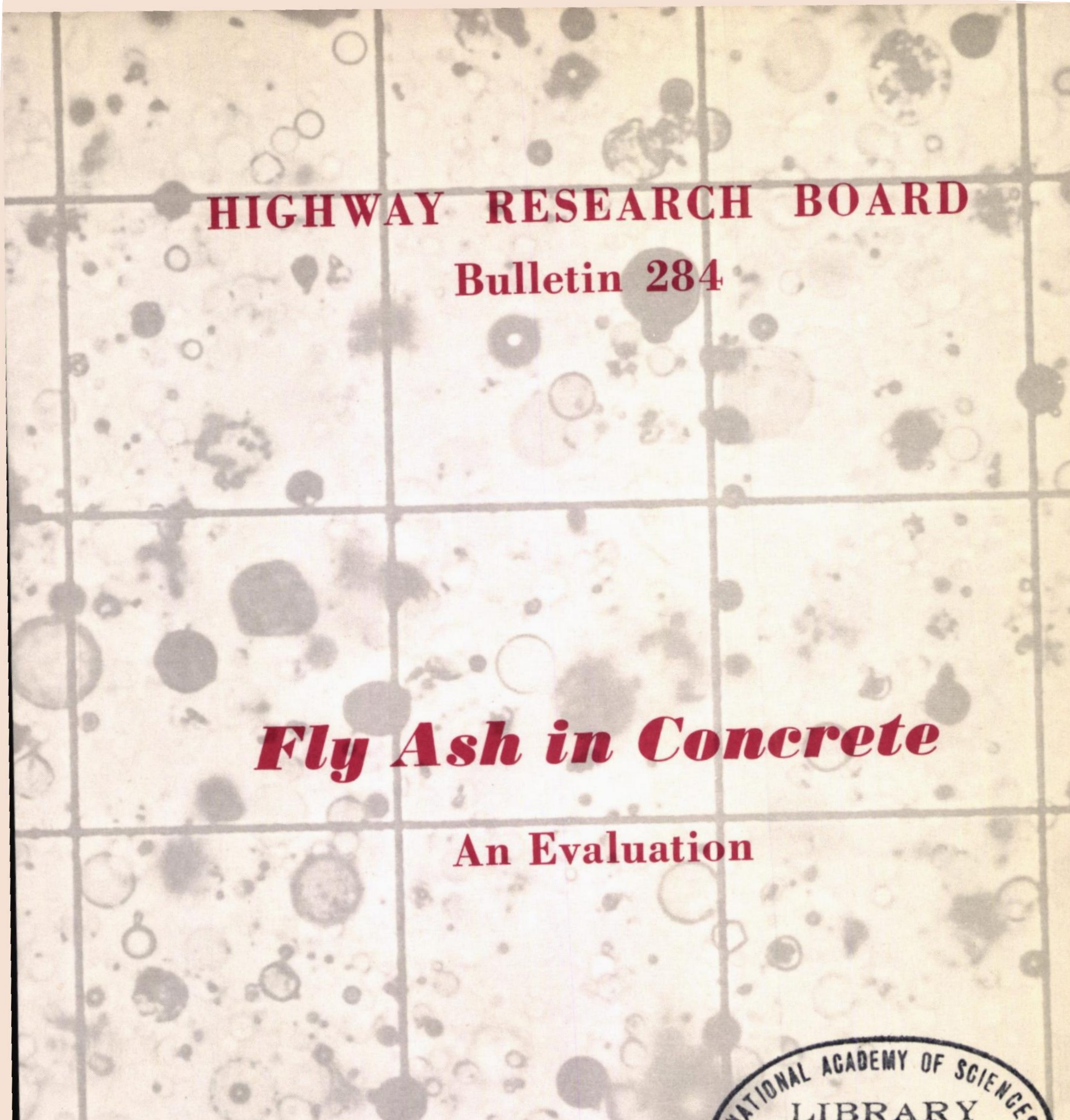

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An Evaluation

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Bulletin 284

Fly Ash in Concrete

An Evaluation

by

EDWARD A. ABDUN-NUR

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Preface

This evaluation of the use of fly ash in concrete is based on a review of the literature on the subject from 1934 to 1959, supplemented by examination of structures in which fly ash has been used, visits to laboratories engaged in work on fly ash, discussions with individuals currently engaged in research and construction involving fly ash—all considered in the light of the writer's experience and judgment.

The underlined numbers in parentheses refer to the bibliography items. Because some topics have been treated extensively by so many authors, it has been necessary to limit the references, in these cases, to a few significant items.

The aim has been to cover all information of importance, and to include in the bibliography all technical papers relevant to the subject. It is felt that the coverage has been sufficiently comprehensive to permit a complete picture to be developed.

Every effort has been made to maintain objectivity throughout the work. In abstracting, the abstractor may not always be successful in developing the author's viewpoint. It is hoped that the authors will bear with the writer in such instances.

The principal aim has been to develop established trends. As a result, generalizations had to be made without detailing all exceptions.

Edward A. Abdun-Nur

COVER PICTURE

Photomicrograph of Fly Ash (X1000)

Note spherical shape of hollow glossy particles, and large irregularly-shaped carbon granules. Superimposed grid is 325-mesh—lines spaced 44 microns center to center, with 1 mm = 1 micron.

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Evaluation of Fly Ash in Concrete

Fly ash, the collected powder from flue gases, consists mostly of fused ash particles, with some unburned granules of coal—the result of combustion of powdered coal in modern boilers. In the past 25 years this waste product has become increasingly expensive to dispose of. It is estimated that about $17,500,000 per year is spent for its disposal. This has resulted in efforts to develop useful applications that will eliminate the disposal problem, and will eventually turn a costly liability into an income-producing asset.

While many uses have been tried and discarded as being uneconomical, uncompetitive, or impractical, and sundry other applications have been found feasible, but do not utilize significantly large quantities of fly ash, its use in concrete work has found favor all over the industrial world where fly ash disposal is a problem. The use of fly ash has a potential that, if fully exploited, might become a solution which could eventually turn a $17,500,000 expenditure into an equivalent amount of revenue from its sale, thus an eventual gain of approximately $35,000,000 annually.

Applications that may offer considerable disposal potential such as soil-lime stabilization (the only practical and economic method known for stabilizing heavy soils), manufacture of brick, special building blocks (not involving portland cement), and other minor uses are not covered in this study.

Bituminous Concrete and Bituminous Products

One of the phases of concrete in which fly ash has proven satisfactory is dense graded high type bituminous concrete and bituminous product mixes. In this application, fly ash as a filler material replaces the presently used limestone dust, or other finely powdered material.

Used in this manner, it has a potential of utilizing larger amounts of fly ash than the asphalt in the mixes. Full benefit of this possibility has not been realized, principally because of the entrenchment of the limestone dust industry, and lack of concerted promotion. Yet, fly ash can generally be delivered to the asphalt plant at a much lower cost than the limestone dust or other fillers. Detroit Edison Company appears to be the principal fly ash producer to take advantage of this application on a large scale.

A conservative estimate of the potential use that could be developed in this field is about 1,000,000 tons of fly ash per year.

Lightweight Aggregate

The lightweight aggregate field, another of the possible uses of fly ash in concrete, is in the opinion of the writer the largest potential. This, because the use of lightweight concrete is increasing at an extremely rapid rate, and because every cubic yard of this lightweight concrete utilizes about one ton of lightweight aggregate (a little less for the structural grade and more for building blocks).

In comparison, a cubic yard of bituminous concrete contains 250 to 400 pounds of fly ash filler, while a cubic yard of regular portland cement concrete will have 100 to 150 pounds of fly ash. These figures will vary widely with the materials and mix porportions, but are reasonable averages for this comparison.

The estimated annual lightweight aggregate production is between 8,000,000 and 10,000,000 tons. If fly ash lightweight aggregate could eventually capture ⅓ of this market, it would mean a potential disposal of 3,000,000 tons of fly ash. The basic scientific principles and processes have already been worked out. Additional research and development are needed to make this a reality.

Portland Cement Concrete

The best known use of fly ash in concrete is as an additional ingredient in portland cement mixes, resulting in a concrete with improved properties, and in most instances reduced cost. Very frequently some savings in cement can be effected. Among the improvements that fly ash imparts to concrete mixes are:

- Pozzolanic properties
- Lower water requirement
- Improved workability
- Reduced segregation
- Reduced bleeding
- Somewhat retarded time of set (well within acceptable limits)
- Lowered heat of hydration
- Reduced volume change
- Increased extensibility and plastic flow at early ages (thus accommodating early shrinkage with less cracking)
- Improved molding qualities
- Adequate strength (varies with mix and fineness of fly ash)
- Increased modulus of elasticity
- Reduced permeability
- Reduced alkali-aggregate reaction
- Reduced cement-aggregate reaction (in sand-gravel aggregate areas)
- Adequate freezing and thawing resistance (with air entrainment and proper curing)
- Increased resistance to sulfate action

Occasional doubts are expressed regarding the resistance of fly ash concrete to salts, to abrasion, and to freezing and thawing, when the concrete is not cured adequately. With no reliable information available regarding these factors, research is required to determine the facts, and develop solutions where necessary.

As an ingredient in concrete mixes, fly ash can be used in amounts varying from 100 to 150 pounds per cubic yard. This use is very well established, and the only drawbacks are the handling and mix control of an extra and somewhat difficult to manage material, and the reputed low early strength. These problems can be solved with present-day knowledge, namely, through proper equipment for handling and batching, and improving the early strength by the use of larger proportions of fly ash, addition of proper trace chemicals, addition of water reducing admixtures, or intergrinding of fly ash with cement clinker.

Building blocks, precast, and prestressed concrete members represent a specially attractive field for the use of fly ash in portland cement, because handling of materials is centralized in a plant and is therefore less of a problem, and because the high temperature curing used in these operations develops the higher early strengths. Advantages of fly ash to these operations are reduced wear on the forms and equipment, better molding qualities, and reduced costs. Thus, this field profits not only from the regular advantages of fly ash in portland cement concrete, but has the added benefit that it does not suffer from the disadvantages, and is therefore an excellent potential outlet.

Fly ash should be considered as an ingredient in concrete imparting certain desirable properties, and not as a "replacement" of cement, as the latter may imply to some, that fly ash is "not as good" as cement. As an additional ingredient, the practical usefulness of fly ash depends on the distance of the source from the large project or the concrete products plant. This potential can be increased manyfold by intergrinding the fly ash with the cement clinker at the cement mill, resulting in a single cementitious product that does away with handling and batching an extra ingredient, and at the same time improves the early strength. This makes it use feasible on every small job, and thus opens up a tremendous field. There has been some resistance to the production of such a cement in this country, but the reports from Europe are very encouraging. Study of the European methods, research and development to adapt them to American conditions, and some method of overcoming the resistance against the production of such a material are needed to permit the realization of full advantage of this development.

Another use in concrete, that has not received much attention in the United States, is as a raw material in the manufacture of portland cement. In this application it competes with other sources of silicates, aluminates, and iron as raw material compounds.

Thus, in addition to minor uses such as grouting mixtures, and sealing of oil wells, there are at least four major fields having large potential for the use of fly ash in portland cement concrete:

1. Light weight aggregate
2. An ingredient in ordinary concrete and precast products
3. Interground with cement clinker to produce a better cement
4. As a raw material for regular portland cement

Research and Development

Research and development have been the cornerstones of industrial advancement and growth. The largest growth has occurred in industries that have engaged in the most active and extensive research. Fly ash is no exception, if its use is to be broadened and extended, and if the large disposal cost is to be eliminated and eventually turned into a revenue. Research on several fronts is clearly indicated by this study, to remove the doubts about certain properties of fly ash concrete, to solve problems, to develop processes, and to accumulate data needed for the proper utilization of the material. The most important are:

1. Research and development work on lightweight aggregate in the light of what has been done in Europe and in this country to adapt processes to American industrial conditions, and to develop background data of its properties and uses as compared to existing lightweight aggregates. The use of fly ash lightweight aggregate in bituminous mixes needs investigating also.
2. Research and development work on the intergrinding of fly ash with portland cement clinker, or with slag and portland cement clinker (in the light of European experience), to permit the elimination of the handling of fly ash as a separate material, thus extending its advantages to the small job and at the same time improving the early strength that has been a deterrent to its use in many structural applications.
3. Research regarding the resistance of fly ash concrete to freezing and thawing when subjected to short, moist curing periods (which are the rule), the resistance to abrasion (which is important in highway work), and the resistance to salts for de-icing highways in winter. Solutions to these problems are probably closely tied up with the improving of early strength through intergrinding, inasmuch as present doubts have resulted from comparing fly ash concrete with plain concrete on the "equal age" basis, rather than on

an "equal strength" basis. The latter becomes realistic with present-day methods of improving early strength. It may very well turn out that these doubts, concerning fly ash concrete, will completely vanish as it becomes more and more practical to compare fly ash concrete with plain concrete on an "equal strength" basis.

4. Research and development work on the use of fly ash as a raw material in cement manufacture to help broaden its present-day limited use in this field.
5. Research regarding the high temperature curing as it applies to building block, and various precast and prestressed units, is needed to determine the best cycles for developing the optimum pozzolanic properties, thus making it possible to increase this field of fly ash utilization.

It has been estimated that about $75,000 is being spent each year on fly ash research. Most of this is carried on sporadically by individual electric generating companies, or individual fly ash distributors. Much of this effort overlaps, and thus incurs an inefficient use of funds. For the research recommended, an over-all coordinated program is needed—one with sufficient funds to push research at a rapid pace, since the faster the information is gained, the earlier the reduction in disposal cost. Properly planned, coordinated, and directed research would in a few years result in information that would clarify the doubts and provide knowledge on the questionable properties and applications of fly ash, which have been revealed by this study.

As estimated, the eventual potential total gain for the fly ash producers is of the order of $35,000,000 per year. The increased use of fly ash as a result of such research is estimated to result in a gain of another $35,000,000, divided between the distributors and the users. The creation of wealth equal to four times the disposal cost cannot be ignored. It is a challenge to everyone concerned.

● FLY ASH is the very fine residue from the burning of powdered coal, collected in the stacks of power plants by mechanical means or by electrical precipitators, or a combination of the two (43, 102, 111, 180, 205, 206). In most instances, the fineness of fly ash equals or exceeds that of portland cement.

Fly ash consists for the large part of solid or hollow spherical particles of siliceous and aluminous glass, with small proportions of thin-walled, multi-faced polyhedrons called "cenospheres," of reddish particles high in iron, and of irregularly shaped, relatively porous carbon or carbon-coated particles (53, 102, 111, 119, 152, 194, 205, 226).

The fineness, chemical composition, and physical properties of fly ash vary depending on the source of coal, method of burning, combustion equipment, variation in load on the boilers, and methods of collection (16, 17, 43, 65). Thus one can expect relatively large variations between plants, but the product of one plant, using one source of coal and operating on a steady load, is generally uniform.

Many chemical and physical analyses of fly ashes are found in the literature, most of which fall within the following ranges (3, 29, 101, 135, 158, 205, 226):

		Percent
Silica,	SiO_2	28.1 - 51.26
Alumina,	Al_2O_3	15.12 - 34.04
Iron Oxide,	Fe_2O_3	3.86 - 26.43
Lime,	CaO	1.00 - 10.59
Magnesia,	MgO	0.55 - 1.91*
Sulfur Trioxide,	SO_3	0.23 - 3.59**
Ignition Loss		0.56 - 31.56

Specific Gravity	1.88 - 2.84
Passing No. 16 Sieve	99.40 - 100.00
Passing No. 325 Sieve	62.4 - 97.9
Fineness, Blaine (square centimeters per gram)	2,007 - 6,073

*Usual range, but occasionally it is found in traces only and at times in excess of 3 percent.

**Usual range, but occasionally it has been found as high as 12 percent. One case of a cyclone type burner is known to have produced fly ash with 17 percent SO_3.

The Fe_2O_3, Al_2O_3, and SiO_2 tend to concentrate in the finer particles, while the carbon predominates in the coarser grain sizes (152).

The color varies from light to dark gray, and in some cases is brownish. Generally, the darker the color, the higher the carbon content.

Fly ash, as collected, is usually basic in reaction. The coarser particles give an acid reaction, while the material passing the No. 400 sieve has a high pH (158).

Grinding, to a fineness of about 10,000 square centimeters per gram, increases the specific gravity to 2.7 (226). Fly ash softens at 1,850° to 2,300° F and fuses at 2,550° to 2,750° F. On calcination, it changes from a gray to a salmon color (53, 243).

HISTORY AND PROBLEM

The fly ash problem developed when the rapid growth in the use of powdered coal in power plants encountered the increasingly restrictive regulations against discharge of smoke, particularly in densely populated areas. The magnitude of the problem may be seen when it is realized that for each ton of powdered coal burned, from 160 to 280 pounds of fly ash are produced. Using the new cyclone burners which utilize crushed instead of powdered coal, as little as 40 to 70 pounds of fly ash are obtained per ton of fuel used. However, only a very small percent of the generating capacity is equipped with these burners at present. With this type of burner, the ash that would otherwise go up the stack as fly ash, is recovered as molten slag, which then presents a problem of disposal in itself, so that in one way or another the ash from the coal presents a disposal problem. As slag, it is good as fill material only, or it might possibly make a pozzolan by grinding (no information regarding this has come to the attention of the writer), but as fly ash it appears to be one of the best pozzolans, a market for which can be developed with a small investment in research and promotion.

The restrictions against the discharge of fly ash through smokestacks led to the development of collecting systems of various types and efficiencies. At first, it was simple to dispose of the relatively small amounts collected, by dumping in nearby locations, but before long, such available sites grew scarcer and more distant while the quantities of fly ash being produced and collected increased at a phenomenal rate. This has been the experience not only in the United States and Canada, but also in other industrial nations utilizing powdered coal, such as Australia, England, France, Germany, and Japan.

In the United States, Weinheimer (158) estimates that the 1953 production of about 6,000,000 tons will increase to nearly 17,000,000 tons by 1963. Homsher's (189) estimate of an eventual production of 17,000,000 tons agrees with the latter figure. In Canada, Durie (238) estimates the present production at about 32,000 tons, and expects it to reach the million-ton mark by about 1975. In Great Britain (163), the 2,000,000 tons estimated as the 1955 production are expected to double by 1960. Jarrige (243) in France estimated the production in 1957 at over 3,000,000 tons.

As the quantities of fly ash being produced increase, the disposal problem becomes more difficult and costly (68). The cheapest form of disposal is dumping near the source. It takes 1¼ to 1½ cubic yards of dumping space for each ton of fly ash (158). Conveniently available dumping areas are therefore fast becoming scarce, and the longer hauls needed to reach available locations increase the disposal cost appreciably. In 1948, dumping costs in the United States varied from 14¼ cents to $1.50 per ton, with an average of 66 cents. By 1954 this average had risen to 95 cents (158), and by now it has probably reached a cost of well over a dollar. In 1954 Weinheimer (158) estimated that the disposal of fly ash loaded the use of pulverized coal with a charge of 7.7 cents per ton, and that when a charge of 22½ cents is made to pulverize coal, other fuels may become more advantageous.

The seriousness of the disposal problem has resulted in concentrated efforts to find uses for fly ash, and turn a liability into an asset (224). Jarrige (243) estimates that the sale of fly ash in France produces revenue equal to the cost of dumping. This is augmented through advantages and savings by its use, and profits in merchandising it, resulting in the creation of wealth equal to the savings for dumping plus the sales price, thus effecting a total creation of wealth equal to four times the cost of disposal. He concludes that no one can afford to neglect such economic possibilities, which turn a loss into an asset four times as large.

USES OF FLY ASH

The efforts to find outlets for this waste product of power production have resulted in developing many uses (2, 5, 12, 14, 23, 24). Many of these uses can utilize very small amounts of fly ash; others, which can account for the use of appreciable quantities, are seasonal in nature, or have encountered strong sales resistance due to already established competitive products for the same purposes (16, 18, 31, 33, 43, 53, 64, 65, 68, 78). The fineness and dust hazard of fly ash, and some of the difficulties in handling it—it has been described as behaving like "liquid smoke"—have developed resistance to its use in many instances (65, 78, 140, 194).

Among the best-known uses are:

Filler in rubber (31, 43, 68, 159)
Filler for paint and putty (68, 78, 102, 152, 159)
Repairing top rot in power poles (27)
As insulation (5, 65, 78)
Raw material for glass (216, 243)
Raw material for bricks (7, 38, 53, 65, 70, 78, 99, 102, 149, 193, 195, 238, 243)
Miscellaneous types of building blocks (2, 5, 6, 12, 14, 34)
Rostone block (2, 5, 6, 12, 14, 68, 78)
Cementing material for miscellaneous aggregates (33)
Filter layer under pavements (243)*
Foundry work (43, 65, 78, 102)
Soil improving agent (43)
Glazed tile (38, 55, 243)
Soil stabilization (43, 65, 78, 151)
Sand-blasting (to replace sand for cleaning turbine blades) (12, 25, 78, 101)
Filler for bituminous concrete (12, 31, 53, 56, 65, 68, 93, 102)
Filler for bituminous products (12, 31, 243)
Lightweight aggregate (34, 36, 53, 75, 161, 214, 216, 238, 243)
Cement manufacture (12, 20, 26, 38, 43, 78, 105, 107, 113, 121, 216)
Concrete construction (various purposes) (3, 12, 16, 31, 45, 79, 81, 102, 216, 226, 243)
Portland cement building block (38, 39, 53, 54, 68, 84, 114, 119, 162)
Concrete pipe (35, 37, 39, 53, 114, 146)
Precast concrete products (5, 159)
Prestressed concrete units
Grouting (49, 53, 246)
Lightweight concrete (43, 88, 104, 118, 149)
Oil well sealing (109)

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*Fly ash can be compacted with an optimum moisture of 25 to 30 percent, and has a relatively high water retention of 40 to 50 percent (243).

SCOPE OF STUDY

This study is concerned primarily with the use of fly ash in concrete construction, and does not deal with many of the miscellaneous uses enumerated above. However, some of the uses related to concrete, which can account for the disposal of large quantities of fly ash, will be touched upon briefly insofar as they have come to the attention of the writer in his study of the concrete problem.

Of the potential uses that could utilize appreciable quantities of fly ash, soil stabilization, special blocks (not using portland cement), and brick manufacture, are being intentionally excluded from this study as being definitely outside the concrete field.

Bituminous Concrete and Bituminous Products

In bituminous construction, fly ash is used as a filler or as a lightweight aggregate. The latter use has not been developed in the Unived States because lightweight aggregate from fly ash is not being produced commercially, so that this discussion is restricted to the use of fly ash as a filler in bituminous work. The earliest work on this utilization was done by the Cleveland Electric Illuminating Company and the Detroit Edison Company, starting in 1932 (12, 31, 43, 56, 78, 94, 95, 158, 209). Detroit Edison Company had this application well under way by 1939, and has since successfully disposed of relatively large amounts of fly ash for this purpose.

In 1952, the Bureau of Public Roads reported tests (93) which indicated that fly ash makes a superior filler for use in asphaltic concrete. Fly ash is hydrophobic and therefore reduces the tendency towards stripping, has good void filling capacity, and provides good stability (56).

In some areas, interests with large investments in plants for making limestone dust for filler have succeeded in thwarting the use of fly ash, even though fly ash delivered to the asphalt plant may cost half what limestone dust does.

Fly ash has been used successfully in bituminous products made in industrial plants (12, 31, 243). This use can account for relatively small quantities of fly ash but is normally a year-round market, as contrasted with the larger construction field, which is of seasonal nature.

Lightweight Aggregate

Many attempts to utilize fly ash for the production of lightweight aggregate have been made, the most successful of which have been in Europe, particularly in England (34, 36, 53, 75, 161, 164, 167, 181, 190, 193, 214, 216, 238, 243). Some activity is under way in the United States, and it is possible that some commercial plants will be producing it competitively before long.

The interest in lightweight aggregate stems from the fact that the demand for this commodity has been increasing at a very rapid rate. The outlook is that the rate of increase will continue to accelerate for many years to come. Advantages for the use of lightweight concrete are not only its lightness which results in structures with lighter foundations and structural members, but also its concomitant sound and heat insulating properties, and resistance to fire.

From the fly ash disposal standpoint, the lightweight aggregate field meets the ideals for a good market as outlined by Weinheimer (158).

SINTERING PROCESS

The most comprehensive work in the field of making lightweight aggregate from fly ash has been carried on in England, where various processes and types of equipment have been tried. The most promising process involves forming the fly ash powder into pellets, then heating these to incipient fusion temperature, thus sintering them to a hard, strong product having a density of 37 to 52 pounds per cubic foot (217)—a weight of the same general order of magnitude as that of many other lightweight aggregates.

Sintering may be defined as the passing of air through a layer of material that will support combustion and thus consolidating the particles by thermal bonding (196, 217). Because of the fine texture of fly ash, it is necessary to pelletize it prior to sintering in order to be able to force air through it.

Normally, very little or no binder is used in the pelletizing process, and no fuel is added as the carbon particles in the fly ash will usually support combustion to produce the required temperatures. As little as 2½ percent carbon in the fly ash will suffice under proper circumstances (238). Fuel may be added in the form of powdered coal if necessary, and a binder is used in some cases to hold the fly ash particles together.

EUROPEAN WORK

A full-scale plant has been built in England (190, 196, 207, 238), for an ultimate capacity of 300 tons per day utilizing two vertical kilns. The aggregate is marketed in three size classifications and is known as "Terlite."

Comparison of this aggregate with three other commercially available lightweight aggregates indicates that with the same cement content and fine and coarse aggregate proportions, Terlite gives the strongest mix, and is the third heaviest. It is estimated that Terlite mixes will require about 1½ sacks less cement per cubic yard of lightweight concrete than other mixes for the same strength (238).

Jarrige (France) (243) describes the different methods of pelletizing, and sintering in vertical furnaces, rotary kilns, and by the use of traveling grates.

Gumz (Germany) (214) describes a sintering belt and shaft kiln used to sinter fly ash for aggregate.

