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REPORT 78–16

FLY ASH FOR USE IN CONCRETE PART II – A CRITICAL REVIEW OF THE EFFECTS OF FLY ASH ON THE PROPERTIES OF CONCRETE

E.E. BERRY AND V.M. MALHOTRA

MINERALS RESEARCH PROGRAM
MINERAL SCIENCES LABORATORIES

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

JANUARY 1978

Available by mail from:

Printing and Publishing
Supply and Services Canada,
Ottawa, Canada K1A 0S9

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Energy, Mines and Resources Canada,
555 Booth St.,
Ottawa, Canada K1A 0G1

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Catalogue No. M38–13/78-16 Price: Canada: $2.25
ISBN 0-660-10129-7 Other countries: $2.70

Price subject to change without notice.

En vente par la poste:

Imprimerie et Édition
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Nº de catalogue M38–13/78-16 Prix: Canada: $2.25
ISBN 0-660-10129-7 Autres pays: $2.70

Prix sujet à changement sans avis préalable.

FLY ASH FOR USE IN CONCRETE - PART II - A CRITICAL REVIEW OF THE EFFECTS OF FLY ASH ON THE PROPERTIES OF CONCRETE

by

E.E. Berry* and V.M. Malhotra**

SUMMARY

Fly ash may be employed as a pozzolan to replace a portion of the portland cement used for the manufacture of concrete. Such replacement is often a means to achieve energy and cost savings and to impart specific engineering properties to the finished product. To use fly ash effectively and economically it is important to develop a fundamental understanding of the differences between fly ash concrete and portland cement concrete. The differences in the rate of strength development between the two types of concrete and the ways in which this may be influenced by methods of mix proportioning are of particular importance.

Within limits, the application of appropriate proportioning methods and the use of a high quality fly ash permit the economic manufacture of concrete of adequate early strength. When properly proportioned and placed, fly ash concrete generally shows improved workability, pumpability, cohesiveness, finish, ultimate strength and durability. It has been found that fly ash is of particular value in high-strength concrete. Its use has often been shown to improve the performance of concretes exposed to sulphate attack or to deterioration caused by alkali-aggregate interactions.

In common with many areas of technology, the use of fly ash in concrete has largely preceeded a fundamental understanding of its properties. As a result, much of the reported research has been concerned with studies wherein fly ash concretes have been compared directly with concretes made with portland cement. Most of these studies have ignored rational proportioning methods and, as a result, the unique properties of fly ash concrete have not been adequately examined.

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It is concluded that research should be carried out to aid in improving the knowledge of fly ash as a concrete material and to assist in developing specifications and test methods that recognize its usefulness. In particular, research is required to elucidate the physical and chemical mechanisms whereby fly ash interacts with portland cement and water. Such factors as degree of hydration, gel-space ratio, strength, porosity, permeability and their inter-relationships should be examined. More extensive studies on the durability of rationally proportioned fly ash concretes, are also required.

LA CENDRE VOLANTE EMPLOYEE DANS LE BETON - PARTIE II - UNE ETUDE DES EFFETS DE LA CENDRE VOLANTE SUR LES PROPRIETES DU BETON

par

E.E. Berry* et V.M. Malhotra**

RESUME

La cendre volante peut être employée comme pouzzolane afin de remplacer une partie du ciment portland employé dans la fabrication du béton. Un tel remplacement est souvent effectué comme moyen de réaliser des économies d'énergie et d'alléger les coûts. Certaines propriétés techniques spécifiques peuvent être transmises au produit fini. Pour employer la cendre volante d'une façon efficace et économique, on doit connaître les différences fondamentales qui existent entre le béton de cendre volante et le béton de ciment portland. Il est important de noter les différences qui existent entre les taux de résistance de ces deux genres de béton et les façons que ceci peut influencer les méthodes de mesure des proportions du mélange.

L'application de méthodes appropriées de mesure des proportions et l'emploi d'une cendre volante de haute qualité peuvent, dans une certaine limite, permettre la fabrication économique d'un béton ayant une résistance précoce convenable. Le béton de cendre volante fait généralement preuve d'une amélioration de la malléabilité, de la capacité d'être pompé, de la cohésion, du fini, de la résistance ultime et de la durabilité lorsqu'il est bien proportionné et mis en place convenablement. Les résultats de recherche ont démontré que la cendre volante est particulièrement appréciée pour la fabrication de bétons de haute résistance. Son utilisation a souvent amélioré le rendement des bétons exposés au sulfate ou à la détérioration causée par les actions réciproques des agrégats alcalins.

Comme c'est le cas dans plusieurs secteurs de la technologie, l'utilisation de la cendre volante a précédé en grande partie la compréhension de ses propriétés fondamentales. Ceci a pour effet que la majorité de la recherche effectuée soit préoccupée de la comparaison directe des bétons de cendre volante avec ceux du ciment portlant. La plupart des études ont ignoré les méthodes rationnelles de proportionalité et, par conséquent, les propriétés uniques du béton de cendre volante n'ont toujours pas été examinées à fond.

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En conclusion, la recherche devrait être effectuée afin d'améliorer notre connaissance de la cendre volante employée comme matériau de béton et aider à la mise au point de normes et de méthodes d'essais susceptibles de reconnaître son utilité. Une recherche devrait être pursuivie afin de connaître les mécanismes physiques et chimiques par lesquels la cendre volante agit réciproquement avec le ciment portland et l'eau. Les facteurs tels que le niveau d'hydratation, le rapport colloïde/espace, la résistance, la porosité, la perméabilité et leur rapport entre eux devraient être examinés. La durabilité des bétons de cendre volante proportionnée rationnellement devrait aussi être étudiée à fond.

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INTRODUCTION

Fly ash is a byproduct of the combustion of pulverized coal in thermal power plants. It is removed by mechanical collectors or electrostatic precipitators as a fine particulate residue from the combustion gases before they are discharged to the atmosphere.

Fly ash particles are typically spherical, ranging in diameter from 1 to 150 μm. The range of particle sizes in any given fly ash is largely determined by the type of dust collection equipment used. The fly ash from boilers where mechanical collectors alone are employed is coarser than from plants using electrostatic precipitators.

The chemical composition of fly ash is determined by the types and relative amounts of mineral matter in the coal used. More than 85 per cent of most fly ashes comprise chemical compounds and glasses formed from SiO_2, Al_2O_3, Fe_2O_3, CaO and MgO. Generally, fly ash from the combustion of subbituminous coals contains more CaO and less Fe_2O_3 than fly ash from bituminous coal. Unburned coal collects with the fly ash as carbon particles, the amount being determined by such factors as the rate of combustion, air/fuel ratio and degree of pulverization of the coal.

The recognition that fly ash frequently exhibits pozzolanic properties has led to its use as a constituent of concrete. A pozzolan is defined(1) as "a siliceous or siliceous and aluminous material which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties".

The properties of both freshly mixed and hardened concretes are intimately and complexly associated with the characteristics and relative proportions of the materials used in their manufacture. In fresh concrete, the coarse and fine aggregates are suspended in cement paste. The consistency of the mass is controlled by the fluidity of the paste and the quantity and grading of the aggregate. In hardened concrete, properties such as strength are functions of the density of the paste, which is controlled by the ratio of water to cement in the original mixture. Hence, there are practical limits to the relative proportions of cement, water, and aggregate in normal concretes. If the aggregates are of satisfactory quality, the performance of concrete in service is primarily influenced by the properties of the hardened paste. For a portland cement of given composition, the strength and porosity of the hydrated mass are dependent almost entirely upon the water/cement ratio. The lower the ratio, the greater is the strength and the watertightness. Durability in service, or resistance to weathering and attack by aggressive environments, is a function of both strength and watertightness.

The inclusion of fly ash in concrete mixes affects all aspects of concrete properties. As a part of the composite that forms the concrete mass, fly ash has a role in part as fine aggregate and in part as a cementitious component. It influences the rheological properties of the plastic concrete, the strength, finish, porosity and durability of the hardened mass, and the cost and energy consumed in manufacturing the final product.

This review is concerned with a critical evaluation of the published data relating to the ways in which the inclusion of fly ash effects fresh concrete, concrete mix proportions, and the behaviour and durability of hardened concrete. Wherever possible, while remaining consistent with a critical overview of the subject, emphasis has been placed in this report on recently published material not included in earlier literature reviews by Abdun-Nur(2), Jarrige(3), Snyder(4), Kokubu(5), and Rosner and Hamm(6), each of which is a valuable source of published material.

This report is the second of a series dealing with the subject of fly ash for use in concrete with reference to Canadian applications. The first report(7) comprised a critical review of the chemical, physical and pozzolanic properties of fly ash. A subsequent report will consider the sources, supply, markets and properties of Canadian fly ashes.

This work is an element of the project dealing with the Utilization of Minerals. The project is part of the Utilization activity of CANMET's Minerals Research Program.

EFFECTS OF FLY ASH ON PROPERTIES OF FRESH CONCRETE

Effect of Fly Ash on Workability, Water-Requirement and Bleeding

The small size and the essentially spherical form of the particles comprising fly ash usually influence the rheological properties of cement pastes causing a reduction in the amount of water required for a given degree of workability from that required for an equivalent paste without fly ash. In this respect, as noted by Davis et al.(8), fly ash differs from other pozzolans which usually increase the water requirement of concrete mixes.

Pasko and Larson(9) examined the amount of water required to maintain a nominal 2.5-in. (63-mm) slump in concrete mixes with partial replacement of cement by fly ash. They found that the water requirement was reduced by 7.2 per cent in a mix in which 30 per cent fly ash replaced 20 per cent cement.

