively, in the blends. All the materials that were added replaced cement.

Blended cements were tested for compressive strength, drying shrinkage, autoclave expansion, sulphate expansion and alkali–aggregate expansion. The type of kiln dust used was found to influence the properties of blended cements with or without the addition of fly ash or slag or both. Test results indicate that properly designed blended cements can be prepared, having properties comparable to those of portland cement. These cements can provide the construction industry with a useful and cost–effective product. They are also energy efficient and can reduce environmental concerns by using waste and by–product materials of various industries.

Keywords: *alkali–aggregate expansion; autoclave expansion; blended cements; compressive strength; drying shrinkage;.*

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59. Elola, A., Szteinberg, A.S. and Torrent, R.J. "Effect of the addition of blast furnace slag on the physical and mechanical properties of mortars cured at high temperatures," Vol. 4, pp. 145–149.

Compressive strength, non–evaporable water content and pore size distribution were studied on mortar specimens cured at 20, 40 and 80°C for different periods, after a delay of one day at 20°C. A portland cement and a slag cement, prepared from the same clinker, were used. The experimental results are discussed with reference to the effect of curing temperature on the acceleration of the hydration process of both cements and on changes in pore structure. The influence of the amount of combined water and pore size distribution on the strength is also discussed.

Both cements showed differentiated behaviours when the curing temperature was raised from 40 to 80°C. No significant differences in behaviour were detected between portland cement mortars cured at 40 and 80°C, whereas for slag cement a higher rate of strength development, coupled with a refinement of the pore structure, was observed at 80°C. Also, slag cement, when cured at a high temperature, showed a different strength–pore structure relation than that found for portland cement cured at normal and high temperatures.

Keywords: *compressive strength; non–evaporable water; pore size distribution.*

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60. Sato, K., Konishi, E., Fukaya, K., Koibuchi, K., Ishikawa, Y. and Iijima, Y. "Properties of very fine blast furnace slag prepared by classification," Vol. 4, pp. 239–244.

The hydraulic hardening capacity of granulated BFS can be improved greatly by making it finer. In this study, two grades of very fine slag were obtained by classifying ground commercial slag. The slag powders thus obtained had a Blaine surface area of more than 8000 cm^2/g. Investigation was carried out on portland blast furnace cement of very fine slag. The mortar strength and shrinkage, the resistance of hardened paste to the expansion caused by the alkali–aggregate reaction and the Cl^- permeability were measured in hardened mortar. For slag particles less than 5 μm in diameter, the mortar strength was much higher than that of ordinary portland cement. Even when the particle sizes were less than 10 μm, mortar strength was also higher than that of ordinary portland cement after seven days. The tendency to shrink was similar to the case of slag with normal fineness. Moreover, the use of very fine slag was remarkably effective in preventing expansion from alkali–aggregate reaction. It was still effective in resistance to expansion when slag of normal fineness was used. The fineness of the slag was not an important factor in the resistance to expansion.

The Cl^- permeability of hardened paste is very small: after soaking in sea water, the concentration of Cl^- ion in the hardened paste was found to be lower than that of OPC subjected to the same conditions. It is concluded that slag powder prepared by classification is applicable to producing very fine slag with excellent properties as a cementitious material.

Keywords: *alkali–aggregate reaction; chloride permeability; fineness; granulated blast–furnace slag; shrinkage; strength.*

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61. Takemoto, K. "The variation of activity index of slag," Vol. 4, pp. 204–206.

The slag activity index is one of the methods of evaluation of the latent hydraulicity of slag. It varies with the slag and with the portland cement used, and therefore the quality control of slag–replacement ready–mixed concrete is made difficult.

Keywords: *hydraulicity; slag activity index.*

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62. Wiebenga, J.G. "Blast–furnace slag cement in the Netherlands," pp. 19–43.