CANADIAN EXPERIMENTS

Ontario Research Foundation of Canada, using Canadian fly ash, conducted experiments in which fly ash was pelletized and fired in a rotary kiln. Because the vitrification range of fly ash seemed to be short, this process was sensitive to over- or underburning. The work has progressed sufficiently to indicate the feasibility of producing lower weight aggregate than that from expanded shale. However, the concrete-making properties of this aggregate are not yet shown (238).

UNITED STATES DEVELOPMENT

In the United States, Leftwich reported mixing fly ash with slag, sintering, then crushing and sieving to proper sizes. The resultant aggregate was used for making building blocks (34).

Another lightweight aggregate known as "Sinter-Lite" was reported being produced in the Bronx, New York, in 1947 (36), by sintering fly ash at 2,400° F, then crushing and grading it. Fly ash was obtained from the Consolidated Edison Company, and contained 6 to 20 percent carbon. The product weighed 34 to 56 pounds per cubic foot, and the production was about 125 cubic yards per 8-hour day. This was used in making building blocks—4,800 units per day.

Research on lightweight aggregate from fly ash was also conducted in 1950 at Alfred University (75). It indicated the feasibility of pelletizing and heating the fly ash in a rotary furnace at 2,200° F, which resulted in lightweight aggregate weighing 38 pounds per cubic foot. Another process, in which fly ash was sintered and then crushed, produced aggregate weighing 40 to 50 pounds per cubic foot.

Garloni (212) obtained a patent on pelletizing and then expanding pellets into lightweight aggregate.

A pilot plant has been developed by Koppers Company in Pittsburgh. The plant uses a traveling grate, and in the process a small amount of binder is mixed with the fly ash prior to pelletizing. In this process a carbon content of 3½ percent will support sintering. Lower carbon fly ash needs additional fuel to support combustion. The work at this experimental plant indicates that 1½ to 3 tons of aggregate per square foot of grate, per day, can be produced. The material weighs 37 to 52 pounds per cubic foot. Cost is estimated at $1.23 per cubic yard of finished fly ash aggregate, exclusive of the cost of the fly ash. This compares favorably with the price of $3.15 to $5.15

per cubic yard for lightweight aggregate in New York City (217).

So far, the vertical furnace seems to be favored in England, the rotary-type kiln has been used in the experimental work in Canada, and the traveling grate seems to be the preferred equipment in the United States. The traveling grate appears to provide more flexible control and continuous observation of the process, but it is claimed to require more fuel, and because of the larger number of moving parts it needs more maintenance (238).

Portland Cement Concrete

The use of fly ash in portland cement concrete and in concrete products has received more attention than all other applications, even though lightweight aggregate has a larger volume potential, per cubic yard of concrete, from the disposal standpoint. The reason for this is that fly ash imparts many desirable properties to concrete, such as increased workability (3, 13, 19, 31, 46, 60, 61), reduced segregation and bleeding (3, 60, 61, 79, 201), reduced mixer and mold wear (masonry units), increased green strength (masonry units), higher ultimate strength (3, 19, 45, 60, 61, 97, 139, 188, 194, 200, 238, 260), enhanced sulfate resistance (3, 21, 60, 79, 187, 245, 260), reduced alkali-aggregate reaction, and lower cost.

In most instances the lowered cost of the concrete makes the use of fly ash advantageous, even without consideration of the other advantages. Some of these advantages are the result of the pozzolanic action of fly ash.

POZZOLANS

Long ago, it was observed that some siliceous materials when mixed with lime produced cementing compounds possessed hydraulic properties. Such a material was a consolidated volcanic ash found near Pozzuoli, Italy (50, 52, 60). As a result, the term "pozzuolana" became generally applied to similar deposits found all over southern Europe. From this has evolved the modern term "pozzolan."

Pozzolans may be defined as siliceous or siliceous and aluminous materials (low in lime content) which possess in themselves little or no cementitious properties, but which in finely divided form will, in the presence of moisture, react chemically with calcium hydroxide, at ordinary temperatures, to form insoluble compounds possessing cementitious properties (16, 59, 60, 79, 111, 146, 177, 191, 194, 205, 211, 227, 228, 237, 258). Fly ashes high in lime do not possess pozzolanic properties (211).

Lime and silica (in the form of sand) combine in a wet environment at 355° F and under a pressure of about 150 pounds per square inch, to form a calcium silicate compound. Lime does not react with ordinary sand at normal temperatures and atmospheric pressure, but it does with certain finely divided sands of volcanic origin known as pozzolans (243).

The hydration of portland cement is accompanied by the liberation of lime (calcium hydroxide) (126, 183), which carbonates progressively, but which can be leached out, leaving a relatively porous concrete, or it can combine with the sulfates in aggressive waters causing expansion which disrupts the concrete.

Pozzolans incorporated in portland cement concrete fix the lime liberated by hydration, increasing the watertightness of the concrete and its resistance to sulfate attack (3, 16, 22, 41, 48, 82, 226, 257).

Many pozzolans with as little as 40 percent silica content exhibit satisfactory performance (60). Those regarded as the better pozzolans contain from 5 to 10 percent alkalies. Some contain as much as 30 percent alumina, and as much as 20 percent iron oxide. The presence of a small percentage of alkalies is more likely to be favorable than unfavorable (146, 211), and those containing an appreciable percentage of alumina and iron oxide are better than those that contain a very high percentage of silica (211).

A variety of tests have been proposed for determining the pozzolanic activity of a material (72, 149, 160, 182, 233, 236, 242, 244, 245, 258). Pozzolans are classified as natural pozzolans and artificial pozzolans (237). Natural pozzolans are materials that are found in nature which possess pozzolanic properties, or which can be converted easily into pozzolans by processing (111). Artificial pozzolans are those derived from industrial waste products (60).

The most important artificial pozzolan is fly ash (61, 79, 111). In many ways, it is produced under conditions simulating very closely the natural conditions under which the volcanic ashes of Pozzuoli, Italy, were produced.

Pozzolans combined or interground with portland cement have definite advantages in concrete (3, 8, 18, 41, 46, 47, 48, 58, 69, 100, 112, 211, 243), among which are:

1. Reduced water demand, in case of fly ash.
2. Improved workability.
3. Reduced segregation.
4. Reduced bleeding.
5. Lower heat of hydration and resulting decreased volume change.
6. Reduced drying shrinkage.
7. Increased extensibility and plastic flow at early ages.
8. Improved formed surface finishes.
9. Increased ultimate compressive strength.
10. Increased ultimate tensile strength.
11. Reduced permeability and leaching.
12. Reduced alkali-aggregate reaction in most instances.
13. Improved freezing and thawing durability when moist cured prior to freezing exposure.
14. Improved sulfate resistance.
15. Reduced cost.

As a pozzolan, fly ash has many advantages over other materials:

1. It comes already in a finely divided form so essential to pozzolanic action, whereas many of the natural pozzolans have to be ground (177).
2. It is already in the proper chemical state, whereas many natural pozzolans have to be calcined at high temperatures to bring out their activity (177).
3. It is a waste product to be disposed of, and therefore already available, whereas natural pozzolans have to be mined or dug out of deposits.
4. It is produced in the centers of population where the largest volumes of concrete are used.
5. Statistical significance of variables in fly ash can be determined more readily than for natural pozzolans, the variables of which are almost infinite (111).

CHRONOLOGY OF USE OF FLY ASH IN CONCRETE

Early Work (1932-1947)

The earliest work on record conducted to find uses for fly ash was carried on by the Cleveland Electric Illuminating Company and the Detroit Edison Company, and was reported in 1932. Insofar as portland cement concrete is concerned, this work touched on its possibilities as a raw material for cement, and as a natural cement (152).

The earliest over-all comprehensive work on the use of fly ash in concrete was reported by Davis and his associates of the University of California (3) in 1937, and in later reports (13, 19, 60, 61, 79, 146). Davis found in general that:

1. Fly ash varies in detailed chemical composition, the principal difference as far as effect on concrete being its carbon content.
2. Fly ash is usually finer than cement, and the particles are mostly spherical in shape.
3. Fly ash exhibits pozzolanic properties, as judged by its ability to combine with lime.
4. Fly ash of low carbon and high fineness can be used as a 30 percent replacement of cement in concrete that is standard moist cured.
5. Fly ash under mass curing conditions may be used in as high as 50 percent replacement.
6. Most favorable results are obtained by using fly ash with cement of normal or

high fineness and of normal or high lime content.

7. Mixing fly ash with cement gives as good results as intergrinding with cement, except that the latter results in higher early strength concrete.
8. Fly ash retards the setting time, but this remains within usual specification limits.
9. Water-reducing agents are more effective in concrete with fly ash, than without.
10. Fly ash can be used in quantities exceeding cement replacement, and such excess can then be considered as replacing the sand fines, thus permitting a reduction in the amount of sand.
11. Suitability of fly ash cement mixtures can be evaluated by standard physical tests for cement; that is, time of set, autoclave expansion, and tensile and compressive strengths of mortar.

Davis further found that the properties of the concrete in which fly ash of relatively low carbon content and high fineness is used, as compared to the same concrete without fly ash, are affected as follows:

1. Water requirement is about the same or lower. The lower the carbon content and the higher the fineness, other things being equal, the lower the water demand, and the latter is lower than for any other pozzolan.
2. Improved workability.
3. Reduced tendency to segregation and bleeding.
4. For a 30 percent replacement and standard curing, the early strength is lower than for plain concrete, but becomes higher after 3 months.
5. Under mass curing conditions, the strength of fly ash concrete is higher than for plain concrete, even at 28 days.
6. By intergrinding 20 percent fly ash with normal fineness cement, using the same total grinding energy, substantially the same 3-day strength as the corresponding Type III cement may be obtained.
7. Increased ultimate compressive strength is not affected by richness of mix.
8. Modulus of elasticity is lower at early ages and higher at later ages, but not significantly.
9. Shrinkage in most instances is reduced.
10. Autoclave expansion is reduced.
11. Resistance to freezing and thawing (5 months' moist curing prior to exposure) is increased.
12. Resistance to sulfates is increased.
13. Heat of hydration is reduced.
14. Plastic flow at early ages is greater, and lower at later ages, with total about same.
15. Permeability and leaching are reduced.

James (5) in 1937 reported on the use of fly ash in cinder blocks and in the patented "Cottrell" (Rostone) block (2). He found that he could obtain cinder blocks of 3,000-psi strength at 28 days using an equal mixture of fly ash and portland cement with crushed cinders. The Cottrell block, which is 90 percent fly ash, was found to have good insulating and fire-resistant properties.

By 1938 and 1939, Thorson and Nelles (12) and Ramseyer (16) were concerned with the problem of disposal and the various possible uses and advantages of fly ash. Many uses were reported and evaluated by these investigators. A great many were eliminated, and the use of fly ash in asphalt as filler, in building blocks, and in concrete appeared to them to be most promising. Ramseyer discussed the disposal problem, and the use of fly ash as a pozzolan, and cited the many advantages which had been found by Davis.

The earliest use of fly ash in concrete that has come to the attention of the writer, is the seawall at State Line Plant in Chicago, placed about 1936. An examination by the writer in March 1958, or 22 years later, shows it to be in reasonably good condition. Lake Michigan water is constantly in contact with it. No information is available regarding its construction. Whether any serious freezing and thawing problem exists is not known, as the condenser cooling water discharged from the power plant may keep the lake water in contact with the wall above freezing. It is still serving its purpose, and appears to be in reasonably good condition. Because of the many unknowns involved, it is felt that no positive conclusion can be reached regarding this structure.

Another early application in concrete was in the pavement for the Northside Sewage Treatment Plant in Chicago, Illinois, in 1938—a WPA project. Sections of pavement with a wide range of variables were installed in this project. Fly ash was used in 18 to 50 percent of the total cementitious materials in the various sections, and the tendency for the concrete to become "gummy" where the fly ash exceeded 30 percent by volume was reported. In 1953, McClenahan (124) evaluated the pavement and found that the skin coat had disappeared, exposing the coarse aggregate (salts have been used for de-icing). Raveling was observed only in low spots where water collects and freezes. Map-cracking was evident in only two sections where no fly ash was used.

The writer examined this pavement in March 1958, or approximately 20 years after it was built. The same scaling described by McClenahan, the raveling and map-cracking were observed and were possibly in a more advanced state. Inasmuch as the pavement was placed and finished by hand, before the days of air-entrainment, it is probable that placing conditions were rather on the wet side, and that a lot of wet mortar was floated to the surface in the finishing process. Considering these factors, its age, the fact that salts are used constantly in winter for de-icing, and that it is still in service, it would seem to have fulfilled its purpose. However, there does not seem to be any consistent pattern that would lead to any reliable conclusions as to the favorable or unfavorable effect of fly ash in this instance, particularly since it had no air-entrainment and has been salted consistently in cold weather.

In 1940 Nelles and Sellke (18) enumerated the properties of fly ash and its advantages in concrete as:

1. Noncombustible particles similar to vitrified clay.
2. Combustible particles—essentially coke.
3. The higher the carbon content, the coarser the fly ash.
4. Fly ash has unit weight of about 46 pounds per cubic foot by ASTM Designation C 29.
5. Improves grading or faulty proportioning of aggregate.
6. Improves workability.
7. Increases plasticity and density.
8. Reduces segregation and bleeding.
9. Provides pozzolanic action.
10. With 20 percent substitution by weight, it results in increased strength after 28 days.
11. Increasing fly ash in excess of substitution produces strength gains at earlier ages.
12. Reduces permeability.
13. Provides superior concrete at lower cost.

The same year Elmer (17) gave details of proper airtight handling systems to assure the collection of higher quality fly ash.

In 1941, in Europe, Kronsbein (20) tested 14 fly ashes and discussed their use in concrete, and as raw materials in cement manufacture. He reached the conclusion that where fly ash is used in concrete and the mix adjusted by reducing the cement content by an amount equal to the fly ash, the concrete can be only used in structural members in which early strength is not important, because of the relatively low early strength of fly ash concrete.

Nelles (22), also in 1941, called attention to the superior resistance of concrete containing fly ash when used in exposure to sulfur water and gave results of 12-year exposures.

In 1942 the Bureau of Reclamation used fly ash in the repair of the Arizona Spillway Tunnel at Hoover Dam (237).

The Germans (23, 24, 26), also in 1942 and in 1943, tried various successful applications of fly ash in concrete—mostly in the less critical locations of structures.

Frederick (29), in 1944, reported its use as a 25 percent replacement for sand in lean concrete mixtures. He found that it produced harder surfaces and denser concrete than plain concrete.

The same year, the report of the American Concrete Institute Committee on Admixtures (30) suggested its use as a pozzolan in amounts of 20 to 30 percent, and as a workability agent in amounts of about 20 percent.

About the same time, Weinheimer (31) gave details of physical and chemical properties of fly ash, and reported on the various uses, and handling problems.

By 1946 Leverett (35) reported on its use in concrete pipe (25 percent) by the Continental Concrete Pipe Company, and the Illinois-Wisconsin Concrete Pipe Company. It resulted in smoother pipe and in a 50 percent higher strength than ASTM requirements, when steam cured at 100° F for 48 hours.

Bessey (38) in England, in 1947, expressed pessimism on the use of fly ash. Although admitting its technical feasibility, he doubted the economics of its use, and described the many unknowns to be faced.

Rapid Expansion (1948-1952)

The big break came in 1948, when the U.S. Bureau of Reclamation (45, 52, 57, 76, 83, 91, 112, 128, 136, 237) decided to use fly ash in the concrete of Hungry Horse Dam. This was the fourth largest dam in the world at the time it was built and was estimated to need 261,000,000 pounds of fly ash and 342,000,000 pounds of cement (57). Extensive testing and research were conducted before the decision was made. The findings confirmed, for the most part, the conclusions which had been reached by Davis and his associates, and may be summarized:

1. Reduced portland cement requirements.
2. Reduced cost due to difference in prices of fly ash and portland cement.
3. For lean mixes fly ash reduces water requirements, but for rich mixes, it does not affect it. On an equal weight replacement basis, it is unique among pozzolans in that it reduces water requirement.
4. Increased workability of concrete.
5. Reduced segregation and bleeding.
6. Greater extensibility.
7. Greater impermeability.
8. The 90-day mortar cube strength was 92 percent and 122 percent of plain portland cement control, for standard and mass curing, respectively, with 35 percent replacement by absolute volume (25 percent by weight).
9. Reduction of expansion in expansion bars for alkali-aggregate expansion reaction, for 30 percent replacement was 59 percent at 14 days, and 81 percent at 90 days.
10. Strength gain of concrete containing 30 percent fly ash is not as rapid as plain concrete, but continues for a longer period. Both reach the same strength at about 1 year.
11. Fly ash increases modulus of elasticity for same compressive strength.
12. Fly ash generates 40 to 50 percent as much heat of hydration as same weight of cement.
13. Moist-cured fly ash specimens show slightly more expansion, and lower drying shrinkage.
14. Fly ash retards autogenous shrinkage at early ages, increases shrinkage of rich mixes at later ages, but compares favorably in amount of shrinkage with lean mixes without fly ash.
15. Fly ash concrete has high thermal coefficient of expansion, but cement brand may be a more important factor in this property.
16. Good freezing and thawing resistance is obtained with fly ash concrete (40 percent replacement), moist cured, 28 days, or 180 days, or 14 days, and then dried at 50 percent relative humidity, prior to freezing cycle exposure.
17. Fly ash reduces permeability of concrete.
18. Early strength is reduced in proportion to amount of fly ash added, but catches

up at age of 1 year, and ultimate strength is higher.

19. Reduction of alkali-aggregate reaction is lower for fly ash than for opaline silica.
20. Optimum replacement, with low carbon and high fineness fly ash, is 30 to 40 percent.
21. Fly ash concrete has considerable variation in entrained air content.
22. Fly ash from different sources requires different amounts of air-entraining agent.

The use of fly ash on this project resulted in a saving of $1,675,000, and together with air-entrainment is credited with permitting the completion of the dam more than 1 year ahead of schedule, while resulting in concrete having 5 to 10 percent higher strength at age of 2 years (237).

The following summer (1949), the McPherson Test Road in Kansas (74, 108, 174) was constructed, in an effort to find a solution to the problems that develop in concrete construction in the Plains area when local sand-gravel aggregate is used. This local aggregate, characterized by having only 5 to 15 percent retained on No. 4 sieve, and usually all smaller than ½ inch, causes excessive expansion in concrete, which results in bad map-cracking. Preliminary laboratory tests had indicated that certain pozzolans, among them fly ash, might be useful in inhibiting part of the expansion due to this cement-aggregate reaction—a reaction that cannot be entirely ascribed to the characteristic alkali-aggregate reaction. The Test Road included sections with different mixes to test the various possibilities that had been suggested as remedies to this detrimental expansion. It was found that:

1. Fly ash permitted retaining same water-cement ratio as control mixes, whereas other pozzolans required more water.
2. Fly ash with air-entrainment permitted a reduction in the cement content of 0.15 barrel per cubic yard of concrete.
3. Placing and finishing were easiest with fly ash mixes due to retarded set, whereas other sections had to be shortened in warm weather, and sprayed with water to facilitate finishing.
4. Fly ash reduced air content, and required more air-entraining agent to maintain required air content.
5. Workability was improved and placing was very simple compared to other pozzolan mixes.
6. Mix was not sticky and gummy like other pozzolan mixes.

An evaluation of this Test Road after 5 years of service (174) indicated:

1. Brand of cement seems to have more influence on inhibiting map-cracking than pozzolans.
2. Only fly ash among pozzolans shows less map-cracking than control mixes.
3. Deterioration is present in air-entrained concrete to a greater degree than in non-air-entrained concrete.
4. Durability of all concrete mixes against freezing and thawing improved by air-entrainment to larger extent than in fly ash mixes.
5. None of the pozzolans have been as effective in inhibiting map-cracking as limestone "sweetening" (additions of crushed coarse limestone aggregate), but fly ash is best of three pozzolans that were used.
6. Measured expansion in field is slight.
7. Field observations inconsistent with laboratory predictions, and evaluations appear contradictory depending on method used.
8. Possibility that a combination of limestone sweetening and fly ash, which combination was not tried on this road, may offer a better solution than anything tried so far.

The writer examined this project in March 1957, or 8 years after it was constructed. Experience has indicated that the age between 8 and 10 years is the most critical period with regard to the appearance of map-cracking due to this type of cement-aggregate reaction. Distress in the form of map-cracking was evident in most slabs. Except for one section, over-all expansion by closing of joints was not observed. Structural and subgrade failures, as well as faulting and pumping, are in evidence. An interesting, but unexplained, observation is the characteristic increase in frequency and intensity of map-cracking from the south towards the north in any given section. The test beams placed at the edge of the right-of-way do not show as much distress as the corresponding pavement. The next few years may differentiate between the behavior of the various sections. However, at present no conclusive pattern of behavior could be determined. All mixes showed map-cracking, the least being in the limestone sweetening sections. Of the various pozzolans, the fly ash appears to have a slightly better performance than the others, and definitely better than the control. Peyton's (174) suggestion (No. 8 above) regarding the possibility of combining limestone sweetening and fly ash, may be worth serious consideration.

This same year, in September 1949, Larson (51, 123, 138, 150) used fly ash in an experimental pavement in Wisconsin. The work consisted of 3.3 miles of pavement on U.S. 10, east of State No. 13. Plain mixes with air-entraining cement, mixes with 21 percent fly ash replacement without air adjustment (thus giving reduced air content), and mixes with fly ash replacement and air-entraining agent added to restore air content to original level, were used in various sections. The use of the last type of mix predominated.

Construction started September 20, and continued till about the middle of November. No reinforcing mesh was used, and curing was by paper. There was some rain and light snow at times during the construction period. Temperature of the concrete as placed was 60° to 70° F. It is reported that there was no bleeding noticeable for the fly ash mix with the added air-entraining agent. Cores taken after 3 years showed no adverse weathering effects on any of the sections.

This road was examined by the writer in June 1958, or 9 years after it was constructed. No differences in the behavior among the three types of concrete could be observed. The pavement appeared in good condition, and there was no evidence of any problem or failure due to the concrete. The concrete was constructed with contraction joints at 20-foot spacing except the middle section (over a mile long), which was all in one piece. This section had many cracks, which was to be expected. At two intersections, where salts are used profusely in winter and where shoulder gravel is ground into the surface by turning cars, scaling was in evidence. No salts are used between intersections.

Another landmark this year (1949) was the beginning of construction by the Bureau of Reclamation of Canyon Ferry Dam, in which fly ash was used in the concrete (110, 112, 132, 155).

In 1950, the Australians, following up on the work of Davis and the Bureau of Reclamation, reported (73) results of successful tests with their East Perth fly ash. Comparing their results with those obtained on American fly ash, they found their material of very good quality for use in concrete. It is high in silica and iron, low in alumina, sulfur and carbon, and very low in calcium oxide. They concluded that:

1. East Perth fly ash has pozzolanic properties.
2. After 6 months the strength of the fly ash concrete is about the same as that of control.
3. Replacement by weight up to 25 percent would be safe.
4. East Perth fly ash is not detrimental to concrete and compares favorably with fly ash already in extensive use in the United States.

About the same time (August and September 1950), because of a cement-aggregate reaction similar to that found in Kansas, Nebraska built an experimental pavement (Fremont to Arlington) utilizing various mixes including fly ash (117). The following year (September to November 1951), another section using fly ash mixes and some admixtures was constructed in Nebraska (Laurel to Belden), under standard construction procedures (87). The preliminary laboratory work for the experimental pavement and the observations during its construction resulted in the following conclusions regarding effect of fly ash (this applies only to the special mixes, which are basically fly ash, cement, sand-gravel aggregate—lacking the normal proportions of coarse aggregate):

1. Reduces expansion with Scholer Exposure No. 2, and improves durability in Nebraska freezing and thawing test.
2. Expansion bars stored at 100° F, made with 30 percent fly ash replacement, showed complete inhibition of expansion.
3. During construction, fineness of fly ash presented handling problems, but not insurmountable.
4. Requires more air-entraining agent, and this seems to be directly proportional to carbon content.
5. Lowers water requirement.
6. Increases workability.
7. Very little bleeding developed.
8. In hot, dry, windy weather, some rubberiness and difficulty in finishing were experienced with the high fly ash replacements, and high air-entrainment.
9. Cores taken from pavement had lower absorption for the fly ash mixes than for the control mixes.
10. Lowers compressive and beam strengths at early ages, but increases eventual strengths.
11. Reduces excessive expansion effect of cement-aggregate reaction.

The regular pavement section built in 1951 used 25 percent replacement in 85 to 90 percent of the area, and plain concrete in the balance. All concrete was air-entrained. No wire mesh was used, and joints were spaced 16 feet 4 inches apart. A maximum limit of 3 percent carbon and a pozzolanic activity test were required by the specifications.

Both projects were examined by the writer in August of 1958, or 8 and 7 years, respectively, after the construction of the experimental and the regular pavements.

The performance does not seem to be as jumbled as in the McPherson Test Road in Kansas. On the experimental pavement, frequent belt marks and tears are in evidence on most sections, possibly an indication of the dry condition of the surface at the time of belting, probably due to hot, windy weather. There is no doubt that the limestone sweetening appears to be the best from the standpoint of absence of map-cracking and shrinkage cracks, although the latter seem to vary with the brand of cement used. The fly ash appears to be next to limestone sweetening in effectiveness, when judged by these criteria.

Considering the fact that it replaces cement at half the latter's price, it would definitely result in a lower cost mixture than the limestone sweetening. It is too early to tell whether the fly ash would perform sufficiently well by itself, or whether a mixture with the limestone as has been suggested for Kansas would be desirable. The next 2 years will be the critical period on this project, and it bears close observation.

The second project built under standard construction procedures shows some wheel track wear concentration in a few places, and occasional shrinkage cracks in various sections, but otherwise no evidence of any distress attributable to the concrete is apparent. Some difficulties must have been experienced in the finishing during the hot, windy weather, as belt marks and tears are in evidence, possibly an indication of the sticky and gummy condition of the concrete surface at the time of belting. This may be minimized by adjusting construction procedures and operations, after once the workmen become familiar with the manner in which fly ash concrete should be handled. In general, this project shows excellent performance for fly ash concrete in the sand-gravel aggregate problem area.