During investigations of the concrete materials for construction of the South Saskatchewan River Dam, Price(10) found that water requirement was not increased when additions of fly ash were made to concrete proportioned with fixed cement contents. The resulting concrete had a lower ratio of water to total cementitious material while workability and cohesiveness of the mixes were improved. Relevant data on mix adjustments reported by Price are given in Fig. 1.

Compton and MacInnis(11) reported that a concrete made by substituting 30 per cent of the cement with Ontario Hydro fly ash required 7 per cent less water than was required for a control concrete of equal slump.

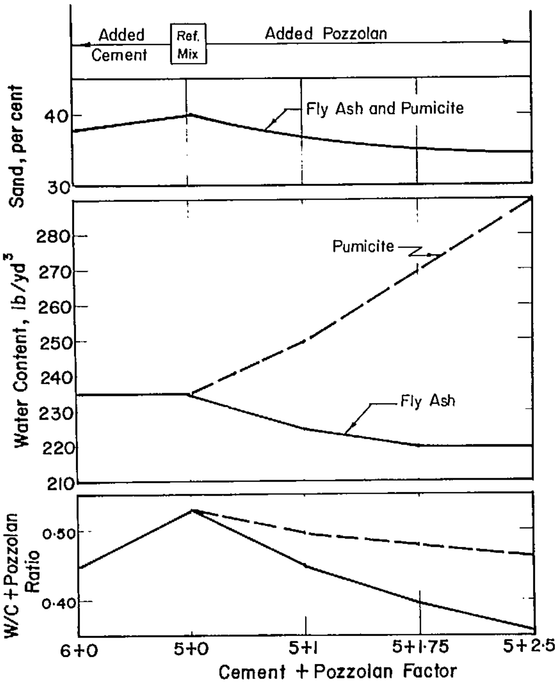

Figure 1. Concrete mix adjustments necessitated by pozzolan additions(10).

The examples cited above are typical of many independent reports of improved plasticity and workability imparted by fly ash to concrete. Abdun-Nur(2), reviewing the subject, considered improved workability to be "almost axiomatic" when fly ash is used in properly adjusted concrete mixes. However, the literature does contain some contrary data.

Brink and Halstead(12) reported that some fly ashes reduced the water requirement of test mortars, others (generally of higher carbon content) showed increased water requirement above that of control mortars. Welsh and Burton(13) reported loss of slump and flow for concretes made with some Australian fly ashes used to partially replace cement, when water content was maintained constant. Rehsi(14) reported that experience with a number of Indian fly ashes showed that all those examined increased the water requirement of concrete.

Concrete using fly ash is generally reported to show reduced segregation and bleeding and to be more satisfactory when placed by pumping than plain concrete placed under the same circumstances. An example of data relating to bleeding of fresh concrete is given in Figure 2.

In line with the improved plastic properties, and as a result of the fine particulate content, fly ash in concrete gives a very marked improvement in finish when it is used as a replacement for either sand or cement.

Effects such as these make fly ash particularly valuable in lean mixes and in concretes made with aggregates deficient in fines.

Effect of Fly Ash on Temperature Rise of Fresh Concrete

The hydration or setting of portland cement is accompanied by an evolution of heat which causes a temperature rise in the concrete. The role of heat of hydration in constructing mass concrete structures has been summarized by Philleo(15) as follows:

> "The heat of hydration of cement may be as high as 180 Btu per pound (100 calories per gram) so that in structural concretes there might occur a temperature rise of 135°F (75°C) if no heat were lost. Fortunately, in most concrete structures heat is lost to

the environment almost as fast as it is generated so that no problems of thermal stress result. In mass concrete, however, portions of the interior may remain in an essentially adiabatic state for a period of weeks after the concrete is placed. Two problems result from this situation. First, as the concrete near the surface cools, the differential in temperature between surface and interior may produce thermal gradients which result in tensile stresses exceeding the tensile strength of the young concrete. Second, and more important, the interior concrete must eventually cool to the mean temperature of its environment. If it acquires its structure at a high temperature and if it is restrained against volume change, the cooling inevitably results in the development of tensile stress. Unreinforced concrete cannot hope to withstand anything approaching a 135°F (75°C) temperature drop without cracking. A practical limit is of the order of 45°F (25°C). Mass concrete is not normally reinforced against tensile failure as is structural concrete. It is assumed in design that the concrete will be so manipulated during construction that a critical temperature drop does not occur."

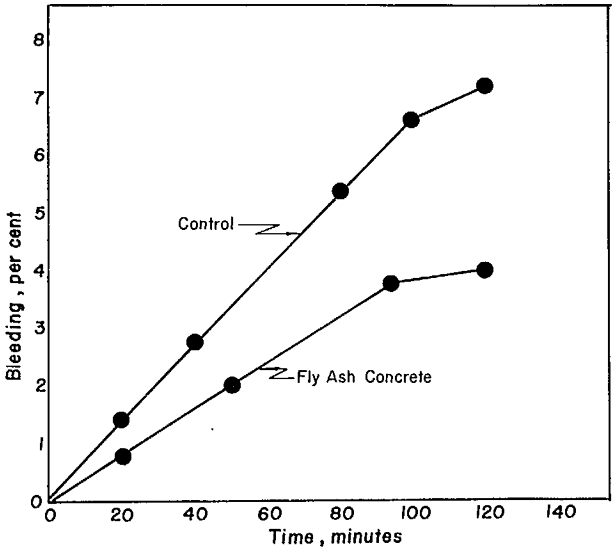

Figure 2. Relative bleeding of ordinary portland cement concrete and fly ash concrete(16).

Data reported by Elfert(17), show the effects of fly ash and a calcined diatomaceous shale on the temperature rise of mass concrete (Fig. 3).

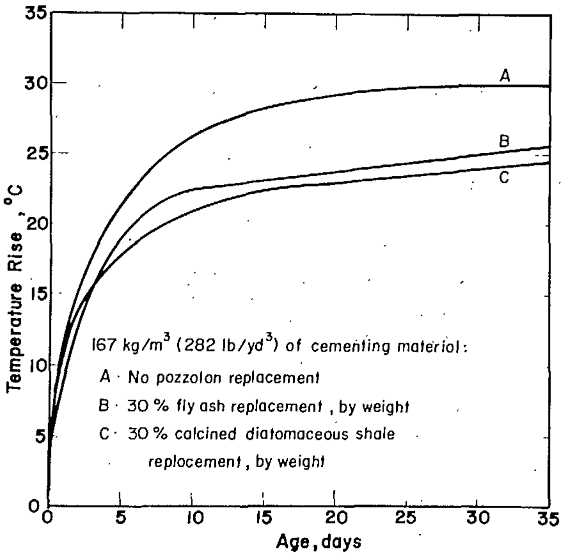

Figure 3. Effect of pozzolan on temperature rise of concrete(17).

Compton and MacInnis(11) reported the temperature-time curves shown in Fig. 4 for two experimental concretes, one of which was made with a 30 per cent substitution of Ontario Hydro fly ash for cement.

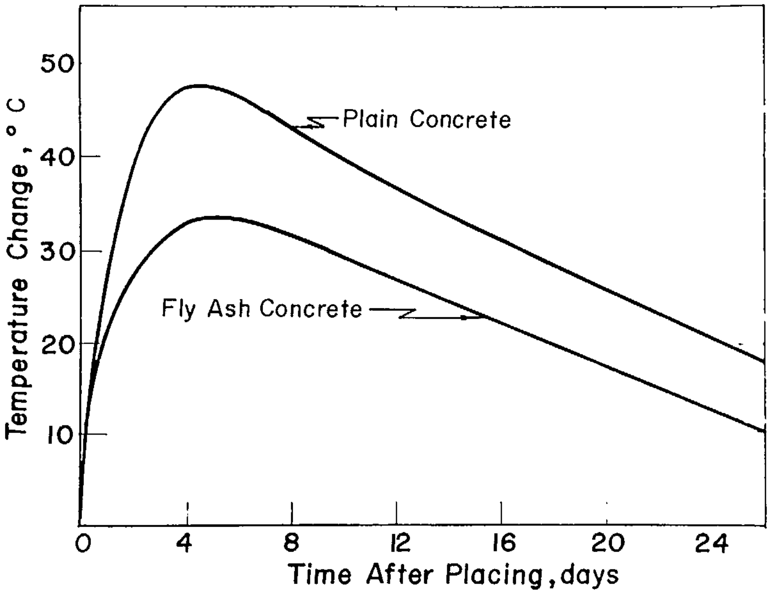

Figure 4. Temperature rise curves for fly ash and plain concrete test sections(11).

Effects of Fly Ash on Air-Entrainment in Fresh Concrete

Frequently the use of fly ash adversely affects air-entrainment in fresh concrete. Fly ash usually causes an increase in the quantity of the air-entraining agent required to produce a given degree of air-entrainment. A detailed discussion of this aspect of fly ash use is given in a subsequent section of this review dealing with concrete durability (page 28).

EFFECTS OF FLY ASH ON PROPERTIES OF HARDENED CONCRETES

Strength Development and Proportioning of Fly Ash Concretes

The subject of the development of strength in fly ash concretes is intimately related to the mix proportioning

Indeed it has been claimed that(18) apart from the quality of the fly ash and the cement, the method of mix proportioning is the most important single factor influencing the properties of fly ash concrete. Three basic mix proportioning approaches have been developed with a view to obtaining either reduced heat of hydration or, more recently, to overcome difficulties encountered in getting acceptable levels of strength in concrete at early ages.

The three mix proportioning techniques are described as follows:

(a) partial replacement of cement,
(b) addition of fly ash as fine aggregate,
(c) partial replacement of both cement and fine aggregate.