When discussing the properties of concrete made with BFS cement, it is important to realize which specifications are met by the particular brand of the cement in question. It appears that a wide range of qualities may be possible in different countries. In the Netherlands there is more than half a century of experience with BFS cement produced in a similar way to that in Canada. Dutch manufacturers have always aimed at interchangeability between portland cement and BFS cement. The specifications in the national standards make no distinction between the strength requirements of portland cement and BFS cement. Naturally the two types differ substantially in various properties, and these differences are indicated in this paper. In particular, one negative aspect and one positive aspect of BFS cement in comparison with portland cement are treated in detail. These concern the resistance against de–icing chemicals, specifically the resistance against the penetration of ions, particularly of chloride ions, in concrete made with these cements.

Keywords: *blast–furnace slag cement; chloride ion penetration; de–icing chemicals; strength.*

63. Douglas, E., Wilson, H. and Malhotra, V.M. "Production and evaluation of a new source of granulated blast–furnace slag," pp. 79–112.

A granulation pilot plant was installed at Algoma Steel Corporation, Sault Ste. Marie, Ont. for the production of about 40 t of granulated BFS to be tested for concrete and mine backfill applications. The granulated slag was obtained by quenching the molten slag with jets of high–pressure water. Heat loss had to be maintained at the level expected when the full–size plant is in operation to generate a representative slag sample. The granulated slag was allowed to drain in the slag pit before being transported to the grinding facilities, where it was dried in a converted kiln, reducing the moisture content from 8.0 to 0.3%. The unit power consumption for grinding the granulated slag was similar to typical figures for grinding portland cement clinker in the lower Blaine range.

Quantitative XRD analysis showed that the granulated slag was about 90% glass. The magnesium oxide content was about 18% and was probably in the form of a calcium–magnesium–aluminosilicate glass. Mortar tests performed according to ASTM Standard C 989 showed that the slag ground to 4600 and 6080 cm^2/g met the requirements for grades 100 and 120, respectively. The slag investigated has considerable potential for partial replacement of portland cement in concrete. At comparable fineness, the strength characteristics of the concrete incorporating the Canadian granulated slag are comparable to those of the concrete made with the other Canadian slag (pelletized) used in the investigation.

Keywords: *concrete; fineness; glass content; granulated blast–furnace slag; grinding; mine backfill.*

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64. Douglas, E. and Hemmings, R.T. "Characterization of granulated blast–furnace slag for portland cement replacement in concrete," pp. 113–153.

A Canadian granulated BFS from a new source (Sault Ste. Marie, Ont.) was ground in the laboratory to 4000 and 5000 cm^2/g. The slags were characterized by a range of techniques, including particle size analysis, specific gravity, chemical analysis, SEM–EDXA and X–ray powder diffractometry. The slag was found to be highly vitreous and could be identified as a calcium–magnesium–aluminosilicate glass with melilite as the minor crystalline component. Free MgO was not detected. Slag activity indexes for the two grades were determined as mortars (50:50) at 7 and 28 days. All the slag–cement mortars had lower early strengths than the control ordinary portland cement mortar; however, at 28 days, the 4000 and 5000 cm^2/g slag–cement mortars exceeded the control. The hydration of slag–cement pastes (50:50 and 70:30) was investigated at water/cement ratio = 0.5 and curing ages from 2 hours to 28 days by following the chemical composition of expressed pore fluids and by determining the $Ca(OH)_2$ and chemically bound water by their thermogravimetric analysis. Phase composition by XRD and microstructural features were determined as well. In the early stages of hydrations, Ca^{2+} and SO_4^{2-} were present in the pore fluids but, compared to a control of ordinary portland cement paste, they were mobilized at different rates to form insoluble ettringite. The slag did not appear to contribute significantly to the pore fluid ions at 28 days. Thermal analysis indicated that $Ca(OH)_2$ is probably not formed by hydration of the slag. However, the non–evaporable water contents of the paste confirmed the hydraulic nature of the slags. Further work to identify the hydration phases is needed as part of an evaluation of the long–term durability of the binder.

Keywords: *granulated blast–furnace slag; hydration; mortar; slag activity index.*

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65. Douglas, E. and Zerbino, R. "Characterization of granulated and pelletized blast–furnace slags," pp. 155–170.