An indication of the world-wide problem of fly ash disposal or utilization is the publication of results of work done by the Hydro-Electric Power Commission of Ontario, at about the same time, in 1950, as the Australian reports (59, 97). The laboratory and field tests substantiated in essence the major findings of Davis and the Bureau of Reclamation in the United States.

Using 30 percent by weight substitution in a section of the dam for the Otto Holden Generating Station, fly ash was found to increase workability, and to reduce the water requirement 7 percent from that in a similar adjacent control section. The fly ash mix developed lower heat of hydration, and as a result lower shrinkage. The strength was low up to 15 days, but after that exceeded the control mix. Cores substantiated the cylinder strengths, with the latter cured in a well in the dam concrete to simulate mass curing.

Another experimental pavement using fly ash concrete was installed in 1950 in Baltimore, Maryland (94, 95, 96, 98, 235). Both fly ash and plain concrete sections were placed side by side. In this pavement, located on Cooks Lane near Alson Drive, one sack of air-entraining cement was replaced by fly ash. This reduced the normal 3½ percent air-entrainment to 2½ percent. The fly ash had 5 percent loss on ignition, and a fineness of 3,010 square centimeters per gram. The compressive strength was lower than the control at early ages, and equaled it at age of about 90 days, then started to exceed it, and cores taken after 7½ years shows the fly ash concrete to have a strength of 6,355 psi against the control concrete strength of 5,605 psi. There is very little difference in wearing qualities between the two concretes, and the test section is heavily traveled, with a bus routed over it, and is salted in winter.

The writer visited this test road in 1957, and again in 1959. The pavement is on a sloping hill and the appearance is excellent. Occasional slab corners are beginning to break or ravel, but this is true of both the fly ash and control concrete. This pavement is thus standing up nicely after about 9 years of service.

This same year (1950) research on lightweight aggregate from fly ash, and the development of pelletizing prior to sintering were reported by Alfred University (75). Two laboratory sintering methods were tried successfully.

A big step forward was taken by the French in 1951 (113, 121, 149, 211, 226, 240, 242, 243), when they came out commercially with two cements containing fly ash. These cements develop early strength gains essentially similar to standard French portland cements, while the ultimate strengths surpass the ultimate strength of French super cement. These cements are interground combinations of fly ash, blast furnace slag, and portland cement clinker. A French patent was issued in 1953.

It is claimed that although either binary combination—fly ash-portland cement clinker or blast furnace slag-portland cement clinker—results in a cement that has low early strength, the intergrinding of all three constituents (fly ash, slag, portland cement clinker) in the proper proportions results in a cement of normal early strength and higher ultimate strength than standard portland cement, with the added advantages of pozzolanic properties. Later, in 1956, the French developed a cement with 20 percent finely interground fly ash, which falls within the regular portland cement specification. This cement gives early strength gains essentially the same as plain portland cement, and provides the advantages of pozzolanic cements, although not to as high a degree as the cements containing both fly ash and blast furnace slag. It is claimed that the grinding of the fly ash particles exposes a larger active surface area, which increases early pozzolanic action, thus resulting in the higher early strengths. These cements open the wide field of small concrete construction to fly ash—a field hitherto untapped because of the difficulty of handling and batching fly ash as a separate ingredient, and because of the low early strengths that delay form stripping on structural work.

In 1952, research on fly ash was reported from the Norway Institute of Technology (92). The work covered the use of fly ash as an admixture and as a replacement for cement up to 30 percent. Compressive strength, freezing and thawing, and resistance to sodium sulfate were determined for various mixes. The author defines the efficiency of a cement as being the compressive strength divided by the cement content per unit volume of concrete. This efficiency was found to increase with the percentage of fly ash replacement. Even the efficiency of the cementitious materials (cement plus fly ash), increased up to replacements of 10 to 15 percent. This increase in efficiency was particularly pronounced for lean mixes. Resistance to freezing and thawing, as well as resistance to sulfate action, was found to increase up to replacements of 10 to 15 percent.

The Bureau of Mines felt in 1952 that fly ash had become of sufficient interest to warrant the publication of an annotated bibliography (102).

Scholer (108), also in 1952, found that fly ash used as 20 to 30 percent replacement was sufficient to inhibit the cement-aggregate reaction that develops when the local sand-gravel aggregate is used in the Kansas-Nebraska area. This conclusion was based on a laboratory wetting and drying test that had been found to correlate with outdoor exposure.

Also in 1952, the Bureau of Reclamation started work on Palisades Dam (130), where fly ash was used in the tunnel concrete, and reported results of comprehensive studies of cement-pozzolan reactions, and how fly ash fits into the over-all pozzolan picture, and concluded that fly ash variables were more easily evaluated statistically than variations in natural pozzolans. Another study by the Bureau of Reclamation (110), made in connection with the investigation of materials for Canyon Ferry concrete, measured the effect of fly ash and pumicite on the freezing and thawing durability of concrete. Compared to the control mixes, it was found that:

1. Fly ash in 15 percent replacement increased the resistance of non-air-entrained moist-cured concrete to freezing and thawing, and this increase was more marked with the longer moist curing periods. Higher replacements decreased this resistance.
2. In air-entrained concrete moist cured for 6 months, 30 percent fly ash replacement increased the resistance to freezing and thawing.
3. Moist curing (7 and 14 days), followed by laboratory or outdoor drying, reduced the durability of fly ash concrete in direct proportion to the amount of replacement used.
4. Shrinkage cracks, or low strength at time of starting of freezing cycle, may be the reasons for the lowered resistance after drying.

About this time, the Halliburton Company (109) developed a mixture for oil well cementing using 50 percent fly ash. The advantages claimed are:

1. Lowered heat of hydration and therefore reduced volume change.
2. Improved tensile and compressive strengths.
3. Improved resistance to sulfates.
4. Reduced leaching.
5. Reduced cracking.
6. Lower pressures needed for sealing.
7. Lower cost.

Continuing Development (1953-1959)

Reports of these various early experiences with fly ash concrete were circulated and commented on all over the world, and stimulated further work in this field wherever industrial developments produced large quantities of fly ash. Thus, the various problems encountered in the use of fly ash in concrete were receiving world-wide attention.

In 1953, the Chicago Conference Committee on Concrete Tests made public its test results which showed the advantages of fly ash in concrete exposed to sewage, and other concrete in the Chicago area (120, 166). The resulting general recommendations were:

1. To use air-entrainment for highway work, and to take advantage of saving by use of fly ash in the mix when no urgency for early opening to traffic exists.
2. For heavy concrete sections, it may be advantageous to utilize the reduction of heat of hydration resulting from fly ash substitution with Type I cement, and in extreme cases even with Type II cement.
3. For sewer work use Type II cement or Type I with fly ash, but not Type I alone.
4. All concrete should contain 3 to 5 percent air.
5. Winter curing should provide 70^0 F for 3 days in the case of straight cements, or 5 days at 70^0 F for fly ash blends, after which the concrete should be protected from freezing until it has developed ⅔ of its specified strength.

At about the same time, the Consolidated Edison Company (126) was able to introduce provisions into the New York City Building Code permitting the use of fly ash in concrete.

The same year the Bureau of Reclamation issued several reports on investigations for various projects, using fly ash as cement replacement (128, 129, 130, 131, 132, 133, 134, 135, 136). The results of these investigations confirmed in general the previous findings. The additional findings, with the specific materials used in the tests, and with the comparatively lean mixes used in dam construction, were:

1. Resistance to cavitation is decreased, except for 4-sack concrete mixes, mass cured for 90 days, and with a maximum of 15 percent fly ash, which had better resistance than the control. In spite of this decrease, the values were rated as good for mass concrete.
2. Abrasion resistance is reduced for all conditions tested (3- and 4-sack mixes), mass cured for 28 and 90 days. The lowered values obtained were still rated as good for mass concrete.
3. Fly ash reduced the effectiveness of calcium chloride at 50^0 and 73^0 F using Types II and V cement mixes, but there still was a net gain in strength at the lower temperature as compared to control.
4. Fly ash concrete mass cured for 1 year had a high degree of correlation with fog-cured concrete at 28 days.
5. Fly ash in concrete mixes increased thermal conductivity and diffusivity.
6. Fly ash was more effective in leaner mixes.

In the same year (1953) it was reported that fly ash was used in the concrete of six dams built by the Niagara-Mohawk Power Company (115), and in Liberty Dam (near Baltimore) (116).

In 1954, the use of fly ash in concrete mixes in excess of the amount of cement taken out of the mix (which produces early strength gains comparable to control mixes with cement alone) began to gain ground. This came as a result of the publication in 1953 of test results by Washa and Withey (137) confirming this idea, which had been proposed earlier by several investigators (18, 29, 114).

British interest became evident in 1954, through an investigation for the British Electricity Authority to verify American experiences (139, 157). The results in general corroborated American findings and mentioned increased early strength by use of percentages of fly ash in excess of cement taken out of the mix, while stressing a mill-blended fly ash cement for the smaller jobs. Such blending had been advocated in 1950 by Blanks (58) and by Meissner (69) even for the larger projects.

This same year Fucik (147) reported using fly ash successfully and advantageously in the Guayabo Project, El Salvador.

Also in this year (1954), investigations by the National Ready Mixed Concrete Association were reported (141, 142), with essentially the same findings as those of previous workers.

The French, continuing the intensive studies on the finer grinding of fly ash to overcome the low early strengths, reported successful results (149, 169, 185, 211, 226, 242, 243, 244, 248).

Lilley in Great Britain (101) reported negative results on the use of fly ash in soil-cement mixtures.

Work in the United States continued with increasing stress on the various possibilities of fly ash and on its usefulness as a pozzolan (152, 153, 154, 155, 156, 159, 189, 224). By then, the production of fly ash had increased to such an extent that Weinheimer (158) felt that the problem of its disposal was becoming "mountainous."

In 1955, the British reported the increasing use of fly ash in bricks, in concrete, in building blocks, and in the manufacture of lightweight aggregate (161, 162, 163, 164, 165, 167, 181, 186)—lightweight aggregate being particularly advantageous because of the possibilities of manufacture close to the source of the fly ash.

About this time, the Corps of Engineers began reporting on a series of comprehensive testing programs. This extensive series of tests included the evaluation of various finely divided mineral admixtures, including several fly ashes. The whole series led to favorable results detailed in the various papers (170, 192, 218, 233, 246, 247, 272), and led to the first use of fly ash by this organization on Sutton Dam in West Virginia, as a 25 percent replacement on the basis of absolute volume. Contracts for the use of fly ash on more recent dams are understood to have been consummated.

The writer visited this project in August 1958 while construction was under way, and observed the operation. The main problem appeared to be the maintaining of control on air-entrainment by changing the quantity of air-entraining agent used as the carbon content of the fly ash varied.

As part of the Corps' comprehensive program, concrete blocks using mixes similar to those in dam construction and made with fly ash (45 percent by volume of the total cementitious materials), natural cement (35 percent by volume), and plain concrete control mixes, were made and cured at the Waterways Experiment Station 14 days wet, then outdoor exposure, spring to fall, and then exposed to salt water freezing and thawing at Treat Island, Maine, in the fall of 1953.

The writer had the opportunity of examining these blocks in July 1958. This examination indicates that the fly ash mixes are not standing up, in general, as well as the natural cement, or standard portland cement mixes. There is evident a great deal of scaling and corner raveling.

In 1955 also, India showed interest in fly ash, and as a starting point, reviewed the American and Australian work.

In July 1955, a pavement was built as an entrance to the St. Clair Power Plant between Marine City and St. Clair, Michigan, in which fly ash was used in the mix in different sections—in quantities both equal to and in excess of the cements taken out. This pavement was cured with white-pigmented curing compound, and opened to traffic at the age of 28 days. The fly ash used had 13 to 14 percent loss on ignition, and a fineness of about 3,100 square centimeters per gram. The use of fly ash in the higher proportions does not seem to have improved the early strength in this instance. This pavement carries heavy plant traffic, because of the hauling of fly ash to dumps, in heavy trucks. One section was a plain concrete control section. The pavement is salted during the winter months.

An examination of this pavement was made by the writer in July of 1957, or 2 years after construction. The pavement appears to be in good condition, with a few fine shrinkage cracks here and there. The beginning and end of the pavement show some surface wear, probably due to the grinding by traffic of sand and gravel from the adjacent roads.

This same year (1955), Japanese reports covering work with fly ash indicated their interest in the subject (173, 255, 260). By separating coarse particles from the raw fly ash, they were able to obtain a fineness of 5,790 square centimeters per gram. Their conclusions are essentially a corroboration of the over-all general findings in the United States and in other countries. In general, they obtained:

1. Lower water demand.
2. Better workability.
3. Low early strengths but high ultimate strengths.
4. Reduced drying shrinkage.
5. Adequate freezing and thawing durability with air-entrainment.

The Bureau of Public Roads published, in 1956, results of a comprehensive series of tests on 34 fly ashes in combination with three cements (182, 200). Again, these comprehensive tests corroborated the findings of previous investigators regarding the general beneficial effects of fly ash on concrete in which it is used.

Also in 1956, experiments at Kansas State College indicated the probability that a low limit on SO_3 in fly ash is not a prerequisite to good concrete (184).

A description of the large-scale use of fly ash on dam construction in Great Britain, appeared about this time (187, 253).

In 1956 also, Price (194) summarized the studies of the Bureau of Reclamation on fly ash, and its application to heavy construction.

This same year comprehensive studies were reported from Australia (205, 259), comparing Sydney fly ashes with results obtained in the United States, and with the previously published East Perth Station tests (173) in Australia. General agreement with earlier findings was found, except that the Sydney fly ashes had lower specific gravities (as low as 1.88), which resulted in higher water demand (110-130 percent).

In 1957, the Shippingport Atomic Power Station was constructed utilizing large volumes of fly ash concrete with 20 percent by volume replacement and Type IS cement

(220). The strengths obtained were generally equal to control at 80 days, but lower at earlier ages.

About the same time Peters (223) reported from Germany on the advantageous uses of fly ash in concrete.

In 1958 the Sixth International Congress on Large Dams brought together many papers covering experiences and results of investigations from all over the world—generally favorable to the use of fly ash in concrete (232, 237, 239, 240, 241, 247, 248, 253, 254, 255, 256, 258, 260). Among these, Dexheimer (237) (U.S.) reviewed the favorable use of pozzolans in general, and fly ash in particular, by the Bureau of Reclamation on various projects. He reported that fly ash had been used in four major dams, out of a total of 13 in which pozzolans were utilized, and was proposed for a fifth one. The only other pozzolan used on four dams was calcined shale, while pumicite and calcined clay had been used on two dams each.

Bertier (232) (France) offered an explanation of the mechanism of damage to concrete by freezing and thawing, and the unfavorable role of free lime. He concluded that this damaging effect can be reduced by fixing the lime in the concrete through the introduction of a suitable pozzolan.

Duserre (239) reported satisfactory experience on a French dam, utilizing 15 percent replacement with a fly ash having a 9 percent loss on ignition, and a fineness of 2,025 square centimeters per gram. Fouilloux (240) (France) reported on blended cements which develop early strengths comparable to standard cement, one being a combination of fly ash and portland cement clinker, and the other fly ash, blast furnace slag, and portland cement clinker.

Others reporting at this Congress included Kennedy (247) (U.S.), who summarized the Corps of Engineers' investigations, and concluded that properties of mass concrete need not be adversely affected by judicious use of replacements. Lafuma (248) (France), reported on the influence of grinding fly ash, and concluded that finer grinding improves the early strength. McDonald (253) reported on the use of fly ash in Lednock Dam in Great Britain, with ensuing favorable results. On this project accelerated curing with hot water was tried, but was not developed sufficiently to become reliable. Marshall (254) (Great Britain), found that increasing fineness of fine aggregate in fly ash mixes resulted in unchanged or decreased workability, and unchanged or decreased compressive strength. Mizukoshi (255) (Japan), reported results of use of fly ash on Sudagai Dam, and corroborated the general American findings. Morgan (256) (Great Britain), reviewed advantages of fly ash. Steopoe (258) (Roumania), outlined a very interesting hypothesis for the mechanism of pozzolanic action in hardened concrete. Yamazaki (260) (Japan), reported experimental results on raw fly ash, and fly ash from which the coarse particles had been separated, and corroborated the general findings from the United States.

Friis (241) summarized for the Congress the beneficial results reported for fly ash and pozzolans in 29 papers from 11 countries:

1. Better workability.
2. Lower heat evolution.
3. Decreased shrinkage.
4. Lower compressive strength at 28 days, but same at about 90 days.
5. Better frost resistance.

He concluded that chemical analyses are needed, suggesting that an international standard be set up.

Meanwhile the French had developed simple control tests to check the activity of fly ash, and to determine its proportions in cement samples in which fly ash has been interground (242, 244).

With the disposal of French fly ash becoming a more critical problem, Jarrige (243) reviewed the whole subject, and various possible applications as measures to utilize fly ash.

Karpinski (245) (still in 1958), claimed that the water-cement ratio had an effect on pozzolanic activity and gave a method to correct for this.

Tennessee Valley Authority investigators (249, 250, 251), reported on the successful use of a coarse fly ash with a fineness of 2,000 square centimeters per gram in a structure. The mix utilized 30 percent replacement by weight of cement, plus 8.5 percent replacement of the sand.

The writer visited the work on this lock in February 1958, and was impressed by the smooth surfaces and sharp corners and grooves formed into the concrete. Concreting operations could not be observed because of a shutdown due to unexpected cold weather.

Fly ash has been used in grout mixtures (158, 246) but it is not clear when such use began.

Lovewell and Washa (252) published more data in 1958, indicating that use of fly ash in excess of the amount of cement reduction improves early strength.

The same year Polivka and Brown (257) reported on a method of evaluating resistance to sulfate solutions, and found that fly ash performs well as compared to other pozzolans.

In 1959, the American Society for Testing Materials (261) approved a standard for determining the effectiveness of mineral admixtures in preventing excessive expansion of concrete due to alkali-aggregate reaction.

Bauer (263) summarized advantages of pozzolans as buffers in concrete mixes, and attempted to show incentives for the cement industry to manufacture pozzolanic cements. He stressed advantages for a pozzolan industry association.

Hansen (268) reported early in 1959 that fly ash releases alkalies to the liquid phase of the hardened cement paste and should be taken into consideration when used with aggregates that are known to react with alkalies.

Minnick (271) reported at the 1959 ASTM Annual Meeting on studies made on fly ash in an effort to evaluate results from chemical analyses, physical tests, X-ray diffraction, fluorescent spectrographic analyses, microscopic examination, and differential thermal analyses. He concluded that the differential thermal analysis correlated with strength or X-ray data may prove a useful tool for initial evaluations.

Pepper and Mather (272), also at the 1959 ASTM Annual Meeting, reported further on the continuing series of investigations by the Corps of Engineers and gave minimum quantity of each material required in the mixes to prevent excessive expansion in test bars due to alkali-aggregate reaction. These quantities ranged from 10 to 45 percent.

Also in 1959, the Bureau of Reclamation summarized (273) studies on the release of alkalies from various combinations of pozzolans and lime, as compared to the expansion in pyrex mortar bars in which the same pozzolans had been used. No apparent relationship was found between the amount of alkalies released and the expansion developed by the bars.

BLOCK, PIPE, PRECAST, AND PRESTRESSED UNITS

These products, although made of portland cement, have problems and properties so much in common and yet differing from concrete placed in forms at the construction site, that they deserve further discussion by themselves. All that has been said about concrete applies as well to these products, in varying degrees. The distinctive properties that set them apart from general concrete construction are:

1. They are made in yards or plants under "industrial manufacturing conditions" that permit closer control than on the construction job.
2. The processes are repetitive, the end result being duplicate units produced over and over again.
3. Curing is usually at elevated temperatures using saturated steam to produce heat and at the same time to maintain high humidity conditions.

Most such concrete products are made with very dry mixes, tamped or vibrated in molds or forms. The stripping of molds or forms as fast as possible is an economic advantage in making the forms available for repeated use. The improved green dry strength of fly ash mixes which permits handling very soon after molding is therefore advantageous (62).

Sharp corners, fine mold detail, and smooth surfaces obtained by adding fly ash to the mix, make a better appearing product (12, 35, 39, 62, 114, 199, 206) that has superior sales appeal, and in the case of blocks results in a better looking finished wall. Fly ash reduces the porosity of cinder block (12). Because of the repetitive nature of the production of these items, a small saving in the mix develops into worthwhile reduction in total cost.

The use of fly ash in concrete mixes for precast products thus has multiple advantages (119, 206), among which are:

1. It permits a drier mix to be used, or provides a more workable mix for the same amount of water (62, 206).
2. Because it holds the water in the mix and reduces bleeding, less sand streaking occurs, particularly in pipe and precast units.
3. It provides a better green strength, thus permitting earlier stripping and handling of the units (62, 238).
4. It reduces wear on molds and machinery (114, 206, 238).
5. It provides better finish and better corners, thus enhancing the appearance (39, 62, 206, 243).
6. It permits a reduction in cement in many instances that will result in appreciable over-all savings.
7. In block mixes 20 percent fly ash in the mix has been found to give equal of greater compressive strength (54), and a volume change essentially the same as mixes without fly ash. Replacement in excess of cement reduction is beneficial (199).
8. Because of the higher moist curing temperatures, pozzolanic action takes place faster, and results in higher early strength gains than under ordinary curing temperatures, thus eliminating the early low strength criticism frequently leveled at fly ash concrete (35, 39, 206, 226).
9. Pipe made with fly ash mixes has the additional advantages of improved resistance to sulfate, and reduced permeability and leaching (145, 199).

Over-All Conclusions (Portland Cement Concrete)

This section is essentially an objective summary of the effects of fly ash in concrete in the light of present-day knowledge. It attempts to combine the various findings in the published literature and observations on the various projects that were studied, into a set of over-all conclusions. Some of these conclusions are definite enough to justify positive statements in the light of today's knowledge of the subject, while others warrant only an expression of trends.

In evaluating the use of fly ash in concrete, the views of the various authors, shown in the list of references and highlighted in previous sections, are combined with personal observations of the writer from visits to the various projects and from discussions with organizations and individuals using fly ash, testing it, or conducting research on it.

Although there are conflicting reports and opinions on the properties of concrete in which fly ash is used, the following characteristics are reasonably well confirmed by the studies and experience on the jobs, and may be accepted as a reasonable consensus of available information to date. These characteristics vary in degree with the source of fly ash, but may be accepted as applying in general to those fly ashes that come close to meeting the requirements of specifications such as those issued by the Bureau of Reclamation, Corps of Engineers, American Society for Testing Materials, Bureau of Public Roads, and similar specifications that have been issued by experienced users. Some fly ashes outside the limits of such specifications will have similar influence on the properties of concrete in which they are used, but each case must be judged on its own merit through tests simulating the conditions under which the material is to be used. The reason for the need of such tests is that no single characteristic of fly ash or simple combination of characteristics controls its performance in concrete (19, 20, 179).

RAW FLY ASH

Specifications

Many of the large organizations using fly ash have suggested or issued specifications which have been published (3, 60, 87, 91, 135, 148, 149, 153, 168, 182, 194, 231, 237, 247). The latest Bureau of Reclamation specification is given here as an example:

CHEMICAL COMPOSITION

Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus ferric oxide (Fe_2O_3), not less than	75.0 percent
Magnesium oxide (MgO), not more than	5.0 percent
Sulfur trioxide (SO_3), not more than	4.0 percent
Loss on ignition, not more than	5.0 percent
Moisture content, not more than	3.0 percent
Exchangeable alkalies as Na_2O, not more than	2.0 percent

PHYSICAL PROPERTIES

Fineness:	
Specific surface, square centimeters per gram (air permeability fineness method of test), not less than	3,000
Material retained on No. 325-mesh sieve, percent, not more than	15
Compressive strength:	
With portland cement, percent of control, 28 days, not less than	85
With lime, 7 days, minimum pounds per square inch	900
Change of drying shrinkage of mortar bars, percent shrinkage of pozzolan bar minus percent shrinkage of control bar, not more than	0.04
Water requirement, not more than	103.0 %

Note: The specific gravity of individual samples from any one source shall not vary more than 3 percent from the average established by the 10 preceding samples or by all preceding samples if the number is less than 10.

REACTIVITY

Reduction of expansive reaction at 14 days, not less than	75 percent[1]

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[1] This requirement may be reduced on specific jobs when alkali-aggregate reaction is not considered to be an important factor.

Other organizations such as the Corps of Engineers, Bureau of Public Roads, and American Society for Testing Materials have similar requirements, with minor changes in the limits, the most significant of which is perhaps the loss on ignition, which can be a maximum of 12 percent in ASTM, and the fineness, which can be as low as 2,800 square centimeters per gram in the same specification.

Chemical Properties

Though fly ashes are produced from coals of widely different origin, the differences in the chemical composition do not appear to have a marked effect on the concrete properties except for variations in carbon content (3, 38). Chemical composition alone may not, however, be a sufficient criterion regarding the suitability of fly ash, as the condition in which the chemicals are found affects the action of the fly ash (149). Carbon content is affected by the source of coal, the type of combustion equipment, conditions of combustion, constancy of load, and method of collecting the fly ash (65, 81). Carbon content, with its variable particle size and surface particle conditions, and differences in its activity, is perhaps the most significant factor affecting the suitability of fly ash for use in concrete (3, 38). Methods of separating the carbon particles or reducing their proportion are available, but are not commonly used (152). The effect of carbon content on the concrete properties is not specifically known, but it does affect air-entrainment and the amount of air-entraining agent required to maintain a given level of air content.

Most investigators agree on the need for low lime fly ash for optimum effectiveness (60, 211), but Breckenridge (208) used high lime fly ash successfully in concrete mixes.

Carbon Content

This is one of the most controversial constituents of fly ash in its application to concrete work. No one appears to know definitely whether it has any harmful effects but most users require low-carbon fly ash. Most investigators feel that it is the most significant factor affecting the suitability of fly ash for use in concrete. The higher carbon fly ash should be used only in small percentages in concrete mixes. Carbon in fly ash does not seem to affect weathering resistance (3, 13, 38, 61, 79, 119, 139, 149, 153, 157, 182, 191, 194, 205, 236, 260).