The first approach requires a direct replacement of a portion of the portland cement by fly ash. Much research has shown that any percentage replacement of portland cement in concrete by fly ash on a one-for-one basis (either by volume or by weight) results in lower compressive and flexural strengths up to about 3 months of curing, with the development of greater strengths at and beyond 6 months. In mass-concrete applications, where fly ash first came into use, this reduced early strength was of little structural consequence when considered in the light of the desired reduction in temperature rise; replacement methods of mix proportioning were generally used.

It would be neither possible nor valuable to review all of the reported work on this subject, much of which is specific to certain fly ashes or certain construction projects. A general appreciation of the effects of fly ash used as a replacement for cement can be obtained by considering the work of Washa and Withey(19).

Two cements - an ASTM Type I and an ASTM Type II - were examined with Chicago fly ash in both air-entrained and non-air-entrained concretes. Figure 5 summarizes the strength data for the moist-cured concretes. The authors concluded that the 28-day strengths of the fly-ash concrete were somewhat lower than the corresponding strengths of concrete made without fly ash, but at an age of one year it was stronger in every case.

The general form of strength development in fly ash concrete when partial replacement of cement is used, is shown graphically in Figure 6.

The fly ash addition method requires an addition of fly ash to cement. The cementitious content of the mix is increased by this method and mix adjustments are usually made through changes in aggregate content and depend on the nature of the particular job.

An example of this approach comes from the investigation of concrete materials for the construction of the South Saskatchewan River Dam made by Price(10). For reasons of sulphate resistance it was considered important to use a minimum cement factor and to use pozzolan as a replacement for fine aggregate rather than cement. It was found that addition of fly ash generally produced increased strength in concrete at all ages. Improvements were small at 7 days but ranged up to 6.9 MPa (1000 psi) at 3 months and 1 year.

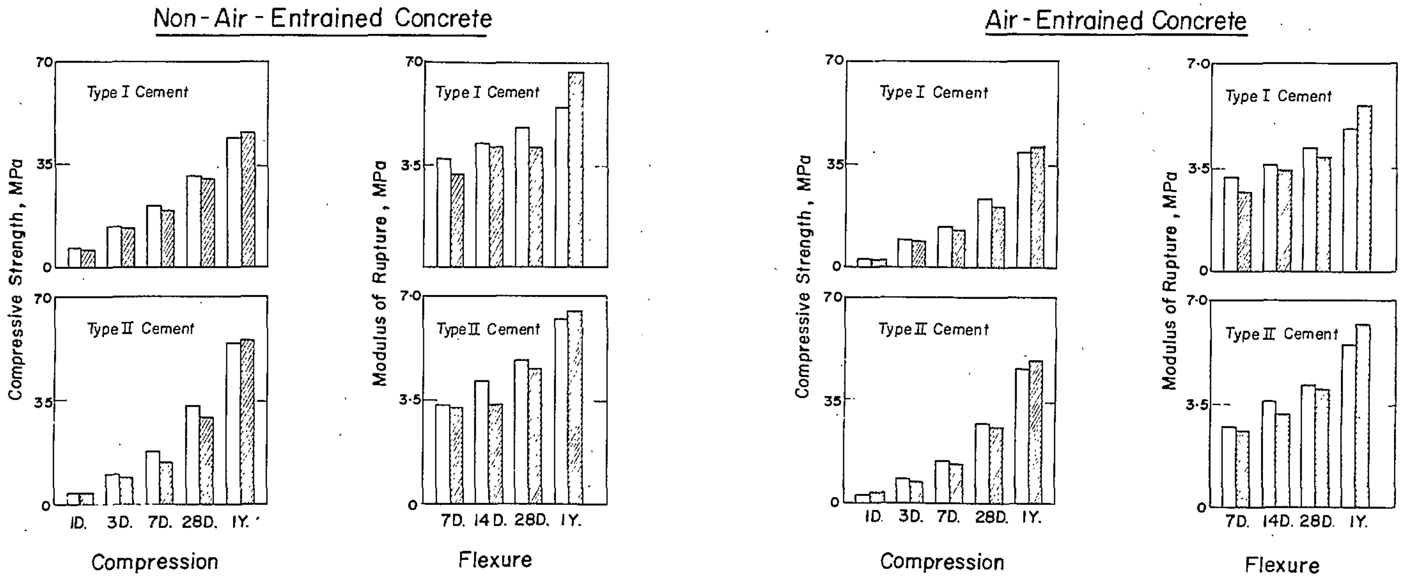

Figure 5. Strength of moist-cured concrete made with and without fly ash(19).

Key ▭ No fly ash

▨ 20 per cent fly ash - substituted for portland cement

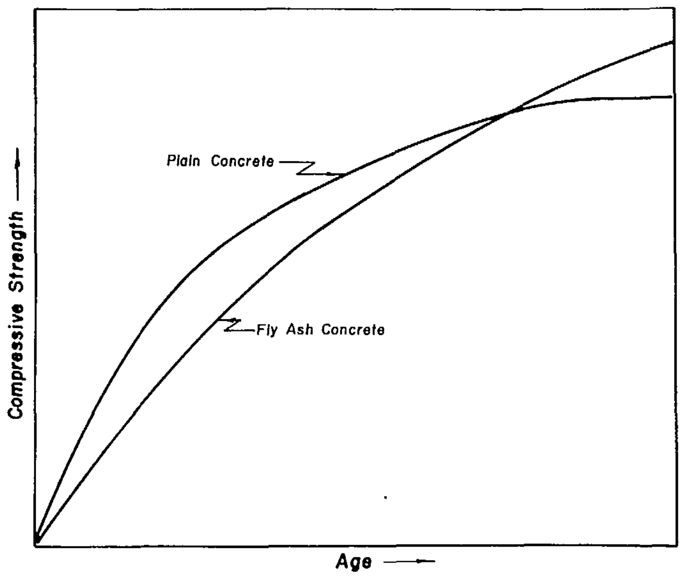

Figure 6. Rates of strength increase of plain cement concrete and fly ash concrete based on partial replacement of cement(15).

In some cases improvements were equal to or greater than those obtained by an equal addition of cement. In contrast to fly ash, the addition of pumicite resulted in reduced strengths at all ages.

The third method developed for proportioning fly ash concrete requires a part of the cement to be replaced with an excess by weight of fly ash with adjustments made in fine aggregate content. The method probably originated in 1958 with the work of Lovewell and Washa(20) who showed that by modification of mix proportions, fly ash concretes could be made which had strengths at early ages comparable with those of control mixes.

The main point of their conclusions was:

> "In order to obtain approximately equal compressive strengths at early ages, between 3 and 28 days, mixes made with fly ash must have a total weight of portland cement and fly ash greater than the weight of the cement used in the comparable strength portland cement mixes."

In 1968, Cannon(21) reported research carried out by the Tennessee Valley Authority on methods of proportioning fly ash concrete mixes to obtain strengths at 28 and 90 days equal to those of conventional control mixes. Cannon employed Abrams' relationship between water/cement ratio and strength, and introduced a factor which took account of the relative costs of fly ash and portland cement. This approach combined with extensive laboratory investigations and field experience allowed Cannon to develop tables and graphs to facilitate proportioning procedures.

Just as Lovewell and Washa had advocated, Cannon's approach results in the use of a combined weight of portland cement and fly ash greater than the weight of the cement used in a comparable control mix. Cost savings using this method rest upon a significantly lower cost per ton for fly ash than for portland cement.

In 1975, Ghosh(22) further extended the approaches developed by Lovewell and Washa, and by Cannon. He published a series of empirical relationships which considerably simplified the mix proportioning of fly ash concrete. Using the basic Abrams' relationship that the strength of a fully compacted concrete is inversely proportional to the water/cement ratio, which he extended to include the water/(cement + fly ash) ratio, Ghosh equated the strengths of fly ash and control concretes in the form:

$R^1 = M + NR$

where R = water/cement ratio of the control (no fly ash) concrete.

R^1 = water/(cement + fly ash) ratio of the fly ash concrete. Using extensive test results from measurements made in the laboratory, the empirical constants M and N were calculated for different ratios of fly ash to cement at selected ages.

Ghosh developed this procedure through the use of tables and graphs from which mix proportions may be made.

Clendenning(23) has stated that by using optimal fly ash/cement ratios and 1976 materials costs, a saving of 57 cents/yd^3 (75 cents/m^3) can be demonstrated.

Smith(24) has published mix proportioning procedures for fly ash concretes similar in approach to that of Cannon but based upon the rather different overall procedure of Road Note 4(25) which is the proportioning method used in Britain.

Smith modified the conventional mix proportioning procedure to obtain values for cement content and water/cement ratio through the introduction of a "fly-ash efficiency factor." This factor was found to be unique for each fly ash and could be determined from the performance of fly ash concrete mixes or from an initial testing program.

Rosner(26) outlined a further procedure incorporating some of the concepts from Cannon(21) and from Smith(24).

The mix proportioning methods discussed above have demonstrated that it is possible to proportion fly ash concretes to have strength at any desired age equal to that of conventional concretes. However a number of factors must be considered when these approaches are used in practice.

(a) As in normal mix proportioning procedure, trial mixes must be made and the concrete components must be adjusted. Additionally, since each fly ash has unique characteristics, knowledge of each fly ash must be developed as an aid to trial mix proportioning.

(b) To truly estimate the economic advantages offered by these mix proportioning methods, allowance should be made for the handling of an extra component when fly ash is used as an admixture and batched separately. Such allowances are not made in the procedures outlined above.