The objective of this study was the characterization of slags from different sources by their chemical composition, glass content, rate and total heat of hydration and compressive strength development, with a view to establishing a relationship between some of their properties and compressive strength. Binders incorporating 50% slag presented the same classification derived from total heat evolved as from slag activity indexes.

Keywords: *compressive strength; granulated blast–furnace slag; heat of hydration; pelletized blast–furnace slag.*

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66. Malhotra, V.M., Carette, G.G. and Bremner, T.W. "Durability of granulated blast-furnace slag concrete in marine environment," pp. 171–201.

This paper deals with the evaluation of normal and lightweight concretes incorporating granulated BFS in marine environment. A series of 87 concrete prisms, 305 x 305 x 915 mm in size, were cast over a five-year period starting in 1978, for long-term exposure at Treat Island, Maine. The prisms were positioned at midtide level on a rack at the entrance to the Bay of Fundy, which represents perhaps the most severe marine exposure conditions for concrete. The test specimens were exposed to repeated cycles of wetting and drying and to an average of about 100 freeze–thaw cycles per year.

The test specimens, which were monitored at yearly intervals, were photographed and rated on a visual basis. Ultrasonic pulse velocity was also determined. After up to eight years of exposure, both normal-weight and lightweight air-entrained concretes showed no degradation of the mass of the concrete; however, some of the specimens showed significant surface deterioration. The amount of deterioration generally increased with increasing water to cementitious materials ratio, and increasing replacement of the cement with the slag. It appears that surface deterioration can be avoided if the cement content is kept to a certain minimum level.

Keywords: *blast-furnace slag; compressive strength; concrete durability; freeze–thaw durability; marine atmospheres; portland cements; seawater; wetting and drying tests.*

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67. Wainwright, P.J. "The influence of slag cements on some of the properties of concrete related to thermal cracking," pp. 203–227.

GGBFS from a number of different sources have been used in concretes as partial replacement for portland cement. In the majority of tests conducted, the concretes have been subjected to an adiabatic curing regime, and a number of properties related to thermal cracking (including early-age compressive creep) have been measured. In an attempt to assess the influence of GGBFS on thermal cracking, a simple mathematical model has been developed. The data obtained from the experimental work has been used in this model.

Keywords: *compressive creep; ground granulated blast-furnace slag; thermal cracking.*

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68. Malhotra, V.M. "Mechanical properties and freezing and thawing durability of concrete incorporating a ground granulated blast-furnace slag," pp. 229–274.

This report gives results of laboratory investigations to determine the mechanical properties and freeze–thaw durability of concrete incorporating a granulated BFS from a Canadian source. A series of fifteen 0.06-m^3 concrete mixtures was made with water/(cement + slag) ratios ranging from 0.70 to 0.45. The percentage of slag used as a partial replacement for normal portland cement ranged from 0 to 100% by weight. All mixtures were air entrained. A number of test cylinders and prisms were cast to determine the mechanical properties and freeze–thaw resistance of concrete.

The test results indicate that the GGBFS can be used to advantage as a partial replacement for portland cement in concrete at 50% or lower replacement levels, especially at water/(cement + slag) ratios of about 0.55 or lower. At seven days, irrespective of the water/(cement + slag) ratios, and regardless of the percentage of replacement of the cement by the slag, the compressive strength of concrete incorporating slag is lower than that of the concrete made with normal portland cement. At all water/(cement + slag) ratios and at all percentages of replacement, the flexural strength of slag concrete is comparable to, or greater than, the corresponding strength of the control concrete. Durability of air-entrained slag concrete exposed to repeated freeze-thaw cycles is satisfactory, as evidenced by the high durability factors achieved.

Keywords: *compressive strength; durability; flexural strength; freeze-thaw durability; granulated blast-furnace slag; portland cement replacement.*

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69. Lewis, D.W. "ASTM standards for ground granulated blast-furnace slag," pp. 275-285.