It has been repeatedly established that carbon affects the amount of air-entraining agent required to maintain a given level of air-entrainment (51, 74, 117, 137, 141, 187, 191, 194, 200). Therefore, control of carbon content in the fly ash for a given project is desirable in order to minimize the problems of controlling the concrete mix (37, 42, 136, 187).

As an organic material, carbon may possibly have a deleterious effect on concrete in the same manner as any other organic compound—it has been standard practice to limit such compounds in aggregates, particularly in sand. Yet Frederick (29) found that carbon content had no deleterious effect on strength.

A very good possibility is that it acts as a diluent of the active pozzolanic materials in fly ash, and thus becomes one of the factors affecting the rate of pozzolanic action, and therefore the rate of development of early strength in concrete (270). Strength loss with inert material replacing carbon is not as high as with the carbon present (187).

Whatever the reasons for carbon being looked upon with disfavor in fly ash used in concrete, it seems to be a well-established practice to limit it to relatively low percentages in all specifications where the fly ash is to function as an ingredient in the concrete mix. The maximum carbon content in present-day specifications varies from 5 to 12 percent, depending on the specifying agency.

There appears to be no logical reason for limiting the carbon in fly ash used for lightweight aggregate, bituminous filler, and other similar applications, as long as it does not exceed reasonable proportions.

SO_3 Content

Although all specifications limit the SO_3 in fly ash to a relatively low maximum (in the same manner that it is limited in cement), work at Kansas State College, reported by Chubbock (184), and in Germany by Kronsbein (20), indicates that this compound may not be as harmful in the final fly ash concrete as has been generally supposed. The sulfur compounds in fly ash are found in lesser amounts than in slag (84). Increase in carbon appears to increase SO_3 content (187).

Physical Properties

From microscopic studies, it is known that the incombustible particles in fly ash are generally spherical in shape, while the carbon particles are coarser and irregular in shape, porous, and cokelike (152). The Blaine fineness varies with the source, but it is usually between 2,000 and 6,000 square centimeters per gram. Generally, the higher the carbon content, the lower the percentage of fines in the fly ash, even though the specific surface reading may be higher due to the porosity of the carbon particles. In general, fly ash used in concrete is finer than the cement it is mixed with.

Because of its fineness and rounded particle shape (it flows like "liquid smoke"), fly ash handling presents problems of dust and requires very tight conveying equipment—all of which creates some sales resistance (31, 53, 78, 262).

The specific gravity of fly ash varies from 1.88 to 2.84, and in general, the finer particles have the higher specific gravities. Its bulk density depends on the variations in specific gravity. Chicago fly ash has a density of 70 to 75 pounds per cubic foot as compared to 94 pounds per cubic foot for cement.

Fly ash should pass the standard soundness test when mixed with cement, to guard against delayed expansion (13).

The heat conductivity of bulk fly ash has been found to be 0.74 Btu per inch per square foot per degree Fahrenheit at 75° F, and 1.04 at 356° F. This compares with 0.01 Btu per inch per square foot per degree Fahrenheit at 200° F for asbestos (31).

Fineness

Fineness is one of the principal variables affecting the suitability of fly ash in concrete (3, 13). Fineness of fly ash is usually expressed in terms of specific surface rather than by sieve sizes.

The desirable fineness of fly ash appears to be practically as controversial as the carbon content. There is reasonable agreement that the finer the fly ash, the better it is for use in concrete mixes. Many investigators, particularly the French (who have ground fly ash to a fineness of 12,000 square centimeters per gram), indicate that the increased fineness leads to accelerated pozzolanic activity and thus to higher early strength—a logical consequence, since most chemical reactions proceed faster with increased fineness (3, 13, 79, 149, 153, 169, 182, 187, 191, 205, 211, 226, 238, 240, 243, 248).

Pozzolanic Properties

Fly ash in general exhibits high pozzolanic properties when used in concrete mixes (3, 31, 45, 60, 61, 73, 111, 139, 149, 185, 188, 193, 194, 201, 205, 211, 226, 233, 236, 270). Pozzolanic activity varies with the source of fly ash, and various tests have been developed to evaluate its potential. Usually, the finer the fly ash and the lower the carbon content, the greater the pozzolanic activity, and therefore the greater the contribution to the strength of the concrete. Cements of normal or high lime content are best for use with fly ash (3, 243). Methods of determining activity of a pozzolan have been proposed by several investigators (21, 72, 87). Pozzolanic activity is influenced by chemical composition and the condition in which chemicals are present. Materials high in silica and low in alumina react slowly at normal temperatures but much more rapidly at elevated temperatures.

FLY ASH IN CONCRETE MIXES

Fly Ash Content

The optimum amount of fly ash to use, in mixes adjusted to obtain cement reduction, depends on so many factors that for large projects it is best to determine the proportions by actual tests using the proposed cement and aggregate. Fly ash used in this manner in the past has been from about 20 percent by weight or absolute volume of the original cement in the mix, to as much as 50 percent (3, 13, 19, 60, 79, 101, 128, 157, 177, 182, 187, 191, 197, 204, 205, 206, 218). Where the mix adjustment is made to obtain sand reduction, maintaining the cement content the same, Frederick (29) found the optimum to be 25 percent of the weight of the sand. If used in too small a quantity, fly ash may induce alkali-aggregate reaction (177).

The higher proportions work well in mass concrete of leaner mixes, where reduction of heat of hydration is important due to the heavier sections, and where early strength is relatively unimportant, or in protected concrete such as foundations and inside buildings (13); while the lower quantities are better in smaller structures with richer mixes and thinner members where heat of hydration is relatively unimportant, and in which early strength becomes an important factor. In any case, there seems to be agreement that the leaner mixes can profit by higher optimum replacements than the richer mixes.

In mixes in which fly ash is used in quantities in excess of cement reduction, the percentage used may be higher yet, but a part of this is considered as taking the place of sand fines, or as an admixture. In such cases, the total fly ash may be as high as 50 percent of the original cement content—considered as about 25 to 35 percent to replace cement, and the balance to take the place of part of the sand and to act as an admixture (3, 12, 18, 29, 51, 101, 136, 146). Stickiness, rubberiness, or gumminess, reported in the mixes with the higher fly ash quantities, may be remedied in most cases by a proper redesign of the mix and modification of handling and placing procedures. Efficiency of cement is increased by addition of 10 to 15 percent fly ash and adjusting mix to reduce cement (92).

Water Requirement

Most studies lead to the conclusion that fly ash used as an admixture or as a replacement in optimum amounts does not increase the water requirement of the mix. In fact, with fly ashes of high fineness and low carbon, a reduction in water demand often results due probably to the rounded particle shape. However, the coarser fly ashes with higher carbon contents usually increase the water requirement slightly (3, 58, 60, 61, 79, 97, 111, 177, 260).

Workability and Plasticity

Fly ash, used in properly adjusted concrete mixes, improves the workability and plasticity of concrete mixes. This fact has been confirmed repeatedly and has become almost axiomatic (3, 58, 60, 61, 79, 97, 111, 139, 154, 187, 194, 201, 206, 241, 259). This property is a great advantage in the harsher mixes, particularly in the manufacture of building blocks, and in lightweight aggregate concrete. Pound for pound, fly ash is a better workability agent than cement (1, 6, 10, 106). As an admixture, without reduction in cement, but with an adjustment of the sand in the mix, fly ash improves the workability more than when the cement is reduced (29).

Fly ash concrete is reported to be more satisfactory when placed by pumping than plain concrete under the same circumstances.

Segregation

Fly ash in concrete mixes reduces segregation. Like improved workability, this has been confirmed by so many independent investigators that it seems trite to repeat it (3, 60, 61, 79, 201, 259). This property of fly ash is particularly helpful in the lightweight aggregate mixes such as those using Haydite (12).

Bleeding

Fly ash in concrete mixes reduces bleeding. This again, has been observed repeatedly and has become an established fact (3, 18, 29, 48, 53, 60, 61, 69, 79, 91, 116, 117, 201). Powers (15) advances a hypothesis that the addition of fines to a concrete mix is one way to reduce bleeding—possibly the very fine particles in fly ash act effectively in this manner. Moran (154) also gives a theoretical discussion on bleeding.

Time of Set

Fly ash generally slows the setting time of cement, but as a rule the times of setting remain within the usual specification limits (3, 226, 238).

Heat of Hydration

Raw fly ash generates about 40 to 50 percent as much heat of hydration as the cement it usually replaces. Therefore, when used in concrete with a resulting decrease in cement content, the net effect is a lower heat of hydration of the total mix (3, 58, 60, 61, 79, 97, 136, 187, 191, 194, 201, 211, 226, 238, 241, 243, 260). However, when used in excess of decreased cement content, this advantage is reduced, and may, if used in large enough quantities, develop a heat of hydration equal to that of an equivalent plain concrete mix. It is not likely that the excess fly ash will be used in such a quantity as to increase the over-all heat of hydration of the mix as compared to the plain concrete, because the concrete will become too gummy and sticky to handle before this point is reached.

In the case of interground fly ash, French investigators have found that the finer the grind the less advantage fly ash has in lowered heat of hydration, and eventually in the finest grinds attempted (close to a fineness of 10,000 to 12,000), the heat of hydration of the mixture is about equal to that with the mix using plain cement (226, 243).

In dams, reduced heat of hydration decreases the required artificial cooling, in addition to lowering thermal shrinkage and reducing cracking. This permits larger blocks to be used and thus speeds up construction.

In Hungry Horse Dam, it has been estimated that the heat drawn from the dam during construction, by circulating cold water in pipes embedded in the concrete, is equivalent to the heat obtained by burning 5,500 tons of coal (57).

FLY ASH IN HARDENED CONCRETE

Curing

For best results, fly ash concrete requires moist curing for long periods in order to develop maximum pozzolanic properties (191, 201). This extended moist curing can be shortened and still achieve the same end results, by:

1. Increasing the amount of fly ash, and therefore the amount of active pozzolan in the mix, thereby getting more concentrated pozzolanic action in a shorter period (3, 18, 199, 243).
2. Intergrinding the fly ash with the cement clinker, resulting in a finer fly ash—more intimately and uniformly mixed with the cement—again accelerating the pozzolanic action through the more active finer particles (3, 21, 226, 243).
3. Higher temperature curing, particularly by steaming or autoclaving—the higher temperature accelerates the pozzolanic activity (35, 37, 39, 59, 89, 149, 198, 221, 226, 243).
4. Addition of slag or cement germ that has set, which act as accelerators (243).

Volume Change and Shrinkage

Fly ash used in concrete continuously fog cured, increases expansion slightly (60, 132). However, it tends to decrease drying shrinkage (3, 58, 61, 79, 194, 200, 201, 226, 241, 243, 260). Fly ash has a tendency to retard autogenous shrinkage at early ages (136) and to increase autogenous shrinkage at later ages in rich mixes (132). Autogenous shrinkage of lean mixes containing fly ash compares favorably with control mixes (136). Because of the lower heat of hydration of fly ash concrete, and therefore the lower temperature rise in concrete members, the thermal shrinkage is decreased (47, 48).

Extensibility and Plastic Flow

Indications are that fly ash concrete possesses increased extensibility and plastic flow as compared to plain concrete (47, 48, 60, 69). These properties at early ages are conducive to decreased cracking due to drying shrinkage (3, 57, 109).

Molding Qualities

Fly ash in concrete mixes appears to produce smoother formed surfaces, and sharper form details and corners. This is particularly advantageous in architectural work, in building blocks, and in precast members (12, 62, 114, 199, 206).

Compressive Strength

The use of fly ash is more effective in increasing strength in lean concrete mixes than in rich mixes (53, 60, 61, 79, 134, 182, 201).

For standard moist curing conditions (70° F), fly ash of high fineness and low carbon content, used in mixes which are adjusted by the reduction of cement on an equal quantity basis, results in lower compressive strengths at early ages (up to about 90 days) but produces much higher ultimate strengths, due to the pozzolanic action at later ages (3, 19, 45, 58, 60, 61, 79, 97, 139, 188, 194, 200, 205, 226, 235, 238, 241, 243, 259, 260). Occasionally there is a report that the early strength is as good as or exceeds the plain concrete (32). The early strength of fly ash concrete is very sensitive to cold weather (226).

As an admixture without reduction in cement, but reducing the sand by 25 percent, the 7- and 28-day strengths exceed those obtained by using plain concrete. For a specified 28-day strength, and 25 percent reduction in sand, there is a saving of 34 to 48 percent of cement over plain mixes (29).

Grinding fly ash to a greater fineness (21, 226), intergrinding it with cement (3, 53), or with portland cement clinker (121, 149, 211, 226, 240, 248) increases the early strength—in many cases to a level equivalent to that obtained with portland cement alone. Intergrinding with blast furnace slag and portland cement clinker results in outstanding early and later strengths.

Experience since 1954 indicates that fly ash used in excess of the reduction of cement, also has the effect of raising the early compressive strength. This depends again on the mix, the materials in the mix, and the excess of fly ash (18, 53, 98, 101, 114, 119, 123, 137, 139, 198, 252, 259).

Under mass curing conditions (70° F for one day and then 100° F), fly ash concrete develops greater strength than the corresponding portland cement concrete, even at the early age of 28 days (3). Under higher temperatures such as steam curing, fly ash concrete develops early strength rapidly (226).

The increased early strength due to intergrinding, to the addition of fly ash in excess of cement reduction, or to the higher curing temperature is probably the result of increased pozzolanic activity due to the finer particles, the larger proportion of pozzolanic active materials, or the higher temperature, respectively.

Davidson and his associates (267), found that the addition of trace chemicals to mixtures of Ottowa sand, lime, and fly ash activates the lime-fly ash reaction, and thus increases early strengths. An addition of 0.5 percent of powdered sodium carbonate to the mix, increased the 7-day strength about 60 times, and the 28-day and 4-month strength about two times.

Wallace and Ore (275), found that the use of water reducing retarders used in concrete mixes containing fly ash increased strengths at all ages.

Flexural Strength

Little information is available on the effect on the flexural strength of fly ash in concrete mixes, and what information is available is somewhat conflicting. In general, it appears to follow the same trends as the compressive strength; that is, that the early strengths are lower than the corresponding portland cement concrete, but after the age of 28 or 60 days is reached, pozzolanic action influences the strength, and results in higher ultimate strength (51, 77, 117, 132, 134, 200, 211, 226). Tensile strength of concrete is increased by fly ash (48, 109, 243), and inasmuch as the flexural strength depends on tensile stresses, one might be justified in concluding that fly ash may improve the flexural strength as compared to plain concrete.

Modulus of Elasticity

The modulus of elasticity of fly ash concrete is lower at early ages, and higher at later ages (3, 60). In general, fly ash increases the modulus of elasticity of concrete when concretes of the same strength with and without fly ash are compared (132, 134, 136).

Abrasion

There is some indication that fly ash concrete may not be as resistant to abrasion as ordinary concrete (129, 132, 191). The lean mixes used in dams seem to be definitely so, but no reliable data are available on the richer paving concrete. Visual observations by the writer on several experimental pavements are inconclusive.

Permeability

Fly ash has been found repeatedly by several investigators to decrease the permeability of concrete mixes in which it is used about 6 to 7 times, and thereby reduce leaching (3, 31, 58, 60, 61, 79, 136, 146, 191, 194, 201, 211, 238, 245).

RESISTANCE TO ADVERSE CONDITIONS

Alkali-Aggregate Reaction

Most fly ashes, when tested in expansion mortar bars, show reduced expansion from the alkali-aggregate reaction in varying degree, depending on the cement, the aggregate, and the fly ash used (31, 45, 58, 60, 61, 79, 111, 122, 182, 188, 191, 194, 201, 205). In the presence of calcium chloride its effectiveness in this respect is reduced (177). Portland Cement Association tests (81), on the other hand, indicate that abnormal expansion occurs in fly ash mortar bars.

Tests for determining the reduction of expansion from alkali-aggregate reaction by the addition of an admixture have been proposed by various investigators. The most reliable test appears to be the mortar bar expansion test, which has been standardized by the American Society for Testing Materials under Designation C 441-59T (72, 100, 233, 261, 272).

Many explanations have been given to show how fly ash inhibits the expansion in the mortar bar test for potential alkali-aggregate reaction. It is a subject about which little is known with any degree of certainty. The explanation given in (111) probably best fits experimental observations and experience with pozzolans to date. The additional following notes represent the ideas proposed by various investigators in an attempt to explain the experimental findings.

Some investigators feel that the presence of alkalies in fly ash may be beneficial (60, 211), even though others find that such alkalies can be leached and therefore may enter into the over-all chemical reactions in the concrete (268, 273).

Fineness of pozzolan, the dissolved silica, and the percentage of alkali retained by the reaction product correlate with the effectiveness of the pozzolan in inhibiting alkali-aggregate reaction (233).

The alkalies in fly ash may be in a less available form than in cement, which could account for the fact that these alkalies do not produce the same reaction with aggregates as alkalies in cement do. Yet, there is evidence that at times more alkalies are released from the pozzolan than from the cement. Possibly, the pozzolanic properties of fly ash may be used partly to overcome the effect of its own alkalies, and partly to compensate for the deleterious effect of the alkalies in the aggregate.

The alkali-aggregate reaction results in the development of alkali-silica gel complexes which are capable of absorbing water and swelling, thus creating substantial pressures that contribute to the development of cracks in the concrete. The capacity of such gels to absorb water is controlled by the alkali to silica ratio. If this ratio is small (that is, too little alkali), the combination will not absorb water and therefore will not swell. On the other hand, if this ratio is too high, the gel readily dissolves in water and is dispersed through the cement paste. When the alkali-silica ratio in the gel is in the intermediate range, it results in gels capable of absorbing water and developing the expansion that is deleterious to concrete. The range of this ratio in which such deleterious action can take place is variable and only ambiguously defined, which accounts for much of the uncertainty in this phase of concrete technology. There seems to be lack of agreement as to whether the alkalies in the pozzolan do or do not participate in all these reactions, and if so whether such participation is advantageous or detrimental. In most instances, the end result appears not to suffer from the presence of alkalies in the original pozzolan (111, 263, 273).

The glassy phase of fly ash is most effective in overcoming the alkali-aggregate reaction, and some fly ashes contain more of this phase, while others have a larger proportion of the crystalline phases which are less effective for this purpose.

Progressive activity of alkali-aggregate reaction requires presence of lime to liberate the alkalies from the alkali silicates. Fly ash and other pozzolans can tie up this lime, and thus prevent it from releasing the alkalies from their silicates (122).

Some tests indicate that about 20 grams of finely divided reactive silica are required per gram of alkali in the cement in excess of 0.5 percent, to inhibit the alkali-aggregate reaction (202).

Cement-Aggregate Reaction (Sand-Gravel Aggregate)

In the Great Plains area where coarse aggregate is scarce or nonexistent, the use of sand-gravel aggregate (with very little material larger than the ¼-sieve size), as a total aggregate, is prevalent. In Kansas and Nebraska where this practice is common, severe map-cracking patterns develop in a few years (the critical period being 7 to 10 years after the concrete is placed), that is not entirely attributable to alkali-aggregate reaction.

Many additions including up to 30 percent of imported crushed limestone coarse aggregate, and various pozzolan combinations have been tried. Although none of the treatments tried to date appear to solve the problem entirely, some of the additions are effective in delaying or reducing this deterioration. One of the most promising of these additions appears to be fly ash, and there is some conjecture that fly ash in combination with a small amount of crushed limestone coarse aggregate may prove to be a complete solution (74, 87, 108, 117). Three test roads in Kansas and Nebraska are being watched with interest, as they are at present going through the critical period.

Corrosion

The question has been raised as to whether the sulfur content of fly ash might promote corrosion of reinforcing steel. The sulfur content of fly ash is limited by specifications and is of the same order of magnitude as that found in cement, so that there is no general over-all increase of sulfur in a concrete mix in which fly ash has resulted in decrease of the cement content. Corrosion is affected by the pH of the surrounding material and is very slight in a high pH environment. Inasmuch as moist concrete exhibits a very high pH, of 12 to 13, little or no corrosion can be expected (80, 86).

The lime in the concrete reacts with the iron in the steel, resulting in a protective film of ferrous hydroxide. In addition, the impermeability due to the pozzolanic action of the fly ash, would prevent or minimize penetration of water and oxygen—necessary elements for corrosion. As for corrosion due to electrical currents, the carbon in the fly ash would theoretically be more likely to affect corrosion (increased conductivity) than sulfur. However, the low limitations on carbon in fly ash specifications, and the fact that it is so well dispersed in properly mixed concrete, would make its effect in electrical conductivity quite minor, and should therefore not be a factor in corrosion (86). Japanese work (269), indicates that the damage from electrolytic corrosion to concrete containing fly ash, is generally overestimated, and that it can be inhibited (where it is likely to occur), by the addition of calcium lignosulfonate to the concrete mix. The French claim that fly ash cement improves the resistance of concrete to electrolytic corrosion (211).

Freezing and Thawing

There are many conflicting and contradictory viewpoints on this subject, and apparently conflicting data obtained by various investigators. The principal reason for such conflicting evidence is because of the different curing methods used, up to the age of testing, as well as the differences in the freezing and thawing cycles employed (210). Powers (175), proposed a completely new approach to this test, but it has not gained wide acceptance as yet.

The most reliable evidence seems to point to the fact that with proper curing and air-entrainment, fly ash concrete exhibits very satisfactory and adequate durability, as measured by laboratory freezing and thawing tests, even though such durability may be lower than that of plain concrete in some cases (3, 19, 58, 60, 61, 79, 110, 187, 191, 200, 237, 241, 258, 260). To equal or exceed normal air-entrained concrete in durability, fly ash concrete has to be wet cured for about 80 days, a procedure rarely practical.

There is evidence, however, that if fly ash concrete is dried at a very early age, and then subjected to freezing and thawing, the durability falls off and is much lower than that of plain concrete treated in the same manner (110, 134). But if the drying takes place in a 50 percent relative humidity atmosphere, no such reduction in durability is observed, or at least the reduction is still within acceptable limits (110, 136).

It also appears that fly ash improves the freezing and thawing resistance of air-entrained concrete containing calcium chloride even though it reduces the effectiveness (early strength gain) of the chloride. A possible mechanism of the improvement of freezing and thawing resistance of concrete by the use of pozzolans is advanced by Berthier (232).

Resistance to Salts

Unfortunately the record is not very definite on this phase of the subject. Experiments of various types have been conducted, but none have been conclusive. Actual pavements in service seem to provide conflicting answers, principally because variables cannot be isolated.

There seems to be at least an indication that fly ash concrete may be less resistant in this respect than plain portland cement concrete, but the evidence is not sufficient to warrant a definite conclusion. With some cements, particularly the blast furnace slag cements, fly ash appears to improve their resistance to salts. It is to be noted that air-entrained concrete without fly ash shows at times unexplainable lack of resistance to salts also (32, 94, 200).

Resistance to Sulfates

It has been shown by various investigators that fly ash increases the resistance of plain concrete to the actions of sulfate water, mild acids, and active waters (3, 22, 58, 60, 61, 79, 139, 187, 191, 201, 211, 226, 238, 245, 257, 258, 260).

MISCELLANEOUS

Grouting

Grouting properties of mixes using fly ash have not been established. An excellent laboratory study reported by Kennedy (218, 246) utilized controlled artificial fissures and several materials, among which was fly ash. It appears that fly ash has some beneficial and some not as desirable properties (49, 53, 149, 154, 211). More work is needed to determine the place of fly ash in the field of grouting.

Lightweight Concrete

Fly ash contributes workability and reduced segregation in lightweight concrete mixes (12). In Europe aerated concrete—a lightweight concrete which obtains its lightness from air voids or gas voids—has been made successfully with fly ash (88, 104, 118, 143, 149, 225).

In this country, "Durox" plants manufacturing lightweight blocks, slabs, and beams, can utilize fly ash where it is readily available. Some of these plants are, in the absence of available fly ash, grinding silica sand to rock flour, and using it instead to obtain pozzolanic action.

Fly ash can be used as the fine aggregate in cinder concrete (43). Fly ash and blast furnace slag mixtures high in calcium sulfate and low in lime produce lightweight concrete of good strength (222).

Oil Well Sealing

The Halliburton Company developed the use of fly ash for oil well sealing, as a 50-50 blend with cement (109). This use is well established in oil well work.

Raw Material for Portland Cement

Fly ash has been used successfully and economically as a raw material in the manufacture of cement. This has been particularly true in Europe (20, 113, 187, 211, 213, 216, 225, 226, 230, 238, 243). In the United States, the writer knows of only two such applications.

Essentially, it is a question of whether the silica, alumina, and iron as raw materials for cement, can be obtained more economically from fly ash or from other sources.

Evaluation

The preceding section gave an objective summary of the effect of fly ash on concrete properties, in the light of present-day knowledge. In contrast, this section is an evaluation of the use of fly ash in concrete based on the foregoing findings, supplemented by examination of structures in service, visits to various research laboratories, and discussions with investigators in this field of concrete technology—all presented in the light of the writer's experience and judgment.

It is an attempt to assess the usefulness of the various findings, and their respective values in this field, in order to sift the reliably established factors from the less certain findings, and from trends and conjectures. Such an evaluation will focalize the research and development needs, and will permit the formulation of a research plan that will provide the required information. The results of such research will permit the full realization of the potentialities and advantages that result from the use of fly ash in the general field of concrete. This in turn will provide the utmost use of a costly waste product, and turn the disposal cost into a revenue and an asset.

BITUMINOUS CONCRETE AND BITUMINOUS PRODUCTS

It appears to be reliably established that fly ash can be used successfully and advantageously as a filler in bituminous concrete mixtures and in bituminous industrial products. Its principal competition at present is limestone dust, which is relatively expensive to produce, but already well established. Where fly ash is available in the same area, the fly ash will be by far the more economical product.

Its future competition (waste products also) will be the rejects resulting from the artificial production of lightweight aggregate from expanded shale and clay. These waste materials will require grinding, as in the case of limestone. Other filler materials are either not abundant, or will require processing, so that this leaves fly ash definitely in an advantageous position—a position that can be realized by proper promotion and aggressive salesmanship to overcome the fact that the competition is already established. Such concentrated efforts should develop a very healthy market for this use, over widespread areas.