(c) Concretes made with fly ash are more sensitive to temperature and moisture conditions during curing than are plain concretes. These factors must be considered when data from trial mixes are used to proportion concrete for construction.

Work by Ryan and Ashby(27) allows a direct comparison to be made of the different forms of strength development obtained for the same portland cement-fly ash combination using both replacement and replacement-addition methods. Ryan and Ashby studied a fly ash from Wangi Power Station (N.S.W. Australia). Among other tests, two series of concrete mixes, proportioned differently but using the same fly ash, the same cement and the same slump of 80 mm, were examined for compressive strength at 7, 28 and 90 days. The mix proportions and strength results obtained are given in Table 1.

This work shows directly that, (a) with the materials studied, equal strength at 28 days was possible with reductions in cement content of 16 to 20 per cent by the replacement-addition method and (b) in all cases concrete containing fly ash required less water than its control concrete for the same slump.

TABLE 1

Comparison of Strength Development in Concretes Made With the Same Fly Ash*

	Replacement proportioning				Replacement-addition proportioning			
$\frac{3}{4}$ in. dolerite aggregate	1960	1960	1960	1960	1890	2080	1970	2020
$\frac{5}{16}$ in. crushed gravel	-	-	-	-	100	100	105	100
River sand	1220	1220	1220	1220	1210	1000	1010	1040
Cement (lb/yd^3)	515	435	410	385	445	390	370	350
Water (lb/yd^3)	345	335	335	335	360	320	330	330
Fly ash (lb/yd^3)	0	60	80	95	0	135	175	140
Compressive strength (psi)								
7 day	2840	2320	1890	1820	2500	2860	2650	2090
28 day	4340	3420	3160	2810	3390	3890	3660	3060
90 day**	5760	4740	4690	4370	4080	5420	5430	4480
% of control at 28 days	100	78.1	72.9	64.8	100	115.0	108.0	90.4
% cement replacement	0	15.5	20.4	25.3	0	12.5	16.9	21.4

* From Reference (27).

** Note: Although the authors did note in their experiments using the cement replacement method that concrete strengths were reduced even at 90 days, it should be pointed out this represents very poor strength development by the fly ash used. Generally, as has been noted above, strength equality can be obtained at or before 90 days even when using the cement replacement method of mix proportioning.

Use of Fly Ash in Combination with Water-Reducing Admixtures

Chemical admixtures have been used in concrete as water-reducing agents for some years. Generally they comprise lignin based, surface-active agents, with or without set retarding capacity, whose main function is to disperse and deflocculate cement particles.

In 1962, the U.S. Corps of Engineers reported(28) work in which fly ash and water-reducing admixtures were combined in making special concrete structures. It was concluded from compressive and flexural strength measurements and estimated costs that such structures could be made more economically with these materials than with portland cement alone.

In 1971, Lovewell and Hyland(29) concluded from research and literature surveys that:

> "... combinations of pozzolans (including fly ash) with water-reducing agents, or with water-reducing-retarder agents, with and without air-entrainment can be used in concrete without creating abnormalities. All such ingredients should be checked for compliance with applicable standards and trial mixes should be made to check compliance of such mixes with specified quality parameters."

In 1975, Samarin and Ryan(18) reported studies made on fly ash concretes proportioned by the replacement-addition method containing water-reducing admixtures. Two trial series of concrete mixes were reported; Series A in which a comparison was made between plain, fly ash, admixture and fly ash plus admixture concretes of comparable consistency and compressive strength; Series B in which a comparison was made between plain and fly ash plus admixture concretes of three different strength levels. The comparative compressive strength results from this work are given in Tables 2 and 3. Corresponding results relating to other concrete tests on the same materials are given in Table 4. From this work Samarin and Ryan concluded as follows:

> "(a) As compared with plain mix, concrete containing fly ash and lignin-based admixture is expected to give:
>
> (i) Higher ninety-day strength
> (ii) Comparable workability
> (iii) Lower bleeding capacity in leaner mixes
> (iv) Slightly reduced modulus of elasticity at twenty-eight days
> (v) Higher indirect tensile strength at twenty-eight days
> (vi) Comparable or lower ninety-day shrinkage
> (vii) Setting times extended by one to two hours.
>
> "(b) As compared with admixture mix, fly ash-admixture concrete is expected to give:
>
> (i) Comparable ninety-day strength
> (ii) Improved workability
> (iii) Slightly lower bleeding capacity
> (iv) Improved indirect tensile strength at twenty-eight days
> (v) Comparable or lower ninety day shrinkage
> (vi) Comparable setting times.
>
> "(c) As compared with fly ash mix, fly ash-admixture concrete is expected to give:
>
> (i) Comparable ninety-day strength
> (ii) Comparable workability
> (iii) Comparable bleeding capacity
> (iv) Comparable indirect tensile strength at twenty-eight days
> (v) Comparable ninety-day shrinkage
> (vi) Setting times extended by one to two hours."

TABLE 2

Series A - Compressive Strength Comparisons*

Mix type	Compressive strength, MPa			
	3 days	7 days	28 days	90 days
1. Plain	25.4	30.1	40.6	41.6
2. Fly ash	23.8	31.1	44.6	49.8
3. Admixture	22.8	31.5	41.3	44.6
4. Fly ash-admixture	20.5	28.5	39.8	49.5

*from References (18,30).

TABLE 3

Series B - Compressive Strength Comparisons*

Mix type	Compressive strength, MPa			
	3 days	7 days	28 days	90 days
1. Plain	31.3	34.2	47.5	54.7
4. Fly ash-admixture	28.7	35.4	47.5	56.4
2. Plain	26.0	30.5	41.5	46.5
5. Fly ash-admixture	21.3	29.0	39.7	52.0
3. Plain	13.7	18.9	27.5	31.6
6. Fly ash-admixture	13.3	19.0	30.4	42.7

*from References (18,30).

TABLE 4

Concrete Tests on Mixes Containing Combinations of Cement, Fly Ash and Water-Reducing Admixtures*

Trial	Mix	Type	Compressive strength 28 days, MPa	Cement content, % by wt	Cementitious content, % by wt	Water demand, kg/m^3	Consistency -slump, mm	Per cent air	Vee Bee, Sec	British compaction factor	Bleeding capacity mortar, kg/m^2	Initial setting time h-min final		Indirect tensile strength, MPa	Modulus of elasticity x10^4, MPa
A	1	Plain	40.6	15.2	15.2	188	80	3.1	1.9	.949	2.5	4.45	6.45	3.95	3.65
	2	Fly ash	44.6	14.1	16.7	182	90	2.3	1.7	.926	2.2	4.40	6.15	4.38	3.61
	3	Admixture	41.3	13.7	13.7	165	80	5.7	2.0	.925	2.1	6.20	8.30	4.00	3.52
	4	Fly ash-admix	39.8	13.1	15.7	170	80	5.2	1.8	.932	2.0	6.30	9.05	4.10	3.41
B	1	Plain	47.5	19.1	19.1	196	80	2.4	2.0	.941	0.9	4.10	5.35	4.49	3.68
	2	Plain	41.5	15.2	15.2	185	85	2.8	1.3	.938	2.4	4.40	6.15	4.52	3.50
	3	Plain	27.5	12.2	12.2	193	80	3.8	1.4	.928	4.9	5.30	7.30	3.56	2.98
	4	Fly ash-admix	47.5	17.0	19.1	173	80	5.2	2.6	.902	1.4	6.10	7.55	4.70	3.55
	5	Fly ash-admix	39.7	13.1	15.7	169	80	5.3	1.8	.916	2.5	6.30	8.25	3.78	3.30
	6	Fly ash-admix	30.4	9.8	13.1	167	80	5.8	1.6	.923	4.3	6.55	8.50	3.37	3.18

*from References (18,30).

Use of Fly Ash in High-Strength Concrete

In recent years there has been considerable interest in the production and use of very high strength concrete- >48 MPa at 28 days. This type of concrete, which is a particular example of the combined practical use of fly ash and water-reducing admixtures, has found applications in the columns of high-rise buildings, especially in the Chicago area. The Chicago Committee on High-Rise Buildings(31) has stated:

> "The use of a good quality fly ash, meeting the specifications of ASTM C618 (Class F), ... is a must in the production of high strength concrete."

For high strength concrete, fly ash functions by providing increased strength at late ages of curing - 56 to 91 days - that cannot be achieved through the use of additional portland cement.

Typical mix proportions for high-strength concrete used in two recent structures in the Chicago area are given in Table 5; the resulting compressive strength values obtained with these mixes are given in Table 6.

Concrete mixes using fly ash of very similar proportions, designed to obtain strengths of 55 MPa (8000 psi) have recently been used in construction in the Toronto area(32).

In recent research studies at CANMET(33), on the performance of crushed sands in concrete, it was shown that fly ash may be successfully incorporated to achieve high strengths. Examples of such mix proportions and the properties of the concretes so produced are given in Figure 7.

TABLE 5

Concrete Mix Proportions and Properties of Fresh Concrete*

Material	Quantity/cu yd	
	Water Tower Place	River Plaza
Cement	846 lb	850 lb
Fine aggregate	1025 lb	1040 lb
⅝-in. stone	1800 lb	--
½-in. stone	--	1730 lb
Water	300 lb	330 lb
Pozzolith 100XR**	25.4 fl oz	43.0 fl oz
Fly ash	100 lb	100 lb
Slump	4½ in.	4½ in.
Air content	--	1.5%
Unit weight	151.9 lb/cu ft	148.8 lb/cu ft

*from Reference (31).
**Proprietary water reducing agent.