The American Society for Testing and Materials has adopted two standards covering GGBFS for use as cementitious materials. The first of these, C 989 Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars, was adopted in 1982. In addition to covering the quality requirements, the standard includes a test method for slag activity with portland cement, and appendices explaining slag effects on concrete strength, sulphate resistance and alkali-aggregate reaction. The second is C 1073 Standard Test Method for Hydraulic Activity of Ground Slag by Reaction with Alkali, a rapid procedure for checking the slag activity, adopted in 1985.

The development of these standards is covered briefly in this report, with a discussion of the major features and provisions of each. It is the writer's opinion that no substantive changes will be made in either of the standards in the near future.

Keywords: *blast-furnace slag; cementitious materials; granulated slag; mortar strength; slag activity; specifications; tests.*

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70. Berry, E.E. "Canadian standards and specifications for the use of blast-furnace slag in concrete," pp. 287-298.

An overview is given of the three Canadian standards regulating the use of granulated BFS as cementing materials. It is concluded that considerable development and rationalization of the standards has occurred in the past 10 years. Some technical strengths and weaknesses in the standards are discussed and some suggestions for possible improvements are presented.

Keywords: *granulated blast-furnace slag; standards; supplementary cementing materials.*

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71. Litvan, G.G. "Carbonation of slag cements," pp. 299–327.

The extent of carbonation of GBFSC concrete exposed for 20 years has been assessed and compared with that in ordinary portland cement concrete. Significant carbonation, up to 40 mm in depth, was found in GBFSC concrete. Furthermore, the $Ca(OH)_2$ reserve was almost exhausted, rendering steel in the concrete vulnerable to corrosion. Mercury porosimetry indicated that carbonation resulted in the coarsening of the pore structure of the GBSFC concrete, whereas the ordinary portland cement concrete became less permeable after carbonation. Accelerated carbonation of laboratory specimens confirmed these findings. Thorough curing of GBFSC concrete minimizes carbonation.

Keywords: *carbonation; granulated blast-furnace slag; mercury porosimetry.*

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72. Dean, M.P. "Selected case histories describing the use of ground granulated blast-furnace slag in the U.K.," pp. 377–396.

The use of GGBFS in the U.K. has increased at a rapid rate during the last few years and is now included in many diverse applications. This paper describes five selected projects, each of which illustrates various properties and characteristics of the material in relation to site practice in particular. The occasional need to alter established methods during construction is demonstrated.

Keywords: *ground granulated blast-furnace slag; work practices.*

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73. Hooton, R.D. and Emery, J.J. "Sulphate resistance of a Canadian slag cement," pp. 397–422.

Tests to evaluate the sulphate resistance of concrete made with portland cement partially replaced by a separately ground pelletized slag from Hamilton, Ont., were initiated in 1977. More than 1000 cylinders were cast from eight concrete mixes made with normal (CSA Type 10), moderate (CSA Type 20) and sulphate-resisting (CSA Type 50) portland cements, and 45, 65 and 72% slag replacement. These samples were exposed to water and different strengths of sulphate solutions ranging from 1000 to 3000 mg/L SO_4 for eight years, after which some were exposed to accelerated 50 000 mg/L SO_4 solutions.

These tests were augmented by a large, two-part series of more than 23 different mortar mixes using a method similar to that which later became the standardized ASTM C 1012 test procedure. These mortar bars were exposed to de-ionized water, and various sulphate solutions ranging from 3000 mg/L to 50 000 mg/L. Variables included C_3A content of portland cements, slag replacement level, alumina content of slag, sulphate salt type and strength at first exposure.

The major findings after 9 to 10.5 years of exposure are that (a) the replacement of 50% by mass of a normal portland cement (12.2% C_3A) with a Canadian slag cement provides sulphate resistance equal to or better than that of sulphate-resistant portland cement (this is a much lower level than the 65 to 70% replacement often quoted in the European literature); (b) sulphate resistance decreases with increasing Al_2O_3 content of the slag (the Al_2O_3 content of the Canadian slag tested was low and typically 8 to 9%); and (c) improved sulphate resistance is attributed to reduced permeability, reduced $Ca(OH)_2$ content and dilution of C_3A. Slag combinations made with lower C_3A cements and/or higher slag replacements appear to provide superior performance but, in the latter case, close attention must be paid to proper proportioning and curing for adequate early-age strength development.