This potential use of fly ash in bituminous concrete in highway and airport paving is very large, when it is realized that the percentage of mineral filler in a high type bituminous concrete mix is generally higher than the percentage of asphalt. The situation is particularly favorable on projects located close to sources of fly ash. No definite or reliable statistics on the total tonnage of asphaltic concrete, utilizing filler, are available, but asphalt cement used in all asphalt paving work is known to be about 8 million tons per year. Assuming conservatively that only between ⅕ and ⅙ of this asphalt is used in high type bituminous concrete utilizing filler material, then about 1,500,000 tons of asphalt are being used in this type of pavement. Again estimating conservatively that the filler is equal in weight to the asphalt used, gives an estimated filler market of 1,500,000 tons. If fly ash as a filler can capture half or two thirds of this potential, it would account for about 1,000,000 tons.

Some bituminous concrete is made with lightweight aggregate. Although there is no logical reason why fly ash lightweight aggregate would not be satisfactory in this application, there is no information available on this subject. Again the information regarding the quantities of such asphaltic concrete is not available but if found acceptable in this service, fly ash lightweight aggregate might account for the disposal of an additional appreciable volume of fly ash. In this case, because this would be a new fly ash application, some research will be needed to establish the adaptability of fly ash lightweight aggregate for this service, once such aggregate becomes commercially available in this country.

In bituminous products, such as roofing, filled mastics, plank, and similar commodities, there ought to be a good outlet, even though the quantities would be smaller than in the paving field. Plants for such products are usually in areas where fly ash is available, which is an economic advantage. A very important benefit of marketing fly ash for bituminous products is the year-round operation of such plants, in contrast to the seasonal nature of construction work applications.

LIGHTWEIGHT AGGREGATE

This phase of fly ash utilization does not seem to have gained momentum in this country. The Sinter-Lite Corporation, mentioned previously, is the only commercial operation that has come to the writer's attention. The British experience in making "Terlite" using a vertical kiln is reported commercially successful, but the experimental work in Canada using a rotary kiln indicates that results are very sensitive to variations in kiln temperatures. A sintering belt has been used in Germany. The traveling grate seems to be the process that has received the most attention in this country (pilot operation only), and is reported to be easily controlled, and to produce a satisfactory lightweight aggregate, although requiring more maintenance, and more fuel or higher carbon fly ash than the other processes.

A study and evaluation of the various processes is badly needed; some development work will undoubtedly be required to permit a transition from the sintering pilot plants presently available to smooth commerical production. In addition, some research and testing will be needed to develop the physical properties, mixes, and other data regarding the advantages and comparisons of fly ash lightweight aggregate with existing lightweight aggregates, so as to provide reliable background information.

A decided advantage in the use of fly ash in the production of lightweight aggregate is that aggregate sintering plants can be located adjacent to power plants to reduce handling of fly ash, and block plants can be located at the same sites also. Lightweight aggregate for structural concrete can be shipped within an economical transportation radius from such strategically located centers of production.

Lightweight construction is on the increase at a tremendously accelerated rate, whether in the form of building blocks, structural concrete, partitions, or roofing slabs. Even precast and prestressed concrete producers are beginning to awaken to the advantages of lightweight concrete in their products.

Inasmuch as there is a ready, constant, and increasing market for both lightweight building blocks and structural lightweight concrete in every section of the United States, fly ash lightweight aggregate will provide a very advantageous outlet for the disposal of large quantities of fly ash, in an essentially constant year-round operation.

Statistics, on the tonnage of lightweight aggregate used in various classes of work, are practically impossible to establish. The Minerals Yearbook for 1957 indicates a lightweight aggregate production of 7,100,000 tons. With the tremendous increase in the last few years, this tonnage may be close to 10,000,000 by now. A safe estimate is 8,000,000 to 10,000,000 tons per year. About two billion building blocks (8" x 8" x 16" equivalent) were produced in 1958, and of these, 56 percent, or 1.12 billion units utilized lightweight aggregate. About 1,000,000 tons of lightweight aggregate were used in structural concrete the same year.

These figures, rough as they may be, are a good indication of the potential in the field of lightweight aggregates.

If fly ash could capture, in the long run, about ⅓ of the lightweight aggregate production, it would result in the utilization of 3,000,000 tons of fly ash. Fly ash of relatively high carbon content and low fineness, that cannot find a ready market as a pozzolan, would most likely fit this application. Thus, lightweight aggregate from fly ash represents not only a large potential tonnage, but a tonnage of material that may be unsatisfactory for many other applications.

Each cubic yard of lightweight concrete, whether in the form of building blocks, structural concrete, precast units, or prestressed members, would utilize about one ton of lightweight aggregate (a little less for high strength structural members, and a little more for blocks), which is about 5 to 8 times the amount of filler in a cubic yard of bituminous concrete (250 to 400 pounds), and about 13 to 20 times the amount of fly ash used as a pozzolan in regular concrete mixes (100 to 150 pounds) (234).

It is evident from the foregoing that this field represents the largest single untouched potential outlet for fly ash.

Research and development are needed on this facet of fly ash utilization in order to develop data and information with which to meet the already established intense competition in the lightweight aggregate field.

PORTLAND CEMENT CONCRETE

This is the field in which most of the development on fly ash has been done, and for which there is a mass of data available.

The available information indicates that, in general, when fly ash is used in the mix, it improves many of the properties of the concrete. Summarizing his experience on Bureau of Reclamation work with fly ash, Blanks stated (48):

> "On the whole, the use of fly ash resulted in concrete of quality equal to or superior to that obtained with portland cement."

Actually, this statement sums up experience with fly ash all over the world. In the United States most experience, conclusions, and this evaluation relate to air-entrained concrete, while most evidence is that European practice has not used air-entrainment as widely.

The following well-established improvements to portland cement concrete by the use of fly ash are obtained in varying degree, depending on the sources of the fly ash, the cement (60), admixtures, and aggregates, and the proportions in which these are used in the mix:

1. Superior pozzolanic action.
2. Reduced water demand (for fly ash with low carbon and high fineness).
3. More effective action of water-reducing admixtures.
4. Improved workability.
5. Reduced segregation.
6. Reduced bleeding.
7. Slower set, but well within standard limits.
8. Reduced heat of hydration.
9. Reduced drying shrinkage.
10. Reduced thermal volume change.
11. Increased extensibility.
12. Retarded autogenous shrinkage at early ages.
13. Improved molding qualities and mold wear.
14. Increased ultimate compressive strength.
15. Increased tensile strength.
16. Increased ultimate flexural strength.
17. Increased ultimate modulus of elasticity.
18. Decreased permeability and leaching.
19. Reduced alkali-aggregate reaction.
20. Reduced cement-aggregate reaction (in sand-gravel aggregate areas).
21. Satisfactory freezing and thawing resistance when used with air-entrainment (after adequate curing).
22. Indications of improved freezing and thawing resistance of mixes containing calcium chloride.
23. Improved resistance to sulfates.
24. Reduced cost due to the ultimate cementing value through pozzolanic action which permits reduction in the more expensive portland cement.

To be considered also are some disadvantages, and some suspected weaknesses of fly ash concrete as compared with plain concrete, which may be summarized:

1. Difficulty of handling fly ash as a separate material which runs like "liquid smoke."
2. Extra effort in batching and control of an additional ingredient in the concrete mix.
3. Reported difficulty in finishing when very high fly ash proportions are used (probably can be eliminated by proper adjustment of the mix).

4. Lower early strength (can be compensated for by present-day knowledge, but such compensations have not become widely known as yet).
5. Possibility of reduced surface abrasion resistance.
6. Possibility of reduced resistance to freezing and thawing if moist curing is not long enough, and if drying at early age occurs (this depends on length of moist curing period, and severity of drying action).
7. Possibility of reduced resistance to de-icing salts.
8. Possibility of higher creep in prestressed concrete.

Handling of Fly Ash

Equipment for handling fly ash without the difficulties encountered in the past is now available when operations are large enough or permanent enough in nature to justify the investment.

On smaller work, fly ash interground with the cement clinker and marketed as one product is the answer. An added advantage of such a product is the improved early strength—low early strength has been a deterrent factor in the acceptance of fly ash for general concrete use.

Finishing Difficulties

Most of the reported difficulties are probably due to poor proportioning or adjustment of the mixes and lack of familiarity of the operators with the best manner of handling fly ash concrete. These same difficulties were encountered when air-entrainment first came into use, and again when water reducing agents were introduced, but one rarely hears of these complaints any more with air-entraining admixtures, and only occasionally with water reducing agents. In the opinion of the writer, it is just a question of the need for more widespread knowledge of fly ash mix proportioning and adjustment, and of handling fly ash concrete under different placing conditions.

Early Strength

There are at least four methods for compensating for the low early strength of fly ash concrete:

1. Addition of fly ash in amounts in excess of cement reduction.
2. Addition of trace chemicals to activate the lime-fly ash reaction (still in experimental stage, but promising).
3. Addition of water reducing admixtures to the fly ash concrete mix (very good present-day practice).
4. Intergrinding with portland cement clinker.

The last named is probably the best method, as it also takes care of the objections against separate batching and handling, and to a large extent of the possible gumminess caused by large separate additions with unadjusted mix proportions.

The development of interground fly ash cement by the French is, in the opinion of the writer, the major breakthrough that places fly ash in a most advantageous position in the whole field of concrete. This technique, by improving the early strength, removes the objections against the low strength on projects that need the early strength—practically all concrete outside of mass concrete in dams. At the same time, the higher early strength permits comparisons between fly ash concrete and plain concrete on an "equal strength" basis, instead of "equal age" basis which has been the general practice. Uniformity is also improved over separate batching on the job, and cost is probably reduced (58, 69).

The custom of comparing fly ash concrete with plain concrete on an "equal age" basis was a natural early development in the use of fly ash in concrete dam work, where early strength is of little importance, and where the higher ultimate strength of fly ash concrete is more frequently used as a basis of comparison.

In dam work, fly ash has established itself a very enviable position. However, the practice of comparing on an "equal age" basis is illogical when applied to other structural work because fly ash concrete is a structural material that has to meet certain engineering requirements, the most important of which is strength.

Just because fly ash concrete has resulted in lower early strength in the past, is no reason why such practice should continue now that ways and means are available to improve the early strength. Thus, the argument against the lower early strength of fly ash concrete loses its validity, and fly ash becomes a satisfactory potential material for all types of construction where early strength is an important factor. A much more logical and more realistic procedure is, therefore, to compare the two types of concrete when they have reached the required engineering property for a structural material—in other words, when they have reached the same strength. It is felt that comparisons made in such a manner will provide some very striking data in favor of fly ash concrete.

Comparisons on "equal strength" basis may very well change the entire picture regarding the reports of possibly lowered resistance to salts, abrasion, and freezing and thawing, as most observations in the past have been made on fly ash specimens placed under test at the same age as the control instead of at the same strength level as the control.

Another advantage of the intergrinding of fly ash with cement clinker is that is permits marketing fly ash and portland cement as one combined material, either as portland cement (where the fly ash addition is low enough to produce a material within the regular cement specifications), or as portland-pozzolan cement (with the higher fly ash and slag additions to obtain more intense pozzolanic and other improved properties contributed by fly ash). This type of merchandising will by itself increase the potential market for fly ash tremendously, inasmuch as it opens its use to all the small jobs which cannot afford the separate fly ash handling and batching.

This would be particularly the case in buildings in which smooth surfaces and architectural details are involved—features that can be obtained more easily with fly ash concrete than with plain concrete. The large projects, centralized at one spot, such as dams, would still utilize fly ash as a separate material, and thus obtain the benefit of flexibility and leeway in adjusting mixes, as long as such work does not require the higher early strength afforded by intergrinding.

It is unfortunate that the term "replacement" has come into use and thus forced fly ash concrete into unrealistic comparisons. Structural materials should be compared on the basis of their engineering properties, irrespective of their constituents, as long as such constituents are not detrimental. Therefore, every effort should be made to direct thinking into comparing the characteristics of fly ash concrete with those of other concretes on the basis of properties and performance without reference to replacements or additions.

There is no justification or logic in pitting fly ash or pozzolans against cement in the mind of anyone. The term "replacement" has an undesirable effect on the cement producer, because he feels that a replacement takes business away from him. Actually, the two products complement each other and result, when properly used, in better and more economical concrete. In the long run, such improved concrete, irrespective of its constituents, will help all the industries that contribute to its making, and therefore its improved performance and economy will be an advantage to the cement industry, through wider usage and applications.

A statement by Davis (146) may be aptly quoted in this connection:

> "In point of fact, however, pozzolan is not a substitute for portland cement but is an extra ingredient of concrete. It is employed for the purpose of enhancing one or another of the important properties of concrete. Its use may and usually will lead to a reduction in the cement requirement, but also, depending upon the character and amount of the pozzolan employed, may and usually will lead to other changes in the concrete-mix design such as reduction in sand content."

In the case of fly ash, the mix adjustment usually also leads to a reduction in the water content, but the writer has never heard anyone calling fly ash a "water replacement."

These are the reasons why the use of the term "replacement" should be discouraged in scientific circles.

Resistance to Abrasion

The evidence of reduced resistance to surface abrasion is not too definite, although it points in this direction both in the laboratory and under observation of existing pavements. Research on this aspect is also needed.

Resistance to Freezing and Thawing

There seems to be some experimental evidence that short curing periods followed by drying reduce the acceptable freezing and thawing resistance of fly ash concrete. On the other hand, short, moist curing followed by exposure to 50 percent relative humidity air prior to freezing provides adequate resistance. A study of this evidence, compared with the apparently satisfactory service records on several experimental highway pavements in the East and Middle West, that have been in service around 10 years, and in which freezing weather is a substantial factor, raises questions regarding the apparent inconsistencies.

It is probable that the short, moist curing period prior to drying, leaves the concrete with a low strength (also possibly minute drying shrinkage cracks), and at the same time the drying stops or slows the pozzolanic action which would eventually have decreased permeability. Thus, the concrete specimens would be relatively weak and of high permeability, and easily susceptible to failure by the freezing and thawing test. On the other hand, the pavements that appear to have performed without evidence of freezing and thawing damage are in locations of relatively high air humidity and probably are in contact with moist subgrade, due to the sealing off of evaporation by the capping pavement itself. Thus, pozzolanic action leading to higher strengths and lower permeability is likely to continue. This, coupled with the less severe natural freezing and thawing cycles, as compared to laboratory cycles, may account for the satisfactory performance. Another factor, that may have an important bearing on the available data, is the difference between the comparatively lean mixes used in the laboratory work, and the richer mixes in the pavements. The resistance to freezing and thawing is of importance to both paving and exposed structural work, where normal curing is for relatively short periods. Research to develop reliable data on this problem is definitely needed.

Resistance to Salts

The resistance to de-icing salts has been investigated, but the results have been inconclusive and the evidence contradictory in some respects. Even though fly ash concrete appears to have reduced resistance to salts, the lower strength at the time of exposure to salts may be a significant factor that does not seem to have been considered. In the case of slag cements, there is some evidence that fly ash actually improves their resistance to salts.

Creep

There is recent evidence that concretes of "equal strength" have essentially the same creep properties. Therefore, the present doubt about creep of fly ash concrete, which may have been a deterrent to its wider use in prestressed units, may very well be eliminated through "equal strength" comparisons.

The effect of various curing methods, particularly steam curing, on creep needs studying as it may be an important factor in prestressing applications.

Basic Uses in Concrete

Essentially, fly ash can be used in regular concrete:

1. As an additional ingredient in the mix
2. Interground with portland cement clinker to provide a superior pozzolanic cement.

3. As a raw material in the manufacture of standard portland cement.

As a separate additional ingredient in the mix, fly ash is very desirable for the large project or for concrete product plants, where the handling and batching of an extra material do not present serious problems, and can be compensated for by the economies obtained.

Intergrinding with portland cement clinker, on the other hand, overcomes the low early strength, and eliminates separate handling and batching. It is very definitely the key to a much wider use of fly ash in concrete. Tests to check the control of the fly ash additions at the mill have been reported by Guillaume (242) and Jarrige and Ducreux (244). The "equal strength" comparisons made possible by intergrinding may not only remove some of the doubts that exist about fly ash concrete but may also show it to still better advantage in the areas in which it is already accepted as being superior to plain concrete.

There has been resistance to intergrinding in the United States, in spite of the potential improvement to concrete, and therefore eventual general advantage to all concerned. Ledyard (41), an American cement industry representative, voiced criticisms over 20 years ago regarding the industry's reticence with regard to marketing pozzolan cements:

> "Since at this time, it is quite clear that portland-pozzolan cements are serving well a definite and important need, ... it appears that the time is over-ripe when the portland cement industry should realize the importance of these implications and lend their support and talents to a complete and constructive study of the pozzolanic materials and portland-pozzolan cements.... Some who read this article may obtain the impression that the writer is not of the portland cement industry, but this is not the case. He is of the industry and has the interest of the industry very much at heart. He is concerned chiefly with having the industry turn out the very highest quality products at all times, and feels that industry has done themselves no favor by not recognizing the potentialities of pozzolans and doing something about developing them."

More recently French and British writers have commented adversely on this attitude in the United States (187, 211). It is hoped that this resistance can be overcome as objective data developed through research demonstrate the overwhelming advantages of pozzolan cements.

A more detailed study of the French experience along these lines, supplemented by research with American fly ashes and clinker, and development work to adapt methods to American industrial practices will be needed for the success of this application.

As a raw material in cement, the use of fly ash has been more extensive in Europe than in this country. Its limited use in this country, for this purpose, is perhaps due to the cheaper availability of other equally satisfactory raw materials, in some cases, and to lack of information in other cases, where fly ash may be the lower priced material. Two such applications are known to the writer, and there are undoubtedly other potential applications waiting for good and reliable engineering and cost data.

Estimates and Recommendations

The potential use of fly ash as an ingredient in concrete is very large. It is estimated that 308,000,000 barrels of cement were produced in the United States in 1958. If research and reliable information will result in the use of fly ash in ⅓ of the concrete, because of its advantages and lowered cost, and if it is assumed that ¼ of the cementitious material in this concrete can be fly ash, then the potential quantity of fly ash that can be absorbed in this application would be around 5,000,000 tons.

To realize such widespread use, research is needed:

1. To determine resistance to abrasion and, if need be, how to improve it.
2. To study French experience on intergrinding with cement clinker and find means of applying it to American practice.

3. To determine relationship between curing prior to exposure to freezing and thawing, and durability.
4. To determine resistance to salts and, if need be, how to improve it.
5. To study high temperature curing cycles and effect on strength and creep.
6. To develop data and procedures for wider use of fly ash as a raw material in cement.

Studies, research, and development can only indicate feasibilities, technical problems and solutions, and develop practical products that will perform in certain patterns. Information and data resulting from these activities will permit the practicing engineer to take advantage of fly ash in his everyday construction.

Block, Pipe, Precast, and Prestressed Units

Much of the discussion in the preceding general section on concrete applies to these products. The disadvantage of lower early strength is minimized by the higher early strength attained, due to the higher curing temperature. Autoclave curing would probably eliminate this difference completely. The utilization of interground fly ash may do so even with lower pressure steam curing. Saturated steam is essential for the pozzolanic action to proceed rapidly, and unfortunately not enough stress is placed on this factor, in the average plant.

Over-all estimates in this field indicate a yearly production of about two billion building block units (8" x 8" x 16" equivalent) and 14,000,000 tons of pipe for 1958. The precast concrete units industry manufactures such a variety of products that there is no readily available, over-all estimate of the quantities, but they must be considerable. The phenomenal growth of the prestressing industry from practically nothing in 1950 to an estimated production of close to $500,000,000 in 1959, with the eventual probability of a billion-dollar industry, indicates the rapid development of this field and the potential volume for fly ash concrete.

The present use of fly ash in these products, particularly block and pipe, is increasing, but the proportion of fly ash, where used, may not be as high as could be added advantageously. The use of fly ash in concrete mixes for precast units and for prestressed units has made little headway. This in spite of the advantages that its use presents.

Specifications that require a minimum cement content, and do not permit the fly ash to be counted as part of the cementitious material, have delayed the acceptance of fly ash in many cases, particularly in pipe, primarily because the cement saving incentive is eliminated by such restrictions.

It is evident that this is a field which offers opportunity for much wider utilization of fly ash. Most plants making concrete products of various types operate on a year-round basis, and do not have the seasonal operation disadvantage that construction work has in many sections of the country. In addition, such plants are usually reasonably close to industrial centers where fly ash is readily available.

Cooling and drying shrinkage from the elevated curing temperatures, long-time creep of steam-cured fly ash concrete (of great interest in prestressing work), effect of fly ash in block mixes on carbonation, actual strength gains under steam curing as compared to control mixes without fly ash—all such information is either absent, or what little is available is buried in the literature so that it has not become "general knowledge."

A program of research to provide adequate data, development to turn the research data into practical solutions for the man responsible for getting results at the plant, and dissemination of technical information to plant operators, architects, and engineers, all teamed together will undoubtedly help to increase the utilization of fly ash in concrete products.

Research and Development

The purpose of this section is to summarize the various suggestions regarding research, scattered throughout the report. This research is needed to develop information on various problems, or to clear some doubts regarding the use of fly ash in concrete.

Lightweight Aggregate

With lightweight aggregate as the largest undeveloped potential outlet for fly ash, it is logical that studies, research, and development be pushed at an accelerated rate, in order to permit the accumulation of data and knowledge to permit of disposing of the huge tonnage of fly ash that this field could absorb. This research should consist of a three-step program:

1. Evaluation of present-day practices in Europe, and of the pilot work done in Canada and the United States.
2. Development and adaptation to American problems, of the most promising procedures.
3. Research necessary to develop the properties, mixes, and related data as a background for concentrated promotion and sales.

Research is also needed on the possible use of lightweight fly ash aggregate, once it becomes available, in bituminous concrete mixes.

Intergrinding with Cement Clinker

Equally as important as lightweight aggregate research, is research on the intergrinding of fly ash with portland cement clinker. The advantages of fly ash in concrete mixes as a pozzolanic ingredient are already well established, and therefore results of research on intergrinding would be more readily acceptable and be usable more quickly perhaps than the research on lightweight aggregate. This again would involve:

1. Evaluation of the French work.
2. Adaptation of it to American operations.
3. Research to accumulate data with American materials, in order to develop the required promotional and sales programs.

This process eliminates separate batching and handling of fly ash, which are deterrents against its use in many instances, provides early strengths comparable to plain concrete (the presently obtained lower early strengths alone being a deterrent in many instances), and permits comparisons on an "equal strength" basis—factors of utmost importance in pavement work on highways and airports, and in structural work.

Closely allied to this field of research is further work on increasing the early strength by the addition of fly ash in excess of the amount of cement reduction.

What it amounts to is that the greatest utilization of fly ash can be made on the average run-of-the-mill job that cannot afford to handle and batch fly ash separately, by intergrinding with portland cement clinker. But on the larger job or cement product plant where a separate material can be handled properly, the most fly ash would be used by adjusting the mix to reduce both the cement and sand and thus obtain the high early strength.

Resistance to Adverse Conditions

The third important phase of fly ash research should be aimed at clearing the doubts regarding:

1. Resistance to abrasion of pavement surfaces due to the grit or sand that is used with de-icing salts, and traffic.
2. Resistance to freezing and thawing, under non-ideal curing conditions.
3. Resistance to de-icing salts.

The favorable clarification of abrasion, freezing and thawing resistance, and de-icing salts problems, would make it possible for fly ash to compete advantageously for the huge yardages of pavement in highways and airports that are being placed all over the country.

Raw Material for Cement

The research needed in this facet is to develop information and data that will permit wider use of fly ash in this application. The breadth of use will depend on competitive materials.

Precast Units

Because of the rapid development of early strength through high temperature curing, used in the production of building blocks, precast units, and prestressed units, research is needed to determine the optimum temperatures and curing cycles. Particular attention to the effect of fly ash used in such cycles as affecting creep, which is so important in prestressing work, is also needed.

Research Program

Research and development have proven to be an unbeatable team in the growth of American industry. It is a well-known fact that there is a direct correlation between research budgets of corporations and their growth. In the case of fly ash, research that will result in the solution of the various problems which have been enumerated and discussed can be the key for converting a large disposal cost into an eventual revenue of at least equal magnitude.

Weinheimer (157) has estimated that the fly ash production will be around 17,000,000 tons by 1963, and that the average disposal cost was 95 cents per ton in 1954.

The total of the estimates of potential fly ash use developed in this study add up to about ⅔ of the total 17,000,000 tons. Because the estimates are conservative, and because the various fields of application are growing at a very rapid rate, it is felt that in time these quantities will increase appreciably, and that at the same time a portion of the fly ash output will be absorbed by other applications, not covered in this study, one of the most important being soil stabilization.

In 1950, Major (68) estimated that the yearly fly ash research expenditure was about $75,000; but this was being spent by individual organizations with little or no coordination, thus reducing the effective returns per dollar.

Weinheimer's estimate of disposal cost of 95 cents per ton has risen, probably to one dollar or more, by now. Thus, the total disposal cost would be around $17,500,000.

Jarrige (243) estimates that the utilization of fly ash eventually converts the disposal cost into an equal amount of revenue. Thus, the $17,500,000 disposal cost would eventually be turned into about $17,500,000 revenue, or a net gain of about $35,000,000. The utilization of this amount of fly ash is also estimated to create another $35,000,000 in wealth divided between profit to the distributors, and savings and advantages to the users.

In other words, the possible reward of research and development can be the changing of a disposal cost of $17,500,000 into an asset of three times this amount—in other words, the creation of wealth equal to four times the disposal cost.

This is an exciting challenge to everyone concerned—a challenge that cannot be ignored.

ACKNOWLEDGMENTS

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Annotated Bibliography: 1934 - 1959

1934

1. McMILLAN, F.R. and POWERS, T.C. "A Method of Evaluating Admixtures." Proceedings, American Concrete Institute, Vol. 30, pp. 325-344, March-April 1934. See Bibliography No. 6, 10, 106.

   Benefits of admixture: (a) physical effects, (b) cementitious properties of its own, (c) pozzolanic effects.

   Workability for given combination of materials depends on: (a) quantity of paste per unit volume of concrete, (b) consistency of paste, (c) gradation of aggregate. Admixtures are considered part of the paste. Workability is influenced more by quantity and consistency of paste than materials of which paste is made.