TABLE 6

Compressive Strength (psi) Test Data*

Age days	Water Tower Place			River Plaza		
	6 x 12-in. cylinders		4 x 8-in. cores	6 x 12-in. cylinders		4 x 8-in. cores
	Air**	Moist		Yard	Jobsite	
7	--	7,640	--	--	7,310	6,750
28	9,150	9,400	--	10,340	9,410	8,100
56	--	10,580	--	11,240	10,500	10,690
90	9,420	--	--	11,630	11,410	10,460
180	9,210	--	--	13,220	--	--
365	9,700	--	--	--	--	--
730	8,960	--	11,560	--	--	--

* from Reference (31).
**7 days moist curing followed by curing at 73°F and 50% relative humidity.

Use of Fly Ash in Superplasticized Concretes

During the past few years there has been an increase in the use of superplasticizing admixtures, particularly in the production of flowing concrete (concrete with slump values in excess of 200 mm). To correctly proportion such mixes it is desirable to use more sand than is employed in conventional concrete. However it has been found that instead of incorporating excessive amounts of sand, it is preferable to use fly ash to provide the necessary fine particles that give cohesiveness to the mixes(34). It is to be expected there will be an increased use of fly ash in the future for this application.

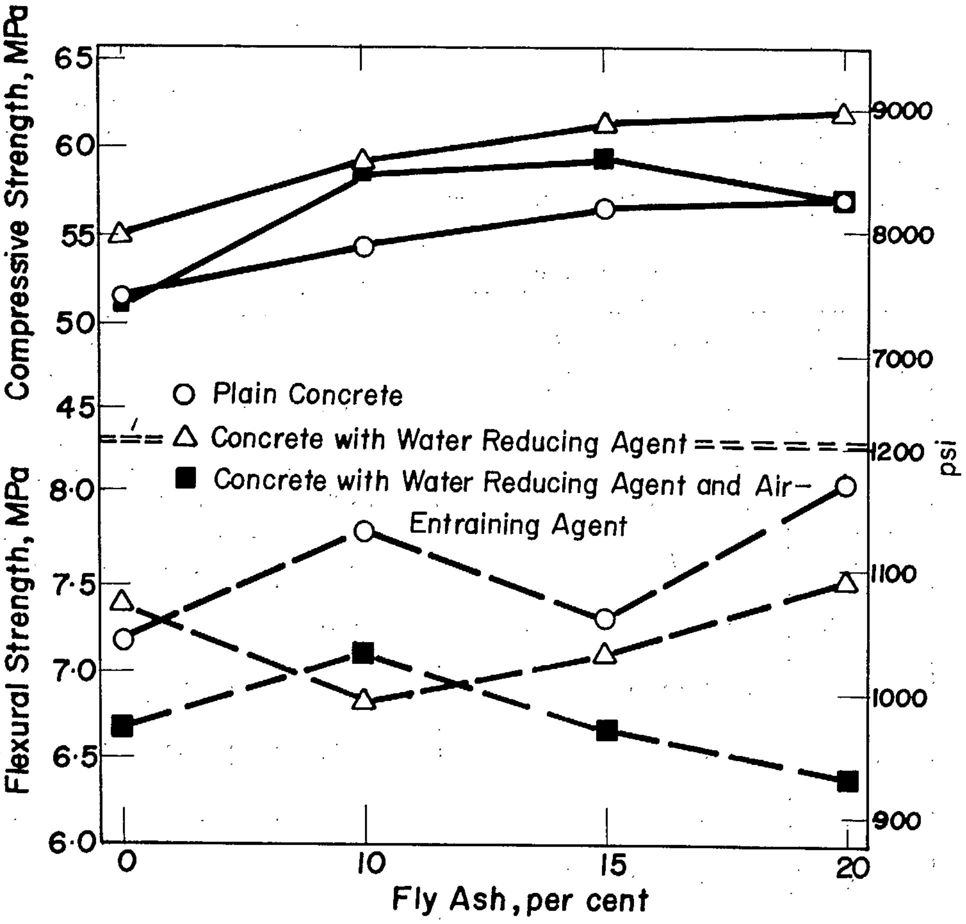

Figure 7. Strength properties vs fly ash content of high strength fly ash concrete mixes at 91 days(33).

From an extensive laboratory study of the combined use of fly ash with superplasticizers, Lane(35) has recently drawn the following conclusions:

> "... superplasticizers are compatible with fly ash in concrete and produce no detrimental effects. The benefits claimed for these admixtures in plain concrete, however, were not as apparent in fly ash mixtures, particularly with respect to compressive strength gains and duration of increased plasticity. Water reductions for equal slump did not exceed 15 per cent, improving this characteristic only slightly over a standard water-reducing agent. The low water reductions can be attributed to the lower water requirement for fly ash concrete as compared to plain concrete for equal consistencies. Since there is less excess water initially available, the addition of water reducers is less effective.
>
> "... superplasticizers are equally effective in attaining a temporary increase in concrete consistency for both fly ash concrete or plain concrete. The highly plastic phase diminishes after 15 minutes and ceases after about 30 minutes with fly ash concrete."

Effect of Fly Ash on Creep Properties of Concrete

Data on creep of fly ash concrete is limited. Lohtia et al.(36) have reported the results of studies of creep and creep recovery under stress-strength ratios of 20 and 35 per cent of plain and fly ash concretes made by placing cement with equal weights of fly ash in the range of 0 to 25 per cent. From this work they drew the following conclusions:

> "(a) Replacement of 15 per cent cement by fly ash was found to be the optimum value with respect to strength, elasticity, shrinkage, and creep for the fly ash concrete studied.

> "(b) Creep-time curves for plain and fly ash concretes were similar with creep linearly related to the logarithm of time.
>
> "(c) Increase in creep with fly ash content up to 15 per cent was negligible. However slightly higher creep took place at fly ash contents higher than 15 per cent.
>
> "(d) The creep coefficients were similar for materials with fly ash contents in the range of 0 to 25 per cent.
>
> "(e) Creep recovery was found to vary from 22 to 43 per cent of the corresponding 150-day creep. For cement replacement beyond 15 per cent, the creep recovery was smaller. No definite trend of creep recovery as a function of stress-strength ratio was observed."

Effect of Fly Ash on Modulus of Elasticity of Concrete

Data on the modulus of elasticity of fly ash concrete is very limited. Abdun-Nur(2) makes the following observations on the basis of five available literature citations.

> "The modulus of elasticity of fly ash concrete is lower at early ages, and higher at later ages(8,37). In general, fly ash increases the modulus of elasticity of concrete when concretes of the same strength with and without fly ash are compared(38-40)."

Effect of Fly Ash on Volume Changes of Concrete

It has been generally reported that the use of fly ash in practicable proportions does not significantly influence the drying shrinkage of concrete. Typical of the conclusions of most researchers in this respect are those made by Davis et al.(8) who comments as follows:

> "For masses of ordinary thickness, such as are normally found in highway slabs and in the walls and frames of buildings, the drying shrinkage at the exposed surfaces of concrete up to the age of one year is for fly ash cements about the same as, or somewhat less than, that for corresponding portland cements. At a short distance from the exposed surface the drying shrinkage up to the age of one year is substantially less for concretes containing fly ash cements than for concretes containing corresponding portland cements. For very thin sections and for cements of normal fineness the drying shrinkage of concrete may be expected to be slightly greater for fly ash cements than for corresponding portland cements. It appears that the drying shrinkage of concretes containing finely ground high-early-strength cements may be somewhat reduced by the use of fly ash."

Figure 8 shows data presented by Elfert(17) comparing the drying shrinkage and autogenous length change of fly ash concrete with plain concrete and concrete made with other pozzolans. Typically, fly ash concrete performed better in these respects than the other concretes studied.

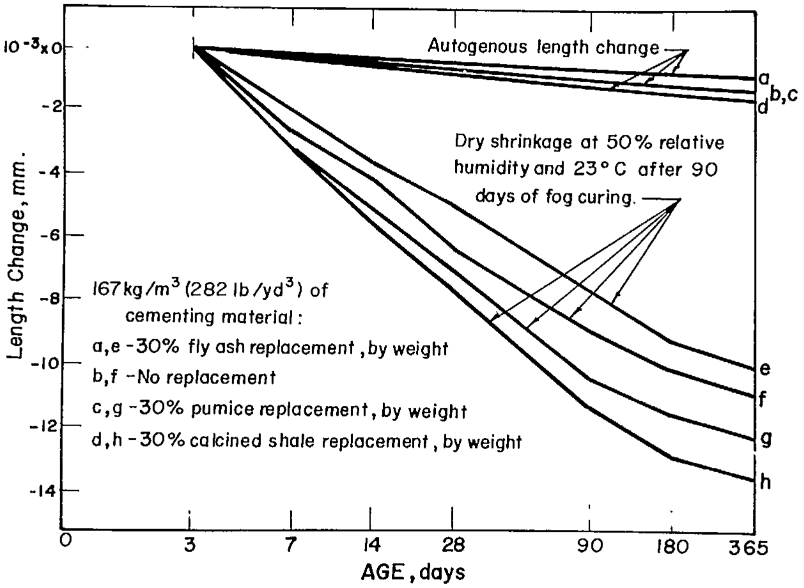

Figure 8. Comparison of drying shrinkage and autogenous length change for concretes made with various pozzolans(17).