Keywords: *expansion; ground pelletized slag; mortar; portland cement replacement; sulphate resistance.*

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74. Bilodeau, A., Carette, G.G. and Malhotra, V.M. "Resistance of concrete incorporating granulated blast–furnace slags to the action of de–icing salts," pp. 459–483.

This paper presents the results of an investigation undertaken at CANMET to determine the combined effect of de–icing salts and repeated freeze–thaw cycles on concrete incorporating granulated/pelletized BFS. Eight air–entrained concrete mixtures, each having a ratio of water to cementitious material of 0.55, were made in this investigation. Three granulated/pelletized slags from Canada and the U.S.A. were incorporated into the concrete as a partial replacement for cement. For each slag, the level of cement replacement was 25 and 50% by mass. Test cylinders and prisms were cast to determine the strength properties of concrete; test slabs were cast to determine the combined effect of the de–icing salts and the repeated freeze–thaw cycles. Sawn sections of the test prisms were used to determine the air–void parameters of the hardened concrete.

Regardless of the percentage and the type of slag used, concrete incorporating slag exhibited considerably more surface scaling than the reference concrete. In general, for concrete containing slag, the surface condition of the slabs after the salt–scaling test corresponded to a scale rating of "moderate." The concrete incorporating 50% slag as cement replacement suffered more surface damage than that incorporating only 25% slag, despite the fact that both concretes had adequate values of the air–void spacing factor, *L*.

Keywords: *concrete; de–icing salts; freeze–thaw durability; granulated blast–furnace slag; pelletized blast–furnace slag; portland cement replacement; surface scaling.*

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75. Soles, J.A., Malhotra, V.M. and Chen, H. "CANMET investigations of supplementary cementing materials for reducing alkali–aggregate reactions: Part I – granulated/pelletized blast–furnace slags," pp. 485–505.

The use of supplementary cementing materials for reducing harmful alkali–aggregate reactions in concrete is being studied by CANMET to investigate the reduction of expansion from such reactions. Three types of reactive aggregates and additives that include fly ash, slag, silica fume and natural pozzolans were used in this investigation. This report covers the study in which granulated/pelletized slags from two Canadian and one U.S. source were used to replace cement in concrete containing the three reactive aggregates. Test data include characterization information on the materials used, their proportions in mixes, concrete strengths and two–year expansion measurements of mortar bars and concrete prisms made with them. The test results indicate the effectiveness of the slags in reducing deleterious alkali–aggregate reactions, and their optimum replacement levels. These slags are effective, particularly with the carbonate rock.

Keywords: *aggregate; alkali–aggregate reaction; cement; concrete; durability; expansion; granulated/pelletized slags.*

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76. Reeves, C.M. "A current review of the uses of ground granulated blast–furnace slag in the U.K.," pp. 507–542.

In 1969, GGBFS was introduced to the U.K. cement market as a means of producing portland blast–furnace cement concrete, following successful development by Slagment Ltd. in South Africa. There was some progress in the first 10 years but it was slow and intermittent. Since 1979, the use of GGBFS has increased greatly; it now accounts for more than 5% of U.K. cement consumption. This paper outlines the developments and describes the current situation.

Keywords: *ground granulated blast–furnace slag; portland blast–furnace cement concrete.*

77. Higgins, D.D. "Development of U.K. concrete standards and specifications, incorporating ground granulated blast–furnace slag," pp. 543–553.

This paper outlines the historical development of British standards for GGBFS and reviews the use of the material within structural and other codes for concrete. The emphasis has moved away from preblended cements, and a new British standard for separately supplied GGBFS has recently been published. The requirements of this standard are discussed.

Keywords: *ground granulated blast–furnace slag; pre–blended cements; standards.*

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