   A table listing indices of relative worth (effectiveness with admixture as compared to plain cement) on basis of strength and workability is given. Strength indices are given for lean and rich mixes. For each type of mix two indices are given, one which holds for a range from 0 to the maximum quantity of admixture which can be represented by a single index with no appreciable error, and the other for a quantity double that maximum. A separate index on workability basis is also given.

   Among the admixtures tested, precipitator ashes are included in the table: (a) Colloy, Lot No. 11893, has strength indices 0.80-0.90 and a workability index of 1.00, and (b) Precipitator Ash, Lot No. 11897, has strength indices 0.50-0.80 and workability index of 1.11.

1935

2. HARRISON, R.L., JONES, P.W., and SHREVE, R. NORRIS. "Rostone Operations." Industrial and Engineering Chemistry, Vol. 27, No. 9, pp. 1023-1026, September 1935.

   Use 100 parts fly ash, 10 parts hydrated lime, ½ part wood rosin (to eliminate efflorescence) and 19 parts water by weight, molded under pressure, and steam cured. Results in smooth block, of low conductivity, and fire resistant. Develops strength of 2,226 psi over whole surface of 8" x 8" x 16" block with 55 percent core space, and weighs about 23 pounds per block.

1937

3. DAVIS, RAYMOND E., CARLSON, ROY W., KELLY, J.W., and DAVIS, HARMER E. "Properties of Cements and Concretes Containing Fly Ash." Proceedings, American Concrete Institute, Vol. 33, pp. 577-612, May-June 1937. See Bibliography No. 4, 9, 13, 19, 60, 61, 79, 146.

   Using 15 fly ashes as replacements in concrete, up to 50 percent by weight of the cement, find that in general: (1) Principal difference in chemical composition of various fly ashes is carbon content. (2) Fly ashes are finer than portland cements and many of the particles are spherical in shape. (3) Fly ashes exhibit pozzolanic activity as judged by ability to combine with lime. (4) For low carbon content and high fineness fly ash, optimum replacement for moist curing is about 30 percent. (5) Under mass curing conditions replacements may be as high as 50 percent. (6) Most favorable results are obtained using fly ash with portland cement of normal or high fineness and of normal or high lime composition. (7) Mixing of fly ash with cement is as good as intergrinding. (8) Fly ash cements have slower set but within usual specifications limits.

With fly ashes of low to moderately low carbon, and moderately high to high fineness, blended with cements of normal or high fineness and normal to high lime composition, the following additional conclusions may be drawn: (9) Water requirement for equal consistency of concrete is about the same or a little lower than when using plain cement, and is somewhat less than for other pozzolans. (10) For 30 percent replacement and standard curing, the compressive strength is lower at early ages and higher after 3 months. (11) Under mass curing conditions, as high as 50 percent replacement, strength is higher than plain concrete even at 28 days. (12) By using 20 percent replacement with normal fineness portland cement and intergrinding the mixture, the resulting fly ash concrete may exhibit 3-day compressive strengths substantially the same as the corresponding Type III cement for which the same energy was consumed in grinding. (13) Contribution (in percent) of fly ash to the compressive strength is not markedly affected by richness of mix. (14) Modulus of elasticity is lower at early ages and higher at later ages, but differences are not enough to significantly affect designs. (15) Shrinkage is, in most instances, somewhat less than for plain concrete. (16) Resistance to freezing and thawing of fly ash concrete is about the same or slightly lower than for plain concrete (judged through 30 slow cycles). (17) Fly ash increases resistance to sulfate. (18) Fly ash reduces heat of hydration. (19) Under sustained loads, fly ash mortar exhibits greater plastic flow at early ages, and lower at later ages, with total plastic flow about equal to plain mortar. This is advantageous in resisting differential stresses during early hardening period.

Paper outlines suggested specifications for fly ash.

4. DERLETH, C.P. "Properties of Cements and Concretes Containing Fly Ash." Discussion of Bibliography No. 3. Proceedings, American Concrete Institute, Vol. 33, pp. 612-1 to 612-4, September-October 1937.

   Contends that: (1) Davis does not give true facts about water requirement being about same, but feels that it takes less water. (2) Moist curing is not a necessity, and intermittent moisture is sufficient. (3) Not only silica but alumina also reacts with lime. (4) Proportions of fly ash should be determined for different services. (5) Early low strengths of no importance, as modern cements give high early strengths anyway and much higher than those of a few years ago. (6) Davis did not stress increased workability sufficiently. (7) Treated or refined fly ash would perform better than plain fly ash and should be included in future tests.

5. JAMES, J.R. "Utilization of Pulverized-Fuel Fly Ash." Transactions, American Society of Mechanical Engineers, Vol. 59, p. 370, 1937.

   Uses cinder blocks made of 100 pounds of portland cement, 100 pounds dry fly ash, and 340 pounds of crushed cinders, all mixed with water. Obtains 3,000 psi at 28 days. The light weight is advantageous for buildings by reducing foundation costs.

   Another block is the Cottrell block, which is 90 percent fly ash. Over-all heat-conductivity for 8-inch wall at 15 mph wind is 0.383 Btu per square foot, per hour, per degree Fahrenheit difference in temperature. If furred and plastered, coefficient decreases to 0.26. When the hollow cells of the blocks are filled with rock wool the coefficient is further reduced to 0.16, and when filled with fly ash the coefficient becomes 0.18. Fire tests of 3 hours at 1,600°F temperature, followed by quenching with fire hose, resulted in only ⅛-inch cracks. Absorption is about 6 percent. Rostone Company, Lafayette, Indiana, holds the patents for the Cottrell blocks.

6. McMILLAN, F.R. and POWERS, T.C. "Classification of Admixtures as to Pozzolanic Effect by Means of Compressive Strength of Concrete." Proceedings, American Concrete Institute, Vol. 34, pp. 129-143, November-December 1937. See Bibliography No. 1, 10, 106.

   Rearrangement of data from reference No. 1, to show effect of additions of admixtures to various cement factor concretes, and then draw lines of equal workability.

   Conclude: (1) Effectiveness of admixture varies with richness of mix, quantity and kind of admixture, and age of test. (2) For concretes of equal workability, those without admixtures are the strongest with one exception (fly ash).

7. PILCHER, J. MASON and VILBRANDT, FRANK C. "Humid Aging of Fly Ash Brick." Industrial and Engineering Chemistry, Vol. 29, No. 4, pp. 427-428, April 1937.

   Using 1,000 parts fly ash, 100 parts hydrated lime, 5 parts rosin, and 250 parts water, made Rostone brick at various pressures, and cured moist instead of by steam. Find: (1) That moist curing eliminates need for rosin and therefore bricks attain higher strengths. (2) Increasing moist curing time increases compressive strength. (3) Addition of gypsum—more than 10 parts per 1,000 parts of fly ash—is detrimental.

8. TUTHILL, L.H. "Portland Pozzolan Cement." Metropolitan Water District of Southern California, Report No. 723, April 1937.

   Report shows that on San Jacinto Tunnel, using calcined shale interground with cement clinker: (1) Workability was improved, segregation lessened, bleeding decreased, and concrete flowed better in place by pumping, and finished better, while remaining plastic longer. (2) In addition it had good strength, water tightness, and lowered heat of hydration.

1938

9. ANON. "Find Favorable Results from Mixtures of Fly Ash with Cement." Concrete, Vol. 46, No. 10, p. 26, October 1938. See Bibliography No. 3.

   Summarize R.E. Davis' work in California in which it was found: (1) Differences in chemical composition not large except carbon content, even though 15 fly ashes tested came from widely scattered areas. (2) Fly ash finer than cement, and particles mostly spherical. (3) Fly ash has high pozzolanic activity, the finer and the lower the carbon the better. (4) For low carbon and high fineness, suggests optimum replacement of 30 percent under standard curing. (5) Under mass concrete curing conditions it may be advantageous to use replacements as high as 50 percent. (6) Best results with cement of normal or high fineness, and of normal or high lime composition. (7) Mixing on job as good as intergrinding. (8) Fly ash concrete sets more slowly but within usual specification limits.

10. DERLETH, C. P. "Classification of Admixtures as to Pozzolanic Effect by Means of Compressive Strength of Concrete." Discussion of Bibliography No. 6. Proceedings, American Concrete Institute, Vol. 34, pp. 144-1 to 144-4, March-April 1938. See Bibliography 1, 6, 106.

Contends that: (1) Evaluation of fly ash concrete on basis of early strengths unfair, because portland cement alone gives sufficient early strength and pozzolan improves concrete strength at later ages. (2) Term "Fly Ash" should be used, and not "Flue Ash" or "Precipitator Ash." (3) Method used by authors of reference article to arrive at fly ash indices is questionable. (4) Asks for complete 6 months data. (5) Insists that the fly ash tested is finer than the portland cement, has 125 percent of the volume of an equal weight of cement, and has predominantly spherical particles, and therefore improves workability comparable to finer ground cement, provides more lubrication than richer mix of cement alone, which has angular, abrasive, and coarser cement particles. (6) Better workability from fly ash in spite of reduced water demand, and gives test results to show that—"Pound for pound, fly ash is more effective as a workability medium than is portland cement."

11. STANTON, T. E., Jr. and MEDER, LESTER C. "Resistance of Cements to Attack by Sea Water and by Alkali Soils." Proceedings, American Concrete Institute, Vol. 34, pp. 433-464, March-April 1938.

Find that: (1) Magnesium salts more destructive than sodium salts. (2) Not all cements equally resistant to attack. (3) C_3A most important criterion in cement durability, the lower the better. (4) Silicious admixtures improve resistance. (5) Use of a minimum 6-sack mix, and low water-cement ratio improves durability. (6) Recommend keeping C_3A below 8 percent. (7) Dependence should not be placed on compound analysis, but on thorough tests with given combinations and for specific exposure.

12. THORSON, A.W. and NELLES, JOHN S. "Possibilities for Utilization of Pulverized-Coal Ash." Mechanical Engineering, Vol. 60, pp. 845-851, November 1938. See Bibliography No. 13, 14.

Give analysis of Trenton Channel Plant fly ash and content that: (1) As filler in bituminous concrete, fly ash is much better and cheaper than limestone dust. (2) As fertilizer, fly ash is not practical because sand is cheaper and does not have dust problem. (3) As filler for rubber, fly ash is too coarse and gritty. (4) To replace calcium carbonate in paint, fly ash color is objectionable. (5) For filler in roofing materials, fly ash has good possibilities. (6) For use in common brick, fly ash proved unsatisfactory. (7) Fly ash gives dense, smooth, waterproof surfaces on cinder block. (8) Fly ash is not satisfactory to replace sand in sand-lime brick. (9) Fly ash is not satisfactory to replace sand in aerocrete. (10) Fly ash is not satisfactory to replace sand in lightweight concrete tile. (11) Fly ash is not satisfactory to replace pumice in acoustic plaster. (12) Fly ash improves haydite concrete by reducing segregation. (13) Fly ash is too expensive for lightweight concrete aggregate manufacture even though suitable. (14) Fly ash is not satisfactory for sodium silicate block. (15) Fly ash reduces porosity of cinder block. (16) Cottrell block made of 90 percent fly ash, 10 percent lime, and ½ percent rosin is good. (17) As concrete admixture, fly ash improves workability and plasticity, and increases strength. About 30 percent is optimum as mix tends to become sticky with larger additions. It decreases permeability and is more beneficial in leaner mixes. Substitutions in rich mixes satisfactory providing cement content is not reduced below 4 bags per cubic yard. Fly ash concrete shows definite increase in strength with age. (18) Fly ash is not suitable as polish for metals. (19)

Fly ash is good for sandblasting, providing high polish with low metal loss. (20) Under certain conditions, fly ash can be used to replace clay in cement manufacture. (21) Due mostly to high cost, fly ash is not suitable for brick-mold dusting. (22) Fly ash is not suitable for petroleum filters in oil refineries. (23) Fly ash is not suitable for foundry molding material. (24) Fly ash can be used as a good wall insulator to fill cores in blocks, etc.

Point out that all construction uses depend on seasonal work and that it would be better to find a good use that is independent of such fluctuation.

1939

13. DAVIS, RAYMOND E. "Possibilities for Utilization of Pulverized-Coal Ash." Discussion of Bibliography No. 12, Mechanical Engineering, Vol. 61, pp. 475-476, June 1939. See Bibliography No. 3, 4, 9, 19, 60, 61, 79, 146.

Principal variables that affect use of fly ash in concrete are: (a) fineness, (b) carbon content, and (c) percent of replacement used.

Fineness cannot be measured by minus 200 sieve, and it is the particles much finer than this size that are of significance in concrete. Specific surface is the proper method to measure fineness, and the finer the fly ash, other things being equal, the better the strength.

High carbon may not affect strength but probably will reduce freezing and thawing resistance.

Wetting fly ash for ease of storage makes handling for use in concrete difficult, even though it may not affect properties. Fly ash should pass standard soundness test when mixed with cement, as a guard against delayed expansion. To be useful commercially, fly ash should be from a collecting system that retains the fines.

For general work recommends 25 percent replacement with specific surface of the fly ash above 2,500 square centimeters per gram, and maximum ignition loss of 7 percent (for concrete subject to drying and frost action). For mass concrete not subject to drying or frost action, as high as 50 percent replacement may be permitted. Higher carbon content may be usable with not more than 20 percent replacement. Recommends higher replacement only in protected concrete such as foundations, inside buildings, and similar locations.

14. JAMES, J.R. "Possibilities for Utilization of Pulverized-Coal Ash." Discussion of Bibliography No. 12, Mechanical Engineering, Vol. 61, pp. 476-477, June 1939.

Advantages of Cottrell blocks using fly ash: (1) Have smooth surface. (2) Have $^2/_3$ weight of concrete or cinder block. (3) Have low heat conductivity, and when filled with fly ash no condensation occurs in Detroit weather. (4) Can be cut with carborundum saw. (5) Are highly fire resistant. (6) Are sound proof. (7) Are readily painted and plastered.

15. POWERS, T.C. "The Bleeding of Portland Cement Paste, Mortar and Concrete." Portland Cement Association, Research Laboratory Bulletin No. 2, July 1939.

Advances hypothesis supported by reasonable experimental evidence that it is the settling of particles until they come in solid contact with one another, that causes bleeding. Only way to reduce it is to reduce size of capillaries, as then contact is established sooner. This can be accomplished by: (1) Reducing slump by decreasing water. (2) Increasing cement. (3) Increasing fineness of cement. (4) Increasing amount of immobile water. (5) Supplementing cement with other fine material of suitable specific surface.

16. RAMSEYER, C.F. "Solving the Fly Ash Problem." Electric Light and Power, Vol. 17, pp. 44-47 and 66, February 1939.

Gives short history of problem. Paper may be summarized: (1) Pozzolanic activity described as reaction with free lime to produce more stable compounds. (2) Estimates annual fly ash production at 2½ million tons, or 10 percent of portland cement production. (3) Fly ash used in concrete, generally as 15-35 percent of cement; therefore, it does not flood the market. (4) Low carbon, high surface area fly ash is best. (5) Fly ash is the best pozzolan commercially available. (6) Fly ash has lower water requirement than cement. (7) As a result of this fly ash concrete has lower drying shrinkage. (8) Estimated savings in cost 25-60 cents per cubic yard of concrete. (9) Principal advantages are: (a) lower water requirement, (b) greater workability, (c) increased density, (d) increased impermeability, and (e) increased strength at later ages. (10) Permeability is usually reduced 6-7 times. (11) Compressive strength curves with 20 percent replacement, show higher strength after 45-60 days than plain portland cement concrete. (12) Improved workability is due to increased fines, with specific gravity of 2.53 against that of cement of 3.15. (13) Fly ash improves resistance to sulfates. (14) Rich mixes of State Line fly ash show same resistance to freezing and thawing as plain concrete, but leaner fly ash mixes exhibit poorer resistance than plain concrete mixes. (15) It is necessary to obtain a balance between air in combustion chamber of boiler and carbon content of coal and temperature to obtain fusion of fine particles. (16) State Line plant can hold carbon down to 2 percent, and some samples have been as low as ½ percent carbon. Unit No. 2 does not show such low carbon, as it has not been in operation long enough to reach final adjustment. Fly ash from this source is very uniform, and is tested prior to storage. (17) Fly ash has its own handling problems.

1940

17. ELMER, N.W. "Profitable Fly Ash Handling." Steel, Vol. 106, No. 7, pp. 64-65 and 79. February 12, 1940

Use airtight conveying system to maintain vacuum on electrostatic precipitator units, thus collecting high grade material of low carbon and high fineness, which is readily marketable in Chicago.

18. NELLES, JOHN S. and SELLKE, A.A. "Fly Ash in Concrete." Proceedings, National District Heating Association, pp. 199-205, 1940.

Fly ash improves concrete physically and chemically: (1) It improves grading of aggregate, or faulty proportioning of aggregates. (2) It provides more plastic and dense concrete. (3) It reduces segregation and bleeding. (4) It has pozzolanic action. (5) Non-combustible particles of fly ash are similar to vitrified clay. (6) Combustible particles are essentially coke. (7) the higher the carbon content, the coarser the fly ash. (8) Fly ash unit weight is approximately 46 pounds per cubic foot, by ASTM Designation C29. (9) Detroit Edison produces uniform fly ash. (10) Have experimented with fly ash concrete using boiler-run cinders from stoker-fed boilers. (11) In lean concrete fly ash improves strength up to 100 percent additions—in rich mixes improves it only up to 20 percent additions. (12) The practical limit is about 30 percent addition. (13) Fly ash improved workability. (14) Fly ash reduces permeability. (15) Fly ash gives increased strength after 28 days, with 20 percent substitution by weight. (16) Increasing fly ash over and in excess of substitution, produces strength gains at earlier ages. (17) Fly ash provides lower cost for superior concrete. (18) Recommends use of 30 percent by weight addition or 20 percent substitution.

1941

19. DAVIS, RAYMOND E., DAVIS, HARMER E., and KELLY, J.W. "Weathering Resistance of Concretes Containing Fly-Ash Cements." Proceedings, American Concrete Institute, Vol. 37, pp. 281-396, January 1941. See Bibliography No. 3, 4, 9, 13, 19, 60, 61, 79, 146.

Using plain (non-air-entrained) concrete with Type II cement and 11 fly ashes having 1 to 17 percent carbon, and with varying fineness, find: (1) No single characteristic or simple combination of characteristics, controls the performance of fly ash in concrete (10 and 20 percent by weight replacements). (2) Fly ash mixes evidence considerably less autoclave expansion, about same drying shrinkage, and with minor exceptions, greater resistance to freezing and thawing (five months' moist curing prior to fast cycle, with number of cycles at 25 percent loss by weight considered as failure). (3) Nine out of eleven of the fly ashes, used as 10 percent replacement, showed concrete strengths higher at 7 and 28 days than plain cement concrete, and at age of 1 year, all were stronger. The 20 percent replacements approached or equaled the 28-day strength of plain cement concrete, and with one exception, all exceeded it at 1 year. (4) Percent replacement has little effect on shrinkage, but the 20 percent replacement concretes were more resistant to weathering than the 10 percent. (5) Carbon content showed no consistent effect on soundness, strength, shrinkage, or weathering resistance. (6) The high fineness fly ash exhibited lower water requirements than the low fineness for a fixed consistency of paste concrete, slightly greater autoclave expansion, greater strength of concrete, about same drying shrinkage, and higher resistance of concrete to the action of freezing and thawing. (7) Fly ash of fairly high carbon content but of reasonably high fineness may be used in small percentages as a replacement for portland cement with the probability that with proper curing and normal exposure, such use will lead to an improvement in the quality of the concrete, particularly as regards weathering resistance. (8) Suitability of fly ash can be ascertained by standard physical tests for cement, that is, time of set, autoclave soundness, and tensile and compressive strength of mortar.

20. KRONSBEIN, W. "Fly Ash as Hydraulic Admixture in the Manufacture of Binders for Mortar and Concrete." Zement, Vol. 30, pp. 503-506 and 518-520, 1941. Abstracted in Highway Research Abstracts, No. 91, pp. 7-8, June 1942. See Bibliography No. 82.

On testing 14 fly ashes to compare with German trass, finds: (1) If of suitable composition, fly ash can be used in the manufacture of cement or as an admixture at the site. (2) With low carbon, and fineness corresponding to fineness of cement, it has hardening properties similar to trass. (3) With 20 percent replacement fly ash concrete has low early strength but high 1-year strength provided moist curing is carried out, particularly at early ages. Thus, it permits conserving cement in concrete where high early strength is not required—cannot be used in structural members where full load comes early. (4) Most fly ashes are too coarse, too high in carbon and too variable, especially as to carbon content. (5) Too high a gypsum content is to be feared less than generally supposed. (6) Suggestions are made for requirements respecting fineness, ignition loss, constancy of volume and hardening properties of fly ash to be used as an admixture in concrete or cement.

21. LARMOUR, H. McC., McMASTER, E.L., and JAQUES, WM. "Evaluating a Pozzolan." Rock Products, Vol. 44, pp. 52-56 and 87, March 1941.

Make following points: (1) Lowered strengths can be increased by increasing fineness of pozzolan. (2) Ultimate activity of a pozzolan may be obtained in autoclave by mixing with hydrated lime and determining decrease in insoluble residue. (3) The rate of activity with strength gain for portland-pozzolan cement may be determined by curing parallel specimens at two or more constant temperatures for same period. (4) Pozzolanic action of silicates is influenced by chemical composition and curing temperature. Silicates with low alumina are slowly reactive at normal temperature but highly so at elevated temperature. (5) Desirable fineness for pozzolan may be determined by activity test. (6) Grinding pozzolans removes surface films from particles and accelerates activity.

22. NELLES, J.S. "Concrete Exposed to Sulphur Water." Proceedings, American Concrete Institute, Vol. 37, pp. 441-452, February 1941.

Various combinations of admixtures and types of cement were used in specimens exposed to natural sulphur water for 12 years. Finds that fly ash (25 and 50 percent admixtures) compares faborably with others, although Lumnite probably best. The richer, and lower water-cement ratio mixes performed best.

1942

23. BURKART, W. "Utilization of Fly Ash as a Construction Material." Die Wärme, Vol. 65, No. 15, pp. 134-135, April 1942. Abstract Chimie et Industrie, Vol. 49, No. 1, p. 32, 1943.

Listed in fly ash bibliography in Revue des Matériaux de Construction, without abstract.

24. GRÜN, R. "On Mixed Binders." Zement, Vol. 31, pp. 1-8, 1942. Abstract in Building Science Abstracts, Vol. 15, Abstract No. 710, October 1942.

Mixed binders are distinguished from standard portland cements, by using various materials interground with cement clinker, thus resulting in a product of lower strength and lower manufacturing cost, but still suitable for plaster, concrete foundations, floors and walls of houses, and similar applications. When carbon fly ash was interground experimentally with clinker, it markedly reduced strength and could not be used in excess of 15 percent.

1943

25. COLEMAN, S.H. "Fly Ash Blast Cleans Metal Surfaces." Power, Vol. 87, p. 50, January 1943.

Fly ash makes fine abrasive that takes off very little metal yet cleans surfaces. One very good application is turbine blades.

26. SIMON, WALTER and SPRUNG, HELMUT. "Fly Ash from Brown Coal. A Valuable Raw Material." Chemiker Zeitung, Vol. 67, pp. 150-153, 1943. Abstract in Chemical Abstracts, Vol. 39, No. 11, p. 2392, 1945.

The fine ash from electrostatic precipitation is a good binder for mortar, plaster, and rough building materials. It can be combined with cement, CaO, or gypsum.

1944

27. BARMACK, B. J. "Repairing Top Heart Rot of Standing Poles." Electrical World, Vol. 122, p. 77, December 23, 1944.

    Cut top off, clean hole, apply pentachlorophenol, fill with thick mixture of fly ash with 5 percent pentachlorophenol in fuel oil, fluid enough to pour into cavity. Cover with roofing paper kept away from oil mixture by projecting nails driven into the wood.

28. BOGATUIREV, I. I. "The Use of Ash from a Central Electrical and District Heating Station as an Admixture to Cement." Stroitelnaya Promuishlennost, Vol. 22, Nos. 10/11, pp. 20-21, 1944.

    Results of compressive strength tests are shown for binders consisting of lime and boiler ash in the proportions 30 to 70, and of portland cement and ash in the proportions 70 to 30, 50 to 50, and 30 to 70.

29. FREDERICK, HARRY A. "Application of Fly Ash for Lean Concrete Mixes." Proceedings, American Society for Testing Materials, Vol. 44, pp. 810-820, 1944.

    Using 2- and 3-bag concrete, substitutes fly ash for optimum of 25 percent of sand by weight. Finds: (1) This gives more workable and stronger concrete at 7 and 28 days than plain concrete. (2) Bleeding is reduced. (3) Wet fly ash substitutions not as effective in producing high-early-strength as dry fly ash, but over longer periods both attain essentially the same strength. (4) The 7-day strength is 16-34 percent greater than 28-day in plain concrete. (5) For a specified strength (28-day) fly ash mixes with 25 percent replacement of sand require 34-48 percent less cement than plain mixes. (6) Density and surface hardness of fly ash concrete superior to plain concrete. (7) Strength and workability are not affected by high carbon fly ash, as used. (8) Larger quantities of fly ash can be used to replace sand than cement, and therefore better disposal solution.

30. HORNIBROOK, F. B. "Admixtures for Concrete." American Concrete Institute Committee 212, Proceedings, American Concrete Institute, pp. 73-86, November 1944.

    This information report classifies admixtures into 9 groups. It defines admixture as a substance other than cement, aggregate, or water, that is used as an ingredient in concrete. The classes are: (1) Accelerators. (2) Air-entraining agents. (3) Gas-forming agents. (4) Natural cementing materials. (5) Pozzolanic materials. (6) Retarders. (7) Water-repelling agents. (8) Workability agents. (9) Miscellaneous. Mention is given fly ash in Nos. 5 and 8. It is suggested that fly ash may be used for pozzolanic effect in amounts from 10-30 percent, and for workability in amounts up to 20 percent.