EFFECTS OF FLY ASH ON DURABILITY OF CONCRETE

Effects of Fly Ash on Freeze-Thaw Durability

Cycles of freezing and thawing are extremely destructive to concretes that are not specifically proportioned and carefully enough placed to withstand such conditions. It is now generally accepted that air-entrainment renders concrete frost-resistant. Larson(41), presenting work on the use of fly ash in air-entrained concrete and reviewing the work of other investigators(42-47), concluded that the primary effect of fly ash was upon air-entraining-agent demand, rather than upon air-entrainment as such. He summarized his findings as follows:

> "Air-entraining-agent demand in fly ash concrete is primarily affected by carbon absorption of air-entraining agents. It is predictable from tests made on mortars or concretes. A general relationship exists between the required amount of a particular agent and grams of ignition loss irrespective of the type of fly ash. A more clearly defined relationship exists between the demand of a particular air-entraining agent and the ignition loss for a particular fly ash.....
>
> "....ignition loss is readily determinable by a simple laboratory test. It normally correlates very well with carbon content,...
>
> "....Fly ash has no apparent ill effects on the air voids in hardened concrete. When a proper volume of air is entrained characteristics of the void system meet generally accepted criteria.
>
> "Fly ash concrete durability characteristics are influenced and obscured by all the factors operating on ordinary concrete. They are also related to variations in the fly ash itself and perhaps to the associated phenomenon of increased air-entraining-

> agent requirement. When valid comparisons are made with equal strengths and air contents, however there are no apparent differences in the freezing and thawing durability of fly-ash and nonfly-ash concretes."

In a study of six Type IP cements, Perenchio and Klieger(48) found that air-entraining-agent requirements were higher in every case for the Type IP cements than for comparable Type I cements. Increases ranged from 15 to 210 per cent.

In addition to the general considerations discussed above, it has been noted by Elfert(17) that the type of curing of specimens used to evaluate freeze-thaw resistance greatly influences the results obtained with fly ash and pozzolan concretes. Figure 9 illustrates the differences obtained under moist-curing and simulated field conditions.

Another aspect of freeze-thaw testing procedure has been criticized by Brown et al.(49) who made the following comments on freeze-thaw testing of blended cements:

> "When blended cements are tested according to ASTM C666-73, the standard method for measuring the freeze-thaw durability of portland cement concretes, inferior resistance is usually observed. This is probably because test initiation after only a short curing period does not make proper allowance for the generally lower rate of strength development of blended cements.
>
> "Freeze-thaw studies, when initiated after longer curing periods, have indicated that blended cements, due to development of strengths equivalent or superior to those of portland cements, also develop superior resistance to freezing and thawing."

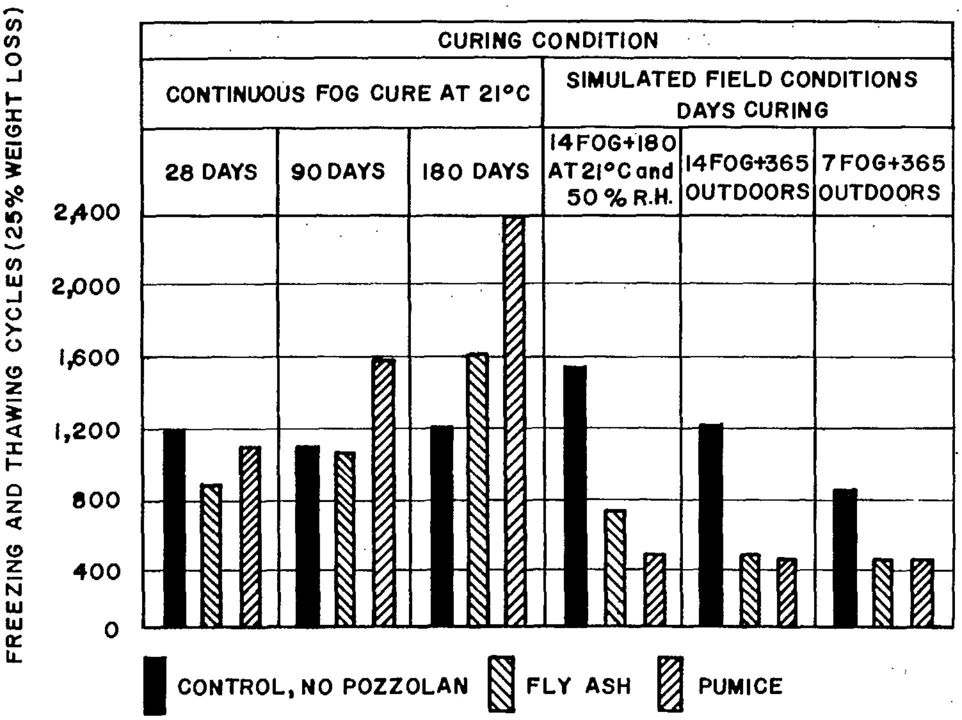

Figure 9. The effect of curing conditions on freeze-thaw durability of concrete containing pozzolan(17).

Effects of Fly Ash on Durability of Concrete Exposed to Chemical Attack

Introducing fly ash as a component of concrete has been shown to influence its durability to chemical attack. Leaching of calcium hydroxide, acidic dissolution of cementitious hydrates, the action of atmospheric and dissolved carbon dioxide and the reactivity of cement components to ions in solution are the main causes of deterioration of concrete exposed to chemical action.

Biczok(50) enumerates four conditions related to concrete quality and the constituents of concrete upon which the destructive effects of aggressive waters depend:

(1) Type of cement used, its chemical and physical properties,

(2) Quality of concrete aggregates, their physical properties and gradation,

(3) Method used for preparing concrete, the water-cement ratio, the proportion of cement, the placement,

(4) Condition of the surface exposed to the water.

Of these, condition (1) relates strictly to the nature of the cementitious binder used whereas conditions (2), (3) and (4) may be grouped under one or more aspects of the permeability of concrete.

With regard to cement type, two factors are influential in determining the relative durability of fly ash concrete:

(i) The chemical composition of the cement, vis-a-vis the cementitious components produced during hydration, has a pronounced influence on the durability with respect to chemical action. The most notable example is the use of low-C_3A, (CSA Type 50, ASTM Type V) cements as a means of controlling attack due to sulphate ions.

(ii) A combination of chemical composition and physical properties, notably fineness, determines the rate at which cement hydration proceeds and, at least for the early life of a structure, must influence its permeability.

Fly ash, used as a replacement for portland cement, has an indirect influence on both factors. At early ages it serves only as an inert component and is therefore similar to reduction in cement content. At later ages it contributes to the formation of cementitious components but, as Kovacs(51) has shown, it does so in a manner which changes the relative proportions of the usual hydrate materials. Finally, it converts some of the calcium hydroxide, that is produced when cement hydrates, to less reactive calcium silicates and aluminates, through the pozzolanic reaction. The removal of free calcium hydroxide by reactive combination with pozzolans was shown by Lea(52) to progress as is illustrated in Figure 10, in which the quantity of free $Ca(OH)_2$ in mortars made with and without pozzolan are compared as a function of age. It is generally considered that in concrete this process leads to long-term gains in watertightness, strength and resistance to aggressive environments.

Except for general recognition of this final point, there seems to have been little consideration given in the research literature to the role played by fly ash in changing the chemical balance of the cementitious components of concrete, either as a factor in concrete durability or in respect to the development of test methods.

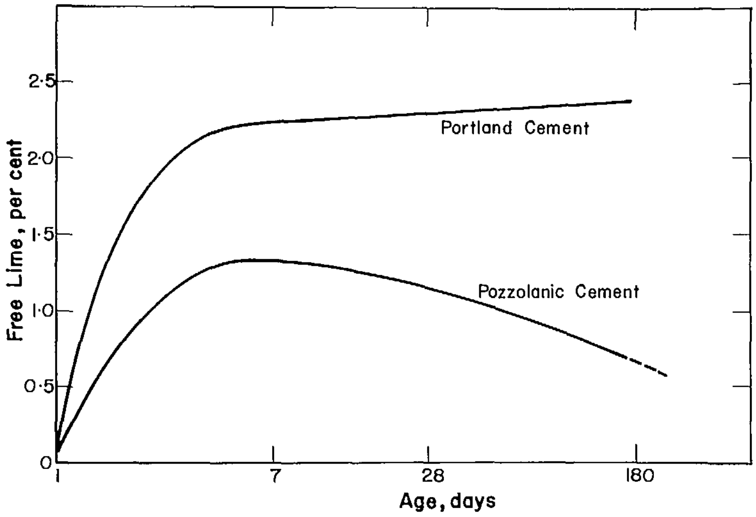

Figure 10. Free lime content of 1:3 cement-sand mortars(52).

Effects of Fly Ash on Permeability of Concrete

The movement into a concrete mass of aggressive solutions or the removal of the dissolved reaction products out of concrete must play a primary role in determining the rate of progress of concrete corrosion caused by chemical attack. Permeability of a concrete mass must therefore be fundamental to determining the rates of mass-transport relevant to destructive chemical action. It should be recognized that all the cementitious hydrates and some of the aggregates from which concretes are made are inherently subject to attack, not only by sulphates, chlorides, acids and organic agents, but by water alone. That concrete survives aqueous environments at all is attributable to (a) the low equilibrium solubility of the hydrated components and (b) the low rate of mass transfer in well compacted, cured concrete. Given any combination of cement and aggregate, it is generally observed that the less permeable the concrete, the greater will be its resistance to aggressive solutions or pure water.

A number of investigations have been made of the influence of fly ash on the relative permeability of concretes. Davis(53) has considered the permeability of concrete pipe containing fly ash substituted for cement in amounts of 30 and 50 per cent. Permeability tests were made on 6 by 6-in. cylinders at ages of 28 days and 6 months. The results of these tests are shown in Table 7.