31. WEINHEIMER, C. M. "Evaluating Importance of the Physical and Chemical Properties of Fly Ash in Creating Commercial Outlets for the Material." Transactions, American Society of Mechanical Engineers, Vol. 66, No. 6, pp. 551-561, August 1944. See Bibliography No. 56, 158.

    Brings out following: (1) Physical properties (particle size, color, particle shape and structure, thermal insulating properties), and chemical properties (pozzolanic action and reducing alkali reactivity), are summarized. (2) Possible commercial uses: concrete, bituminous filler, rubber. (3) Discusses modifying fly ash to meet certain industrial requirements. (4) Handling problem creates sales resistance.

1946

32. GILL, L. J. "Durability Tests on Fly Ash." Combustion By-Products Company, 1946.

Tests made by Robert W. Hunt Company on State Line fly ash interground with Type I cement (Medusa) using 20 percent fly ash. Findings are: (1) Improved cube strength and tensile strength (briquettes), at all ages. (2) Compressive strengths on 3 mixes of varying water-cement ratios are higher in every case at all ages, from 3 days to 2 years, than corresponding controls. (3) Another series of 7 mixes shows little significant difference from control on absorption, and generally reduced compressive strength after 120 and 150 cycles of freezing and thawing (3 months' moist curing followed by cycles consisting of 18 hours at 0°F and 6 hours in water at 70°F). (4) Three other mixes were treated with salts and calcium chloride, and 30 freezing and thawing cycles for each of two periods with summer outdoor exposure in between. Scaling and loss of weight were higher for calcium chloride treated specimens than salt treated. It appears to be less for fly ash concrete than plain concrete.

33. HAHN, H. "Utilization of Industrial Ashes as Cementing Materials" (Utilisation des Cendres Industrielles Comme Liants). Die Technik (German), Vol. 1 pp. 91-95, 1946. Abstract in Chimie et Industrie, Vol. 58, No. 1, p. 48, 1947, and in Revue des Matériaux de Construction, No. 457, p. 293, 1953.

Uses ash from lignite, the lime content of which is 39 percent. Compressive strengths ranged from 28 to 62 kilograms per square centimeter (400 to 880 psi) at 7 days, and from 46 to 106 kilograms per square centimeter (650 to 1,500 psi) at 28 days. Mix used consisted of one part ash and three parts aggregate. Aggregates used were sand, gravel, scoria, crushed brick, and pumice stone.

34. LEFTWICH, R. F. "New Lightweight Aggregate from Fly Ash." Concrete, Vol. 54, pp. 14-15 and 39, January 1946.

Mix fly ash and crushed slag, then sinter, crush, and screen to proper sizes. Use this mixture with cement for making blocks. Control is easy because everything is dry before mixing for block making.

35. LEVERETTE, FLOYD C. "Fly Ash Successfully Employed by Two Midwestern Producers." Pit and Quarry, Vol. 39, pp. 135-138, December 1946.

Illinois-Wisconsin Concrete Pipe Company of South Beloit and Continental Concrete Pipe Company of Blue Island use 25 percent fly ash to give them smoother pipe. Cure with 100°F Steam for 48 hours. Obtain 50 percent higher strength than ASTM requirements, in 48 hours.

1947

36. ANON. "First Sinter-Lite Plant is Making Lightweight Aggregate from Fly Ash." Pit and Quarry, Vol. 39, pp. 199-200, January 1947.

Describes Bronx, New York, plant which sinters fly ash at 2,400°F, then crushes and grades it to supply lightweight aggregate (Sinter-lite) varying from 34 to 56 pounds per cubic foot. Needs no fuel as fly ash contains from 6 to 20 percent carbon, thus furnishing its own fuel. Produces 125 cubic yards in 8 hours.

37. AVERY, WILLIAM M. "Fly Ash Teams Up with Portland Cement to Make Better Concrete." Pit and Quarry, Vol. 39, pp. 157-159, May 1947.

In essence: (1) Fly ash reduces water requirement. (2) Increases workability. (3) Acts as a pozzolan. (4) Develops slow early strength gain, but higher eventual strength than plain concrete. (5) Provides high impermeability at early ages. (6) Strength gain can be accelerated by steam curing 4 to 5 days. (7) Used in pipe manufacture. (8) Control of carbon content is essential.

38. BESSEY, G. E. "Utilization of Pulverized-Fuel Ash in the Building and Civil Engineering Industries." Transactions, Pulverized Fuel Conference of the Institute of Fuel (British), pp. 307-322, June 1947.

Mainly a review of literature. Fly ash can be used: (1) As raw material for cement. (2) In concrete or mortar. (3) As fine aggregate or filler in concrete and concrete products. (4) As raw material for bricks and tiles. (5) For bituminous mixtures. (6) Concludes that although use of fly ash is technically feasible, there are too many unknowns and it has not yet been shown that any of the uses listed are economically advantageous.

39. BRUNENKANT, EDWARD. "Company Engineer Well Satisfied with New Fly Ash Block." Pit and Quarry, Vol. 40, pp. 135-136, December 1947.

Add 100 pounds fly ash to 3 bags of cement for block and 75 pounds of fly ash to 6 bags of cement for pipe and steam cure to get satisfactory strength and finish.

40. HANNA, W.C. "Unfavorable Chemical Reactions of Aggregates in Concrete and a Suggested Corrective." Proceedings, American Society for Testing Materials, Vol. 47, pp. 986-1009, 1947.

Pozzolans inhibit expansion due to alkali reaction. Among pozzolans fly ash is only 1/3 as active as diatomaceous earth or calcined shale.

Discussion by R. E. Davis—All finely divided silicates will do the same thing but in different degrees.

41. LEDYARD, EUGENE A. "Pozzolan Cements." Rock Products, Vol. 50, pp. 134 and 153, December 1947.

Feels that experiments by cement industry are aimed at showing that pozzolan cements are inferior products in which pozzolans dilute good cement, rather than trying constructively to ascertain how portland cement might be improved by the addition of pozzolanic materials.

While pozzolan cements have relatively low early strength, it is not so low as to interfere with construction progress, and their higher ultimate strength, resistance to sulfates, alkali soils and seawater make them advantageous to use.

By overcoming the later age tendency of portland cement to a retrogression in strength, pozzolans exert a stabilizing influence on the former.

Alkali-aggregate reaction with the general limitation of 0.6 percent for the total alkalies in low alkali cement creates a problem for some cement manufacturers in meeting such a requirement. Pozzolans of suitable nature overcome this limitation.

Since portland-pozzolan cements are serving a definite need, "it appears that the time is overripe" for the portland cement industry to lend their support and talents towards a constructive study of pozzolanic materials and portland-pozzolan cements. It is possible that a portland-pozzolan cement can be developed that will exceed the durability and workability of any cement developed to date. Urges and outlines research to answer some of the many facets of pozzolans that are still not known.

42. TAYLOR, T.G. "Effect of Carbon Black and Black Iron Oxide on Air Content and Durability of Concrete." Proceedings, American Concrete Institute, Vol. 44, pp. 613-624, April 1947.

Using emulsions for coloring concrete, finds that carbon black emulsions reduce air content and freezing and thawing durability of concrete unless made specifically to counteract this reduction by inducing air entrainment to compensate for the loss.

43. THOMPSON, P.W. "Stack Dust Collection and Disposal." Power Plant Engineering, Vol. 51, pp. 108-110, October 1947.

Describes electrostatic and mechanical collectors and storage of fly ash in bins. Uses of fly ash: (1) Substitute for cement and/or sand in concrete. (2) As aggregate in cinder concrete. (3) Raw material for cement manufacture. (4) Filler for asphalt paving. (5) Soil improving agent (lightens soil). (6) Inert filler for rubber goods. (7) Ingredient for foundry cores. (8) Combined with other waste products may be useful for fill, or for stabilization of soil.

1948

44. MEISSNER, H.S. "Expansive Cracking in Concrete." Reclamation Era, Vol. 34, pp. 74-75, April 1948. See Bibliography No. 52, 69.

Describes alkali-aggregate reaction, in popular terms, and the effectiveness of pozzolans in reducing it. Pumicite, calcined shale or clay, and fly ash are listed as pozzolans.

45. U.S. BUREAU OF RECLAMATION. "Physical and Chemical Properties of Fly Ash—Hungry Horse Dam—Hungry Horse Project." Laboratory Report No. CH-95, June 21, 1948. See Bibliography No. 52, 57, 76, 83, 91, 112, 128, 136.

Gives data and conclusions from tests on 5 samples of fly ash: (1) The 90-day compressive strength on mortar cubes is 92 percent and 122 percent of plain portland cement control for standard curing and mass curing, respectively, using 35 percent fly ash by absolute volume (25 percent by weight) replacement. (2) Alkali reduction for 30 percent replacement averages 59 percent at 14 days and 81 percent at 90 days. (3) Time of set with lime rather slow, indicating only mild pozzolanic action.

1949

46. BLANKS, ROBERT F. "The Use of Portland-Pozzolan Cement by the Bureau of Reclamation." Proceedings, American Concrete Institute, Vol. 46, pp. 89-108, October 1949. See Bibliography No. 47, 48, 58.

Extensive studies by the Bureau of Reclamation indicate definite advantages of portland-pozzolan cement in mass concrete. These are: (1) Lower heat of hydration and resulting decreased volume change. (2) Increased tensile strength. (3) Satisfactory compressive strengths. (4) Improved sulfate resistance. (5) Increased extensibility and plastic flow. (6) Reduced permeability and leaching. (7) Improved freezing and thawing durability when fog cured but not when dry cured prior to freezing and thawing cycles.

(8) Reduced alkali-aggregate reaction in most instances. Fly ash less effective than other pozzolans although it inhibits expansion in standard bars. Discussion of some hypotheses of the favorable action of pozzolans in alkali-aggregate reaction.

47. BLANKS, R. F. "Better Concrete for Our Future Dams." Technology of Cement and Concrete—Lectures at Harvard University Graduate School of Engineering, 1949. See Bibliography No. 46, 48, 58.

Amongst other things: "The right kind of pozzolans in combination with Type II portland cement improves the qualities of concrete for dam construction as follows: (1) Reduced temperature rise. (2) Reduced thermal shrinkage. (3) Slow early strength development but high ultimate strength. (4) Increased water tightness. (5) Improved extensibility or crack resistance. (6) Increased plasticity or stress-adjusting characteristics. (7) Reduced drying shrinkage. (8) Increased resistance to sulfate attack. (9) Reduced dissolution or solubility of the paste. (10) Reduced water content. (11) Improved workability." One of the pozzolans discussed favorably is fly ash for use on Hungry Horse.

48. BLANKS, R. F. "Practices, Experiences, and Tests with Pozzolanic and Other Types of Cement in Concrete." Technology of Cement and Concrete—Lectures at Harvard University Graduate School of Engineering, 1949. See Bibliography No. 46, 47, 58.

Gives history of pozzolans and covers following points: (1) List of pozzolans includes fly ash among pozzolanic industrial by-products. (2) Discussion of cement composition and effect on properties of concrete. (3) Bureau of Reclamation experience with sand-cement used in Arrowrock and Elephant Butte Dams. Advantages mainly low cement content with lower heat. (4) Experience with high silica cement used on Bay Bridge in San Francisco and in Bonneville Dam. (5) Bureau of Reclamation application of pozzolan on concrete at Friant Dam and Altus Dam. (6) Pozzolan in concrete overcomes biggest problem of cracking due to large expansion and contraction (thermal) by permitting low cement contents without the attenuated harshness and low strength. (7) Pozzolans increase tensile strength. (8) Pozzolans in concrete give low early compressive strengths but satisfactory later strengths. (9) Other advantages of pozzolans are: increased resistance to sulfate, improved extensibility (therefore reduces cracking), increases impermeability and therefore resistance to leaching. (10) The durability in freezing and thawing of blended cement concrete is not as good as plain concrete. (11) Pozzolans inhibit expansion due to alkali reaction.

In addition to general discussion of pozzolans, contains following specific comments on fly ash: (a) "On the whole, the use of fly ash resulted in concrete of quality equal or superior to that obtained with portland cement." (b) water requirement generally less than plain cement—only pozzolan with this property, (c) improves workability through reduction in segregation and bleeding and increase in plasticity, (d) compressive strength low at early ages but high at later ages—usually greater at 1 year than plain concrete, (e) lower heat of hydration, (f) with low carbon fly ash, slightly lower drying shrinkage than plain concrete, (g) resistance to freezing and thawing improved, (h) improves resistance to sulfate attack, (i) reduces alkali reaction, (j) more economical than cement in most places.

49. CHICAGO DISTRICT ELECTRIC GENERATING CORPORATION. "Fly Ash Makes Better Concrete." August 1949.

Summary on State Line Fly Ash used in concrete: (a) increased strength after 28-60 days, (b) decreased permeability, (c) increased resistance to freezing and thawing, (d) increased workability, (e) improved appearance of formed surfaces, (f) improved grouting properties, (g) reduced cost.

50. HANDY, WALTER. "Use of Fly Ash in Concrete." Symposium on Fly Ash Disposal, American Society of Mechanical Engineers Annual Meeting, Paper No. 49-A-81 (mimeographed), 1949. See Bibliography No. 64, 234.

Traces history of pozzolans: Fly ash acts similar to old Roman "pozzuolana." Lists organizations doing research on fly ash in concrete. Fly ash used in Kansas test road, in many power company structures, and in Hungry Horse Dam.

51. LARSON, GUY H. "Effect of Substitutions of Fly Ash for Portions of the Cement in Air-Entrained Concrete." Proceedings, Highway Research Board, Vol. 29, pp. 225-235, 1949. See Bibliography No. 123, 138, 150.

Laboratory tests using Universal Atlas Type IA cement with no air-entraining agent added, and State Line fly ash, finds: (1) Increase of water-cement ratio. (2) Decrease in air content. (3) Increase in flexural strength after 28-day moist curing with substitution of 25 percent fly ash. For strength purposes, optimum fly ash replacement appears to be 25-35 percent. (4) Increase in loss of strength after freezing and thawing (slow cycle which was discontinued when 30 percent loss in sonic modulus was attained, after which specimens were tested for strength).

52. MEISSNER, H. S. "Pozzolan—How Hungry Horse Dam and Other Massive Structures of the Bureau Benefit Through Research." Reclamation Era, Vol. 35, pp. 191-192, September 1949. See Bibliography No. 45, 52, 57, 69, 76, 83, 91, 112, 128, 136.

Popular history of pozzolan back to Roman and Greek days and how fly ash saved $1,000,000 on Hungry Horse Dam acting as "ball bearings," reducing water requirements, and thus water-cement ratio, and increasing strength. Used as 30-50 percent replacement of cement produces concrete of equal or improved quality as compared with mixes without fly ash.

53. MINNICK, L. JOHN. "New Fly Ash and Boiler Slag Uses." Technical Association of the Pulp and Paper Industry (TAPPI), Vol. 32, pp. 21-28, January 1949. See Bibliography No. 70, 101, 153, 271.

Fly ash normally consists of 3 phases: (a) white, ashlike, very finely divided particles, (b) red material high in iron, finely divided, (c) black carbon or carbon coated particles. Hollow spherical particles abound, especially in Chicago fly ash.

Fly ash has pozzolanic properties, varying amounts of soluble salts (sulfates, alkalies, etc.), variable pH, and is glassy in composition, with a softening temperature of the glass of 2,156-2,300°F.

In the ceramic field it can be combined with boiler slag, to make very good brick—better than shale brick. With clay it does not make very good brick but still better than brick made from clay alone.

In concrete it acts as a pozzolan and develops later high strengths when used as a replacement of cement, and as a filler (25 percent of weight of sand) it permits higher early strengths. Maximum strength is obtained when cement and fly ash content correspond to voids of sand in mortars and concretes.

General conclusions on use of fly ash in concrete and construction field: (1) Increases concrete strength, lowers permeability, increases freezing and thawing resistance, increases resistance to acid water, improves appearance, lowers bleeding, and increases workability. (2) Interground, up to 30 percent with portland cements it meets requirements for specifications for portland-pozzolan cement, and gives strengths equivalent to high early portland cement. (3) In lean mixes as additive, or 20-30 percent sand replacement, increases strength and improves other properties. (4) Benefits rich concrete mixtures, but not to same extent as lean mixes. (5) Can be used as cement replacement but not advocated. (6) May be used to improve both plain or air-entrained concrete. (7) Improvement may be obtained in (a) ready mixed concrete, (b) concrete sewer pipe, (c) concrete building blocks, (d) cinder blocks, (e) burial vaults. (8) May be used as filler for bituminous mixes, asbestos products, in pressure grouting, as lightweight aggregate, and in miscellaneous other minor uses. (9) Handling presents some problems, but these are not insurmountable.

54. OLSON, O. NEIL. "Effect of Some Admixtures on Physical Properties of Concrete Masonry Units." National Concrete Masonry Association, 38 So. Dearborn Street, Chicago, 1949.

Used both sand and gravel aggregate, and cinder with plain cement for control, and following admixtures: (1) Fly ash, 10 and 20 percent. (2) Natural cement, 15 and 25 percent. (3) Lime, 5 and 10 percent. (4) Air-entraining cement. (5) Calcium chloride, 1.5 and 2.5 percent. (6) Plastiment, 1 percent addition, and 1 percent replacing 20 percent cement. (7) Darex. (8) Pozzolith, 1/2 percent addition and 1-1/2 percent replacing 15 percent cement. (9) High early strength cement.

Based on compressive strength, reaches following conclusions: (1) Fly ash and natural cement up to 20 percent replacement are satisfactory. (2) Higher strength with air-entraining portland cement. (3) High early cement gave higher strength for sand-gravel, but lower for cinder blocks. (4) Lime was found to be detrimental to strength of sand-gravel mixture, but beneficial to cinder mixture. (5) Calcium chloride increased strength of sand-gravel but decreased that of cinder block. (6) Plastiment and pozzolith as replacements reduced strength. (7) Plastiment as addition improved sand-gravel strength but reduced that of cinder block. (8) Pozzolith as addition improved sand-gravel strength and reduced that of cinder block. (9) Darex had little effect on strength but improved texture and appearance. (10) Cinder in blocks gives low strength because of low density and high core space.

55. PIRANI, M. and SMITH, W.D. "Utilization of Fly-Ash." Fuel, Vol. 28, pp. 73-76, April 1949.

Fly ash can be fused into tile and glazed. Metal inserts can be embedded in such tile. Use only low carbon fly ash or burn carbon out and fire it at 1,150°C. This results in a porosity of 10 percent, and a density of 1.7. Can attain compressive strengths of 2,000-4,000 psi, with a shrinkage of about 8 percent. Fly ash can be used for bitumen-bonded tiles.

56. WEINHEIMER, C.M. "The Use of Fly Ash in the Bitumastic Road Industry." Symposium on Fly Ash Disposal, American Society of Mechanical Engineers, Annual Meeting Paper No. 49-A-82 (mimeographed), 1949. See Bibliography No. 31, 158.

Research done by Detroit Edison reveals good field for fly ash as bituminous filler and it is being used as such in many places. Fly ash hydrophobic, thus reducing tendency towards stripping. It has good void filling capacity, meets specifications for mineral filler, and provides good stability.

1950

57. BACKHOUSE, F.N. "Fly Ash Builds Giant Dam." The Municipal Journal (British), Vol. 58, p. 603, March 3, 1950. See Bibliography No. 45, 52, 76, 83, 91, 128, 136.

News item about Hungry Horse and use of fly ash: (1) Fourth largest dam will use 261,000,000 pounds of fly ash, with 342,000,000 pounds of cement. (2) Provides stronger, harder, more polished surface. (3) Requires less mixing water in concrete. (4) Resulting concrete is susceptible to less cracking and uses less cement. (5) Fly ash is pozzolanic in action. (6) Heat drawn from dam during construction equal to burning of 5,500 tons of coal.

58. BLANKS, ROBERT F. "Fly Ash as a Pozzolan." Proceedings, American Concrete Institute, Vol. 46, pp. 701-707, May 1950. See Bibliography 46, 47, 48.

Improves workability and required less water, improves late strength, good durability which decreases as fly ash is increased, shows superior resistance to sodium sulfate, improves impermeability, lowers heat of hydration, decreases drying shrinkage, effective in reducing alkali reaction, but less so than other pozzolans. Blended cement would be more uniform than fly ash batched separately at concreting plant.

59. COMPTON, F.R. "Fly Ash in Concrete." Hydro Research News, Hydro-Electric Power Commission of Ontario, Toronto, Canada, July-September 1950. See Bibliography No. 97, 238.

Defines pozzolan and gives following advantages for fly ash: (1) Generates less heat, an advantage in mass concrete. (2) Provides higher eventual strengths, which may be indicative of other desirable qualities. (3) Requires less water in laboratory tests of two fly ashes with three Canadian cements, using 3½, 4½, and 5¼ bag mixes. (4) Stiffens as rapidly as plain concrete. (5) The finer fly ash of the two gave higher 6-month strength even up to 50 percent replacements, while the coarser fly ash gave strength increases only up to 30 percent replacement. Early strength gain is faster at 93°F curing, than at 70°F (moist). (6) Reduces shrinkage due to decreased generation of heat.

Field tests are being made.

60. DAVIS, RAYMOND E. "A Review of Pozzolanic Materials and Their Use in Concretes." Symposium on Use of Pozzolanic Materials in Mortars and Concretes, American Society for Testing Materials, Special Technical Publication No. 99, pp. 3-15, 1950. See Bibliography No. 3, 4, 9, 13, 19, 61, 79.

An excellent general review on the subject in which fly ashes are singled out as differing from other pozzolans, and in most instances compared favorably due to the lower water requirements. (1) Pozzolanic reaction with calcium hydroxide. (2) Classification of pozzolans into "natural" and "artificial." (3) Use of pozzolans with portland cement, with a trend towards separate additions at mixer. (4) Additions versus replacements, with the latter gaining due to better results. (5) Magnitude of replacements (25 to 50 percent). (6) Effect of type of cement due to amount of calcium hydroxide produced. (7) Properties of fresh concrete: workability, decrease in segregation and bleeding, and increased plasticity. (8) Properties of hardened mortars and concretes: (a) strength of mortars—improved tensile and compressive strengths at later ages, (b) compressive strength of concretes—more improvement in leaner mixes than in richer, (c) elasticity and creep—generally lowered modulus of elasticity and increased plastic flow and creep, (d) volume changes—slight increase on wetting and drying, (e) weathering resistance—much better than plain concrete in presence of air-entrainment, (f) resistance to aggressive waters—better resistance to sulfates, (g) heat of hydration—lower heat of hydration, (h) permeability—decreased permeability, (i) alkali-aggregate reaction—inhibit reaction. (9) Specifications. (10) Bibliography.

61. DAVIS, RAYMOND E. "Use of Pozzolans in Concrete." Proceedings, American Concrete Institute, Vol. 46, pp. 377-384, January 1950. See Bibliography No. 3, 4, 9, 13, 19, 60, 79, 146.

Defines pozzolans and how they can be used as replacements for cement. Concretes thus treated are more plastic, bleed less, and exhibit less segregation. Use of air-entraining agent results, in some cases, in larger reduction in water requirement than when used with straight portland cement. Use of fly ash for large replacements, and superfine diatomites for smaller replacements, economical where natural pozzolans are not available. Fly ash perhaps most important artificial pozzolan. Lower early compressive strengths, but high at later ages. More effective in lean than in rich mixes. Improves watertightness, reduces heat of hydration, and more resistant to sulfate attack, also to weakly acid or low pH waters. Pozzolans, including fly ash, may improve freezing and thawing resistance in laboratory, but lower weathering resistance when used without air entrainment. However, with air entrainment, resistance is improved. Carbon in fly ash does not seem to affect weathering resistance. Pozzolan concrete has in general greater drying shrinkage than plain concrete. But low carbon, high fineness fly ash with up to 30 percent replacement has about the same or lower shirnkage than normal concrete. Fly ash reduces expansion from alkali-aggregate reaction but not as effectively as other pozzolans.

62. FOSTER, BRUCE E. "Use of Admixtures in Concrete Products." Proceedings, American Concrete Institute, Vol. 47, pp. 32-35, September 1950. See Bibliography No. 63.

Discusses accelerators, air-entraining agents, gas-forming agents, water-repelling agents, and workability agents. Among the latter is fly ash, which improves harsh mixes by providing the deficient fines. It is also used to replace part of the cement since it is pozzolanic. A 20 percent replacement gives satisfactory results. Workability agents reproduce fine mold detail, and decrease permeability. Decrease in breakage of green products is observed through their use. Better compaction and flow around reinforcement may be expected.

63. FOSTER, BRUCE E. "Use of Admixtures as Integral Waterproofing and Dampproofing Materials." Proceedings, American Concrete Institute, Vol. 47, pp. 46-52, September 1950. See Bibliography No. 62.

Discussed calcium chloride solutions, soaps, butyl stearate, oils, workability agents, and finely divided dry materials. Fly ash falls in last category. Increase in cement is more effective in decreasing permeability of concrete than other finely divided powders. In massive concrete, desirability of maintaining heat evolution and subsequent shrinkage at minimum, may make it desirable to substitute other fines for part of the cement.

Discussion by R.E. Madison: Indicates more favorable permeability reduction due to addition of fines other than cement, than suggested by author (pp. 52-3 and 52-4).

64. HANDY, WALTER N. "Fly Ash in Concrete." Utilization, pp. 24-26, November 1950. See Bibliography No. 50, 234.

For fly ash concrete: (1) Water requirements—same or lower than portland cement. (2) Increase in workability. (3) Compressive strength—slow early gain but greater increase at later ages. (4) Lower heat of hydration. (5) Lower shrinkage on drying. (6) Increased watertightness. (7) Reduced solubility of cementing gel. (8) Increased resistance to freezing and thawing—requires air as a prerequisite. (9) Reduced alkali-aggregate reaction.

Article lists some applications.

65. JACOBS, H. L. "Fly Ash Disposal." Sewage and Industrial Wastes, Vol. 22, pp. 1207-1213, September 1950.

Estimate of fly ash produced by utilities is given as over 3,000,000 tons. Carbon varies from 1 to over 60 percent. Advantages of various types of collectors are discussed. In concrete, fly ash used up to 25 percent substitution results in: (1) About same water requirement. (2) Improved workability. (3) Slower strength development at 70°F or lower, but reaches higher ultimate value. (4) Lowered heat of hydration. (5) Lower drying shrinkage. (6) Increased resistance to freezing and thawing by 50 percent or more. (7) Reduced alkali reaction.