It is clear from these data that the permeability of the concrete was directly related to the quantity of hydrated cementitious material at any given time. After 28 days curing, at which time little pozzolanic activity would have occurred, the fly ash concretes were more permeable than the control concretes. At 6 months this was reversed. Considerable imperviousness had developed, presumably due to the pozzolanic influence of fly ash. Elfert(17) reported the data shown in Figure 11 comparing the permeability rates of fly ash and non-pozzolan concretes.

Effects of Fly Ash on Sulphate Resistance of Concrete

Resistance of fly ash concrete to sulphate attack is one of the most important aspects of the behaviour of fly ash in concrete. In 1967, Dikeou(54) reported the results of sulphate resistance studies on a total of 30 concrete mixes made

TABLE 7

Relative Permeability of Concretes With and Without Fly Ash*

Fly ash		W/(C + F) by wt	Relative permeability	
Type	Per cent by weight		28 days	6 months
None	-	0.75	100	26
Chicago fly ash	30	0.70	220	5
	50	0.65	1410	2
Cleveland fly ash	30	0.70	320	5
	50	0.69	1880	7

*from Reference (53).

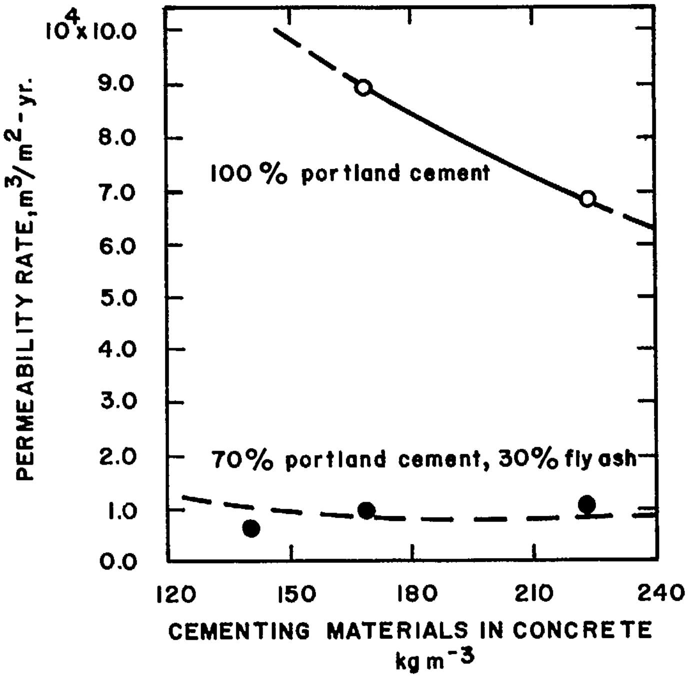

Figure 11. Permeability of concrete with and without pozzolan(17).

from 8 portland cements, 3 portland-fly ash cements and 12 fly ashes. From this work it was concluded that all of the fly ashes tested greatly improved sulphate resistance. The relative order of improvement found in this work is shown in Figure 12.

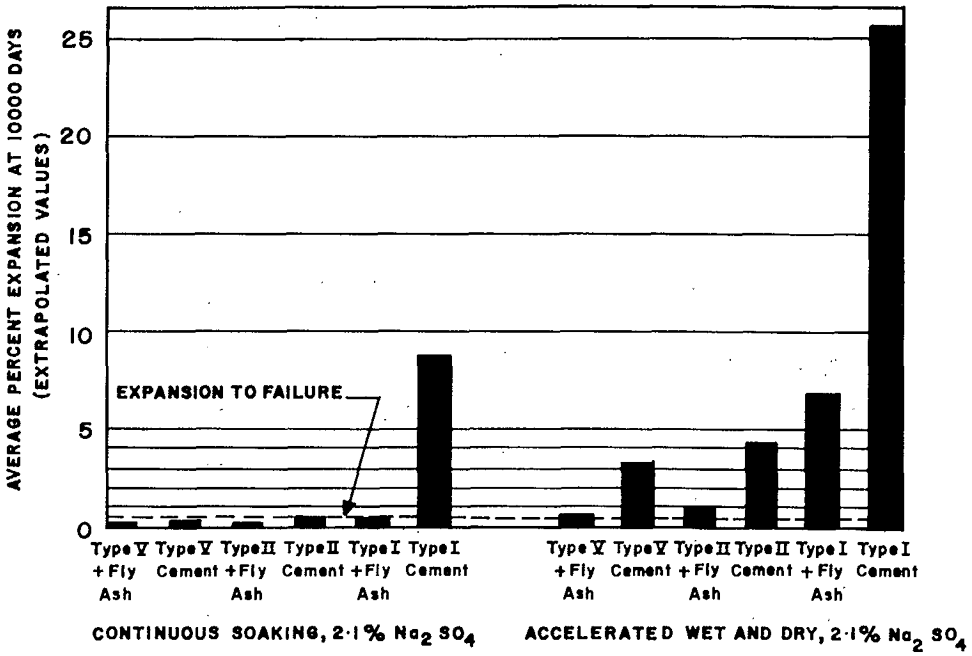

Figure 12. Expansion of concretes containing 30 per cent fly ash[17].

Kalousek, Porter and Benton(55) reported studies on the requirements of concrete for long-term service when exposed to sulphate. From this work they concluded that:

> "1. Eighty-four per cent of the ASTM Types V and II cement concretes without pozzolan showed a life expectancy of less than 50 years.
>
> "2. Certain pozzolans increased very significantly the life expectancy of concrete exposed to 2.1 per cent sodium sulphate solution. Fly ashes meeting present day specifications were prominent among the group of pozzolans showing the largest improvements.
>
> "3. Concretes for long-term survival in a sulphate environment should be made with high quality pozzolans and a sulphate-resisting cement. The pozzolan should not increase significantly, but preferably decrease, the amount of water required.
>
> "4. Cement to be used in making sulphate-resisting concrete with pozzolan of proven performance should have a maximum C_3A content of 6.5 per cent and maximum C_4AF content of 12 per cent. Restrictions of cements to those meeting present day specifications for Type V cement does not appear justified."

The fly ash samples examined by Dikeou(54) and those examined by Kalousek et al.(55) all originated from bituminous coals. In 1976, Dunstan(56) reported the results of experiments on a total of 13 concrete mixes made using fly ashes from lignite or sub-bituminous coal sources. On the basis of this work he concluded that the lignite and sub-bituminous fly ash concrete generally exhibited reduced resistance to sulphate attack.

Effects of Fly Ash on Durability of Concrete in Sea Water

In many ways the action of sea water on concrete is similar to that of sulphate-containing ground waters. For many years pozzolanic cements have been recommended for resistance to sea water attack and it is to be expected that suitably active fly ash could be used for this purpose. This, together with other aspects of the chemical durability of fly ash concretes, urgently requires research.

The mechanism whereby pozzolans reduce sulphate attack is not understood. Lea(52) has reviewed a number of hypotheses and has suggested that the hydrated calcium silicate gel formed by reaction between the pozzolan and calcium hydroxide is deposited as an impervious coating over the surfaces of the alumina-bearing phases. Too little attention has been given to the effects of specimen permeability and degree of hydration at the time of testing to allow a decision on mechanism to be formulated on the basis of past studies. Physical and chemical (both kinetic and reactive) factors are probably involved and much closer control of test variables is needed if this important aspect of pozzolanic activity is to be understood.

Effects of Fly Ash on Alkali-Aggregate Reactions in Concrete

Control or suppression of the alkali-aggregate reaction between cement alkalies and soluble silica in aggregates is a well established property of many pozzolans, including fly ash. Pepper and Mather(57) reported the minimum percentage replacement by volume of cement by fly ash required to reduce expansion in test specimens by 75 per cent. Their results are shown in Table 8.

Elfert(17) reported data of a similar nature from work carried out at the U.S. Bureau of Reclamation (Fig. 13).

While it is clear that some fly ashes are effective in controlling alkali-aggregate expansion, it is questionable whether the early strength losses caused by replacement of 36 to 48 per cent of the cement by fly ash would be tolerable for more than a limited number of applications. The use of such large amounts of fly ash to reduce alkali-aggregate interaction, if required, would certainly demand reproportioning of concrete if acceptable early strengths were to be attained.

During a study of alkali-reactive aggregates in Nova Scotia, Duncan et al.(58) showed effective suppression of expansion by replacement of moderate alkali cement - 0.71 per cent as Na_2O - with as little as 25 per cent of fly ash. Some data are shown in Figure 14.

TABLE 8

Minimum Percentage Replacement of Cement by Fly Ash for Effective Control of Alkali Aggregate Expansion Measured by Mortar-Bar Test

Replacement material	Minimum percentage (by volume) replacement for effectiveness		
	14 days	6 months	Average
Fly ash I	46	36	41
Fly ash II	48	36	42
Fly ash III	52	36	44
Fly ash IV	45	34	40

*from Reference (57)

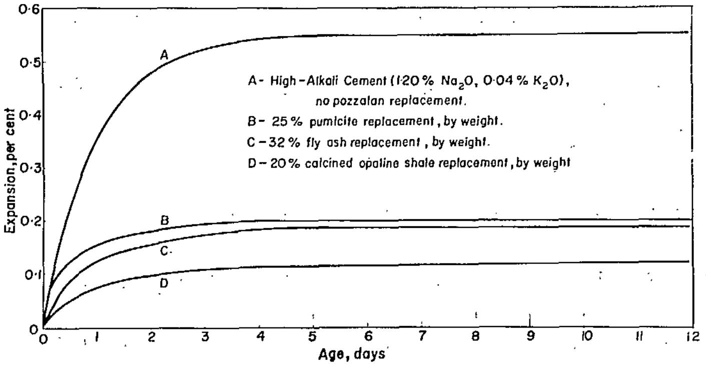

Figure 13. Effect of pozzolan on reactive expansion of mortar made with alkali cement and crushed Pyrex glass sand(17).

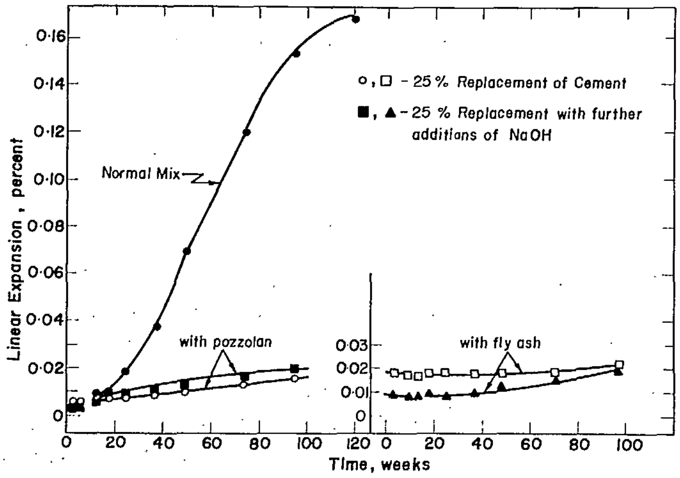

Figure 14. Expansion of concrete prisms made with a metagreywacke aggregate with 25% of cement replaced by a calcined volcanic tuff pozzolan or a fly ash(58).

While it is clear from the above work that the expansive effects of alkali-silica reactions frequently may be reduced by the use of pozzolans, a second form of alkali-aggregate reaction, alkali-carbonate rock reaction, has been shown to be relatively unresponsive to pozzolans(59). As a result, this problem, found in Ontario in connection with dolomitic limestone aggregates from several locations along the southern edge of the Canadian Shield, probably cannot be rectified by the use of fly ash. The long-term ineffectiveness of fly ash as a control of the expansion found with this particular alkali-aggregate reaction is illustrated in Figure 15.

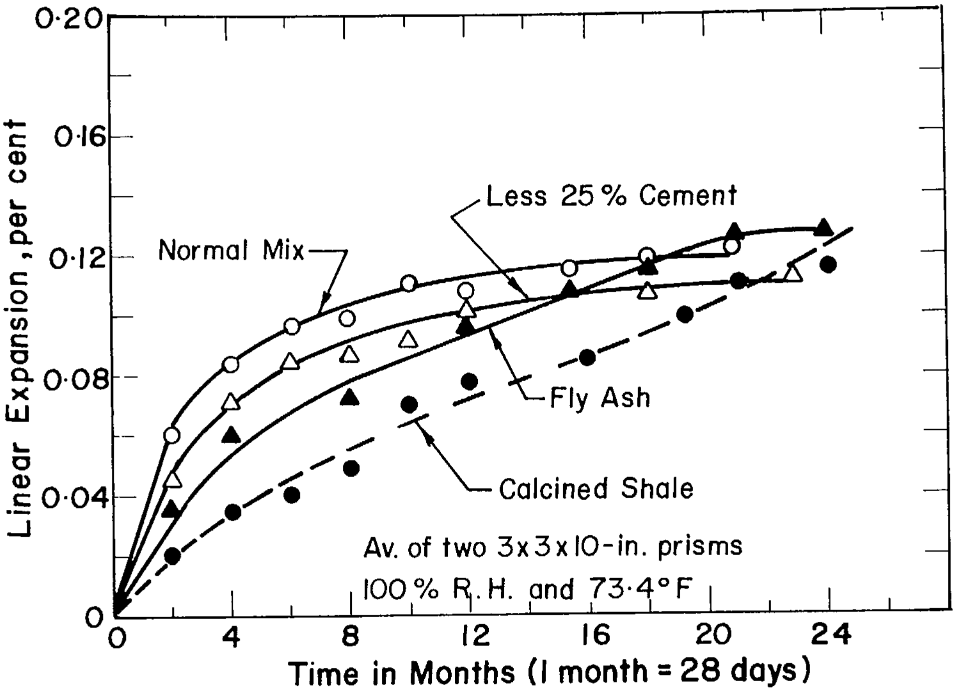

Figure 15. Influence on expansive concrete of reduction in cement and of partial replacement of pozzolans(59).

Effects of Fly Ash on Corrosion of Reinforcing Steel in Concrete

In 1950 the question was raised(60) as to whether there was a possibility of corrosion of reinforcing steel in fly ash concrete by the sulphur-containing components of fly ash. Gilliand(61) noted that most sulphur in fly ash is present as sulphate and therefore would have an effect similar to the sulphate components in portland cement. Further, he pointed out that corrosion of steel is greatly effected by pH - at the high pH prevailing in concrete, corrosion rates would be expected to be slow. Ryan(62) presented further information on the same point and drew the following conclusions.

> "1. The alkaline condition which prevails within concrete so long as the lime is not leached out tends to maintain a protective film of ferrous hydroxide upon the steel surface. This film prevents the easy penetration of water and oxygen to the steel to further corrode the surface. Fly ash does not materially change this alkalinity.
>
> "2. Fly ash, by its pozzolanic reaction, seems to increase impermeability of concrete, thereby decreasing penetration of oxygen and water to the steel. The pozzolanic gel also seems to decrease the amount of the lime which can be leached out of the concrete. This may be due entirely to a physical resistance to the passage of the water due to its peculiar structure, or to a chemical fixing of the lime as some investigators believe.
>
> "3. Sulfur compounds in fly ash are usually so limited by specifications that they are not materially different in the concrete, whether fly ash is used or not. Moreover, the alkaline condition in the concrete is unfavorable to a sulfate attack on steel.

> "4. Carbon in fly ash would appear by theoretical considerations to be much more significant in concrete than is sulfur. The actual effect should be investigated. However, if it is kept under 3 per cent in the fly ash its percentage in the concrete becomes so small that if it is well dispersed its effect on the electrical conductivity of the concrete, and therefore upon the corrosion of the steel, should be quite minor."

These conclusions seem to be generally acceptable in the light of reported research which has shown that fly ash concrete does not decrease the corrosion protection of steel reinforcing when compared with normal concrete (14,63,64). One recent study by Larsen et al. (65,66) has found that corrosion protection is increased by the inclusion of fly ash in concrete.

GENERAL COMMENTS AND RECOMMENDATIONS FOR RESEARCH

Almost all of the research literature on the subject of the use of fly ash as a pozzolan in concrete concerns studies wherein fly ash concretes have been compared directly with a portland cement control mix. As Rosner (26) has pointed out, in most of these studies the realization has been lost that unique products are being compared. Fly ash concrete is a material similar to portland cement concrete but with significant differences and with specific properties that may or may not suit given performance requirements.

For example, fly ash reacts as a pozzolan to form cementitious hydrates similar in composition to those formed by portland cement (51). However, the rate at which this occurs is very much slower than that of portland cement. To attain satisfactory early strength, concrete mixes must be proportioned to accommodate this property. This may range from a simple weight-for-weight substitution of fly ash for cement, where the job does not require early strength, to a very careful reproportioning for the job that demands the early strength normally obtained with portland cement. The literature provides methods to this end which combine a knowledge of the properties of a specific fly ash and the freedoms of proportioning available with concrete materials. This freedom of proportioning results from the fact that concrete strength is not uniquely determined by the rate of formation of cementitious hydrates. Material gradation and total void space, as influenced by water-cement ratio, are variables that allow the concrete engineer to accommodate the use of fly ash to attain desired properties while minimizing the effects caused by reduction of the portland cement content. In a simplified way it may be useful to regard fly ash used to partly replace portland cement as an inert component during the earliest stages of curing that subsequently, at a relatively slow rate, becomes a contributing part of the cementitious mass, thereby increasing the gel-space ratio, contributing to strength and reducing permeability.

Taking this approach allows a coherent view of the behaviour of fly ash concrete to be developed as follows:

(1) Immediately on mixing, cement hydration commences as it does in ordinary concrete. The presence of fly ash modifies the relative proportions of cement and fine

aggregate. Those characteristics of fresh concrete that depend upon the relative proportions of water and solids are modified by the specific properties of the fly ash and may be accommodated by mix proportioning procedures.

(2) As curing proceeds, the contribution made by fly ash to the cementing phases increases if, and only if, (a) the ash is an adequate pozzolan; (b) the mass retains or is provided with enough water to support the pozzolanic action.

(3) A time is reached when the strength, and perhaps more fundamentally the gel-space ratio, of fly ash concrete and a comparable portland cement concrete are equal. Prior to this time, durability, impermeability and strength are likely to be reduced for the fly ash concrete. After this time they progressively increase and ultimately may exceed the same properties in a comparable portland cement concrete.

This overview of the role of fly ash in concrete points to some directions that future research could take to delineate the limitations and advantages of fly ash concrete. For example:

(1) Equal strengths at any age to that of a control concrete can be obtained in fly ash concrete by correct mix proportioning techniques. The controlling factors are fly ash properties and relative costs. There seems no reason why equal or better durability and permeability

properties cannot be attained through similar proportioning methods if research is applied to the fundamental aspects of the durability of fly ash concretes.

(2) The inter-relationships between degree of hydration, gel-space ratio, strength, permeability, and durability of fly ash concrete should be examined.

(3) Specifications and testing methods should be developed which recognize and utilize the differences between ordinary and fly ash concretes, rather than assuming only that fly ash is a substitute to be tolerated more than valued. For example, there is little to be gained by comparative evaluation of fly ash and portland cement concretes for sulphate, freeze-thaw and leaching resistance at stages of curing prior to the time of equal strength or equal degree of hydration.

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