Resistance to its use is mostly lethargy against new things, and poor performance that has been experienced in concrete with fly ash of high carbon content, of which there is a large volume produced.

Used successfully as mineral filler in bituminous concrete. In lesser amounts, it is used in insulating materials, brick, soil stabilization, and foundry sand.

66. JULLANDER, INGVAR and OLSSON, BERTIL. "Physical-Chemical Investigation of Fly Ash from Pulverized Coal." Svensk Papperstidning, Vol. 53, pp. 199-204, 1950 (in English). Abstract in Chemical Abstracts, Vol. 45, p. 884d, January 1951. See Bibliography No. 67.

Procedures are described for establishing various physical and chemical properties of fly ash obtained from a boiler using pulverized coal containing 14 percent ash.

67. JULLANDER, INGVAR and OLSSON, BERTIL. "Physicochemical Investigation of Fly Ash from Sulfite Waste Liquor." Svensk Papperstidning, Vol. 53, pp. 518-21, 1950 (in English). Abstract in Chemical Abstracts, Vol. 45, p. 5405g, June 1951. See Bibliography No. 66.

When sulfite waste liquor is concentrated and then burned, fly ash is obtained from the flue gases, with a dust collector. Compared to fly ash from coal burning power plants, it has same specific gravity by pycnometer method, of 2.04 but apparent density in air of 0.15 gram per milliliter as against 0.64 gram per milliliter. Sedimentation velocity in water is much slower. Fractionation by specific gravity gave different frequency curves, the heavy fraction in the coal fly ash containing Fe_3O_4 being absent in the sulfite liquor fly ash. Give photomicrographs of various particles.

68. MAJOR, WILLIAM S. "Fly Ash Disposal Can be Profitable." Industry and Power, Vol. 59, pp. 78-81, August 1950.

Outlines some of the problems of disposal of fly ash and some of the uses that have been found for it: (1) Rubber filler. (2) Substitute for pumice in mechanic's soap. (3) Paint filler. (4) Replacement of sand in fertilizer. (5) Filler in asphalt pavement. (6) With by-products of oil refineries makes road mixes. (7) Sand blasting. (8) Soil conditioner. (9) In cinder concrete to reduce porosity. (10) Building blocks. (11) Filtering material.

(12) Putty filler. (13) Rostone blocks. (14) Cement replacement in concrete.

Estimates $75,000 spent on research per year.

69. MEISSNER, H. S. "Pozzolans Used in Mass Concrete." Symposium on Use of Pozzolanic Materials in Mortars and Concretes, American Society for Testing Materials, Special Technical Publication No. 99, pp. 16-30, 1950. See Bibliography No. 44, 52.

Examples of 8 dams constructed by U. S. Bureau of Reclamation, using pozzolans. Pozzolans in such construction save cement by acting as replacements, reduce heat of hydration, increase workability, have high later strength, reduce segregation and bleeding, have greater impermeability and extensibility (crack resistance) than ordinary concrete.

The only dam in which fly ash was used by the Bureau of Reclamation is Hungry Horse. Investigations by R. E. Davis showed fly ash to be a good pozzolan. Also work by McMillan and Powers showed fly ash concrete to have continued strength development, indicating a good pozzolan. Davis dam studies showed fly ash to have high pozzolanic activity as determined by pozzolan-lime-sand mortar strength test, high reduction in alkalinity, and to be reasonably, effective in reducing expansion. Thirty percent by weight replacement was used at Hungry Horse, with resulting improved workability, and strength expected to equal that of plain concrete at the age of 1 year. Workability is probably due to spherical shape of the fly ash particles which act like little ball bearings.

If furnished as blended cement, might prove cheaper than batching two cementitious materials separately.

70. MINNICK, L. J. and BAUER, W. H. "Utilization of Waste Boiler Fly Ash and Slags." American Ceramic Society Bulletin, Vol. 29, No. 5, pp. 177-180, May 1950. See Bibliography No. 53, 101, 153, 271.

Using fly ash and slag, make good appearing brick, stronger than regular brick. Used with shale or clay, fly ash also makes a good brick.

71. MORAN, W. T. "Use of Admixtures to Counteract Alkali-Aggregate Reaction." Proceedings, American Concrete Institute, Vol. 47, pp. 43-46, September 1950. See Bibliography No. 72, 154.

Some fly ashes reduce the alkali-aggregate reaction, but others do not. Gives details of expansion bar test.

72. MORAN, W. T. and GILLILAND, J. L. "Summary of Methods for Determining Pozzolanic Activity." Symposium on Use of Pozzolanic Materials in Mortars and Concretes, American Society for Testing Materials, Special Technical Publication No. 99, pp. 109-130, 1950. See Bibliography No. 71, 154.

Reviews the following tests: (1) Chemical composition. It is generally agreed that silica and alumina are the active portions, but no correlation between analysis and activity has been shown. Davis and associates at one time felt that fly ashes high in carbon might be less reactive than those with smaller amounts, but later work showed this effect to be due to fineness—the finer ashes are normally of low carbon content. (2) Solubility. (3) Lime absorption. (4) Optical methods including petrographic and X-ray—can differentiate natural materials from industrial such as fly ash. (5) Pozzolanic lime mixtures (a) time of set, (b) compressive and tensile strength, (c) determination of remaining uncombined lime, (d) insoluble residue methods. (6) Pozzolan-portland cement tests (a) strength tests, (b) insoluble residue and uncombined lime, (c) resistance to leaching, (d) lime solubility, (e) resistance to sulfate solutions, (f) reduction in expansion.

Paper provides details of methods in appendices, and a good bibliography on the subject.

73. MUNT, V.C. and MUNRO, D.C. "Use of East Perth Power Station Fly Ash as a Pozzolan." Journal of the Institution of Engineers, Australia (Sydney), Vol. 22, No. 9, pp. 207-213, September 1950. Abstract in Proceedings, American Concrete Institute, Vol. 48, p. 279, November 1951.

Reviews work done in America at Bureau of Reclamation, by Davis at University of California, and at Purdue University. Comparing East Perth fly ash with published American standards; finds it of admirable qualities for use in concrete. It is high in silica and iron, low in alumina, very low in calcium oxide, low in sulfur, and low in carbon.

Replacement of cement up to 25 percent of fly ash showed delays in compressive strength attainment at early ages, but higher ultimate strength at 12 months.

Standard lime-mortar fly ash cylinders showed 977 psi at 7 days and 1,561 psi at 28 days.

Cylinders with 25 percent fly ash replacement, when suspended in sewers, which are noted for quick sulfate action on concrete, showed much less deterioration than controls without fly ash.

Conclude: (1) East Perth fly ash has pozzolanic qualities. (2) After 6 months the strength of fly ash concrete is about same as control. (3) It could be safely used to replace 25 percent by weight of cement. (4) It would not be detrimental to concrete and compares favorably with pozzolans already in extensive use in U.S.A.

74. SCHOLER, C.H. and PEYTON, R.L. "Experience with Pozzolanic Materials in Kansas." Symposium on Use of Pozzolanic Materials in Mortars and Concretes, American Society for Testing Materials, Special Technical Publication No. 99, pp. 31-42, 1950. See Bibliography No. 108, 174.

Preliminary tests at Kansas State College using fly ash with high-alkali cement (0.97 Na_2O equivalent) and aggregate from local pit. The fly ash reduced air content of concrete and needed more air-entraining agent. Exposure 10 indicated lowered expansion with fly ash substitutions of 25 to 35 percent.

Field observations in placing McPherson Road: (1) Fly ash permitted retaining same water-cement ratio and cement content as normal concrete, whereas other pozzolans required more water. (2) Fly ash with air-entrainment permitted reduction of cement content by 0.15 barrel per cubic yard. (3) Placing and finishing were easiest with fly ash, with no difficulties, whereas other pozzolans required shortening sections in warm weather and spraying surfaces. (4) Fly ash reduced air content of normal concrete 2 to 3 percent and required more air-entraining agent in air-entrained concrete. (5) Placing was very simple compared to shale mixes. Carbon and fine spherical particles may be responsible for this. (6) Workability and finishing characteristics of fly ash concrete were better than normal concrete. (7) Color slightly darker. (8) Mix was not sticky and gummy like shale mixes.

75. WASHBURN, LUCIUS C. and SIMPSON, H.E. "The Utilization of Fly Ash in the Development of Light Weight Aggregates." New York College of Ceramics, Alfred, N.Y., Ceramic Research Department, Monthly Progress Report No. 168, June 1950.

Summarize briefly the fly ash disposal problem and some of the most common uses that have been developed. Describe two experimental methods of producing lightweight aggregate: (1) Sintering fly ash and then crushing product, resulting in lightweight aggregate of 40 to 50 pounds per cubic foot. (2) Making a mixture of 90 percent fly ash, 5 percent whiting, and 5 percent bentonite, and water to a soft mud consistency. This is forced through a 4-mesh screen to pelletize the material, which is fed in turn to a rotary furnace at 2,200°F. The resulting pellets $\frac{1}{8}$ to $\frac{3}{8}$ inch in size weigh 38 pounds per cubic foot.

Feel that field for lightweight aggregate is good, and demand on the increase. Pelletized aggregate would be for block manufacturé, while the crushed would fit in the structural class concrete.

76. WHEELER, W.E. "Concreting Methods at Hungry Horse." Western Construction News, Vol. 25, pp. 71-75, April 15, and pp. 75-79, May 15, 1950. See Bibliography No. 45, 52, 57, 83, 91, 112, 128, 136.

General description of concreting plant and operations at Hungry Horse. Fly ash added as economy measure and to increase workability. Up to 50 percent by weight of pozzolan may be used without decreasing the strength of finished concrete. Fly ash batched in bulk in the same manner as cement.

1951

77. BLOEM, D.L. and WALKER, STANTON. "Laboratory Tests of Fly Ash in Concrete." National Ready Mixed Concrete Association, Miscellaneous Publication No. 36, August 1951. See Bibliography No. 141, 142.

Using two fly ashes with 7 and 11 percent loss on ignition, made mixes with absolute volume replacement ranging from 0 to 40 percent both for plain and air-entrained concrete. This was divided into two investigations which varied in some details.

Conclude: (1) Lowered compressive strength at early ages, also lowered flexural strength, but not as much as compressive strength. Suggest that at later ages strength would be expected to come up. (2) Find no reduction in water or sand requirements. (3) Air-entraining agent, required to maintain given air content, increased with increase in fly ash. (4) For given percent fly ash, compressive strength of air-entraining concrete was reduced less than plain concrete. (5) Freezing and thawing durability improved with increase in fly ash, especially for specimens in which curing involved drying period. (6) Caution acceptance of these results under different conditions and with other materials.

78. COBBS, WALTER H., JR. "Using Powdered-Coal Fly Ash." Power, Vol. 95, pp. 87-89, May 1951.

Very short but well-worded summary of uses, and a bibliography of 70 items. Among uses: (1) Concrete—low early strength, high later strengths. Drying shrinkage is less for carbon content less than 10 percent. Water requirements unchanged, improved workability, lower heat of hydration and temperature rise. With 2½ percent entrained air and 20 percent fly ash, resistance to freezing and thawing 1¾ times standard concrete. Fly ash reduces expansion due to alkali-aggregate reaction. (2) Filler in bituminous concrete. (3) Vitrified brick. (4) Insulating cement. (5) Soil stabilizing agent. (6) Cottrell blocks. (7) Impregnating agent for wood. (8) For fine blasting sand. (9) For foundry sand. (10) For bleaching clay, after acid leach. (11) Raw material for portland cement. (12) Heat resistant paint filler. (13) Filler for music records. (14) In asbestos cement. Handling problems are expensive for the customer. Gives five patent numbers and what they cover.

79. DAVIS, RAYMOND E. "What You Should Know about Pozzolans." Engineering News-Record, Vol. 146, pp. 37-40, April 5, 1951. See Bibliography No. 3, 4, 9, 13, 19, 60, 61, 146.

Pozzolan is a silicious material containing a substantial portion of amorphous silica not possessing cementitious properties in itself, but reacting with free lime in concrete to produce cementing properties. Best of artificial pozzolans is fly ash of high fineness and low carbon. Has lower water requirements in concrete than any other pozzolan. Among beneficial properties of pozzolan in concrete: (1) Improve plasticity, reduce bleeding and segregation, particularly in lean mixes. (2) Fly ash has lower water requirement in spite of fact that it has more volume than the replaced cement. (3) Remolding apparatus (Powers) is more desirable as measure of workability than slump. (4) Lower early strength, but higher later strength—with water reducing agent and air-entraining agent, higher strengths at all ages. (5) Contribute more to strength in lean mixes than in rich. (6) Drying shrinkage for fly ash with high fineness and low carbon is less than plain concrete. (7) Water reducing agent and air-entraining agent reduce shrinkage in most pozzolan concrete. (8) Without air-entrainment, usually less resistant to weathering, except low carbon fly ash with about 30 percent replacement, but significant improvement with air-entraining agent. (9) More impermeable, particularly in lean mixes at later ages. (10) Reduce alkali-aggregate expansion. (11) Improve resistance to sulfate and to acidic waters. (12) Reduce heat of hydration generated in concrete. (13) Fineness and carbon content are most important in judging suitability of fly ash—carbon should not exceed 7 percent and specific surface by air permeability should not be less than 2,500. (14) Use 20 to 30 percent replacement.

Discussion on opaline shales and diatomites, pumicites, calcined opaline shale, calcined diatomaceous earth, other calcined materials.

Gives list of sources for pozzolans.

80. GILLILAND, J. L. "Relationship of Fly Ash and Corrosion." Proceedings, American Concrete Institute, Vol. 47, p. 397, January 1951. See Bibliography No. 86.

In answer to a question regarding possibility of chemical and electrolytic corrosion of steel in concrete due to presence of sulfur in fly ash used in concrete mixes: (1) Analyses by Davis indicate computed SO_3 content (made by oxidizing all sulfur to sulfate form) of fly ashes from various sources ranges from 0.42 to 2.34 percent. (2) Limited tests by Bureau of Reclamation indicate that sulfur in fly ash does not need to be oxidized to sulfate as it already is in that form. (3) It seems probable that it is present as calcium sulfate and alkali sulfate, and thus would have similar effect in concrete as the gypsum in cement. Amount of sulfate in fly ash actually about the same as in cement. (4) Rate of corrosion of steel is greatly affected by pH of its environment. At high pH, corrosion is very small. Therefore, in the highly alkaline condition prevailing in most concrete, little corrosion can be expected, regardless of whether or not fly ash is present.

81. KLIEGER, P. "A Survey of the Literature Pertaining to the Use of Fly Ash in Portland Cement Concrete." Portland Cement Association, Chicago, p. 16, 1951.

Annotated bibliography and discussion.

82. KRONSBEIN, W. "The Hydraulic Properties of Coal Fly Ashes and Their Influence on the Behavior of Portland Cement with Respect to Sulfates." Zement Kalk Gips, Vol., 4, pp. 123-127, May 1951. Abstract in Revue des Matériaux de Construction, No. 433, p. 34-D, 1951. See Bibliography No. 20.

Fly ashes may under certain conditions, show favorable pozzolanic action, and can increase the resistance of mortars and concretes to the action of water containing sulfates.

83. LENHART, WALTER B. "Hungry Horse Dam." Rock Products, Vol. 54, pp. 98-105, February 1951. See Bibliography No. 45, 52, 57, 76, 91, 112, 128, 136.

Gives mixes used and discusses differences of opinion among engineers regarding advantages of fly ash in concrete. Also gives specifications and handling procedure used on this project.

84. LIEDLOFF, K. O. "The Utilization of Fly Ashes in Concrete Block Manufacture." Betonstein Zeitung, Vol. 17, pp. 109-111, May 1951. Abstract in Revue des Matériaux de Construction No. 433, p. 34-D, 1951.

It is possible to use the fine ashes from coal recovered by dust filters. These contain little sulfur in contrast with slag. They have hydraulic porperties and contribute to decreasing cement requirements. Economies are possible through their use.

85. PALMIERI, MARIO. "Fly Ash—A Pozzolanic Material of Great Usefulness." Concrete, Vol. 59, pp. 20-22, June 1951. See Bibliography No. 103.

Using volume replacement and water curing for 180 days, obtains best strength with mixture of 85 percent cement plus 31 percent fly ash. A mix consisting of 100 percent cement plus 31 percent fly ash was next lower in strength, and 100 percent cement without fly ash was lowest.

Straight replacement not as good as a little excess fly ash, with 85 percent cement plus 31 percent fly ash providing optimum condition. A mix containing 82 percent cement plus 18 percent fly ash was more resistant to 10 percent sodium sulfate exposure than plain portland cement. All fly ash used was treated with alkali in accordance with the thermic process, U. S. Patent No. 2,140,-850. The free lime in hydration process of normal portland cement is subject to attack and therefore the weak link in concrete. Pozzolan ties the free lime up so it is not available to react with attacking agents, once it has already reacted with the pozzolan and formed a cementitious material.

86. RYAN, JOSEPH P. "Relationship of Fly Ash and Corrosion." Proceedings, American Concrete Institute, Vol. 47, pp. 481-484, February 1951. See Bibliography No. 80.

Discussion in answer to a question as to the possibility of increased corrosion of reinforcement in concrete in which fly ash is used, possible because of its sulfur content. Chemistry of corrosion is outlined.

Concludes: (1) Alkaline condition in concrete, so long as lime is not leached out, tends to maintain a protective film of ferrous hydroxide on the steel surface. This film prevents easy penetration of water and oxygen to further corrode the surface. Fly ash does not materially change the alkalinity in concrete. (2) Fly ash reduces permeability of concrete, thereby decreasing penetration of oxygen and water to the steel. The pozzolanic gel formed with fly ash in concrete seems to decrease the amount of lime which can be leached out. This may be due to an increased physical resistance to the passage of water, or to a chemical fixation of the lime. (3) Sulfur compounds in fly ash are usually so limited, in amount, by specifications and are similar to those in cement, so that they are not materially different in the concrete whether fly ash is used or not. Moreover, the alkaline condition in concrete is unfavorable to the sulfate attack on steel. (4) Carbon in fly ash would appear by theoretical considerations (increased conductivity) to be much more significant in concrete than sulfur. However, the usual low specification limit on the fly ash makes the percentage in the concrete so small that if it is well dispersed (as it would be in a good mixing action), its effect on the electrical conductivity should be quite minor.

1952

87. ANON. "Nebraska Paves with Fly Ash Concrete." Roads and Streets, Vol. 95, pp. 70-72 and 133, March 1952. See Bibliography No. 117.

This is a regular paving job 5.8 miles long on U. S. 20 between Laurel and Belden, Nebraska, built in 1951. Uses 165 pounds fly ash and 5¼ sacks cement per cubic yard in 85 to 90 percent of area. Balance of area has concrete with 7 bags plain portland cement mix. Air entrainment used in all mixes. Pavement is 8-inch uniform thickness, 24 feet wide, and employs local sand-aggregate. Expansion joints are used at 16-foot 4-inch intervals. Longitudinal deformed centerline joint with tie bars at 2-foot 6-inch spacing. No reinforcing steel used. Ideal cement from Superior, Nebraska, and fly ash from Chicago.

States that fly ash advocates claim improved concrete placeability, reduced permeability, improved resistance to sulfate, lower heat of hydration, reduced expansion due to cement-aggregate reaction, and resistance to frost action. The use of fly ash lowers early strengths, and 28-day strengths are generally higher.

On this project, 1,000 feet or more full width pavement were placed per day. Outlines fly ash specifications used on this project and the pozzolanic activity tests made on 2- by 4-inch cylinders, stored in sealed containers at 70°F for 12 hours, then at 100°F for 12 hours, and then at 130°F until tested. The activity test specified is made with 2 parts fly ash, 1 part hydrated lime (high calcium finishing lime), and 9 parts standard Ottawa sand with sufficient water to make a workable mix. The required 7-day strength under these conditions is 600 psi. A limit of a maximum carbon content of 3 percent, and maximum ignition loss of 10 percent, are also specified.

88. ANON. "Fly Ash as Aggregate for Foamed Concrete." Concrete Buildings and Concrete Products (London), p. 71, April 1952.

Bibliography on fly ash in concrete.

88. ANON. "Fly Ash as a Construction Material." (Original in Spanish "Las cenizas volantes como material de construcción." Informes de las construcción, Madrid, Vol. 42, June-July 1952). Abstract in Revue des Matériaux de Construction, No. 449, p. 56-D, February 1953.

Mixed with lime or cement, fly ash produces with steam curing, specimens with densities between 0.6 and 0.8, and strengths of 56 kilograms per square centimeter (800 psi).

90. ANON. "Fly Ash as an Admixture in Cement and Concrete." Cement and Concrete Association, (London), Library Record Chapter 27, 5 pp. December 1952.

Bibliography covers the subject for the period 1937 to 1952.

91. ANON. "Fly Ash in Concrete for a Dam." Concrete and Constructional

Engineering (London), Vol. 47, No. 12, p. 373, December 1952. See Bibliography No. 45, 52, 76, 83, 112, 128, 136.

Considerable saving in cement is being effected in the construction of Hungry Horse Dam by the Bureau of Reclamation. Mass concrete contains 90 pounds of fly ash and 188 pounds of cement per cubic yard of concrete, using 6-inch maximum aggregate, and develops in excess of 4,000 psi at 90 days. The strengths at early ages are lower than control but ultimate strengths are higher. Fly ash results in more workable concrete which is less permeable and less subject to bleeding and separation, and which generates less heat of hydration, but its value in counteracting alkali in aggregate is low.

Fly ash with low carbon content is only pozzolan with lower water requirement than cement, in spite of its lower specific gravity and therefore higher bulk. Gives U.S. Bureau of Reclamation specifications for Hungry Horse fly ash and typical analysis of material being used. Fly ash is delivered in covered hopper-bottom rail cars and trucked to plant. Dust created more than in cement.

92. BERNHARDT, C.J. "Use of Fly Ash in Concrete." Betongen Idag (Oslo), Vol. 17, No. 2, pp. 29-53, April 1952. Abstract in Proceedings, American Concrete Institute, Vol. 49, p. 349, December 1952.

Fly ash used in experiments, made at Norway's Institute of Technology, as an admixture and as cement replacement up to 30 percent. Compressive strength of various mixes, at 7, 28, and 90 days, freezing and thawing resistance, and resistance to 10 percent sodium sulfate solution were determined for replacement mixes.

The efficiency of a cement is defined as the compressive strength divided by cement content per unit volume of concrete. The efficiency of the cement was found to increase with the percentage of fly ash replacement. Even the efficiency of the cement plus fly ash increased up to replacements of 10 to 15 percent. This increase in efficiency was particularly pronounced for lean mixes.

Resistance to freezing and thawing as well as resistance to sulfate solution storage, increased up to replacements of 10 to 15 percent.

93. CARPENTER, CARL A. "A Cooperative Study of Fillers in Asphaltic Concrete." Public Roads, Vol. 27, No. 5, pp. 101-110, December 1952.

Finds traprock fines make satisfactory filler, and fly ash makes superior filler, as far as resistance to water softening. Conclusion is based on 120°F water immersion for 4 days, and 75 percent retention of dry strength. For border line cases, immersion may need to be extended to 7 or 14 days. When measuring compressive strength or stability, it is important that specimens be made from freshly prepared mixtures without reheating or reprocessing.

94. CHILCOTE, W.L. "Where to Use Fly Ash in Portland Cement and Bituminous Concrete." American City, Vol. 67, No. 10, pp. 98-99, October 1952. See Bibliography No. 95, 96, 98, 235.

Fly ash is a by-product of burning pulverized coal. It lowers cost of concrete and increases its strength and density, and reduces efflorescence. Carbon content of fly ash should not exceed 12 percent. Fly ash has pozzolanic characteristics and mixes with lime freed by hydration of cement. Fly ash concrete has good workability, lower heat of hydration, and lower permeability. Because it makes denser concrete, its action is opposite of air-entrainment, which makes lighter concrete. Air-entrainment is necessary for resistance to freezing and thawing and action of salts on pavements.

Tests are required to determine whether or not fly ash concrete will resist these factors to the same degree.

In October 1950, Baltimore constructed a fly ash concrete pavement alongside plain air-entrained concrete pavement sections. One sack of cement was replaced by fly ash and air-entraining cement was used. The fly ash reduced the normal 3½ percent air content to 2½ percent and made it more variable. The fly ash concrete had lower strength up to 100 days, then exceeded the plain concrete. It is good in mass concrete. In plants for bituminous concrete, fly ash goes up the stack, and therefore, is not as good as limestone dust.

95. CHILCOTE, W.L. "Fly Ash." U.S. Navy Civil Engineer Corps Bulletin, Vol. 6, pp. 279-281 and 300, October 1952. Discussion by Craig J. Cain, February 1953, p. 19. See Bibliography No. 94, 96, 98, 235.

General discussion of fly ash which may be summarized: (1) Maximum carbon of 12 percent should be limit for use in concrete. (2) Has pozzolanic characteristics. (3) Increased strength after 100 to 110 days. (4) Low heat of hydration. (5) Reduced entrained air. (6) Summary of Baltimore pavement work. (7) Less cement, greater strength, lower heat of hydration, higher impermeability, lower water requirement and less efflorescence—good for dams. (8) In highway work it is better to get durability with air entrainment and forego advantages of fly ash. (9) In bituminous concrete it goes up the chimney unless collected—better use limestone dust. (10) Product has merit and well worth trying, but should be careful what use is made of it.

Discussion by Craig J. Cain: (1) Air entrainment can be maintained at required level by addition of more air-entraining agent. (2) It is useful as bituminous filler and need not be run through the drier, and therefore, cannot reach stack and thus be lost.

96. CHILCOTE, W.L. "Highway Department Tests Fly Ash in Pavement Mixes." Engineering News-Record, Vol. 149, pp. 40-41, October 23, 1952. See Bibliography No. 94, 95, 98, 235.

Used fly ash in a 6½ bag basic mix with a 1 bag replacement, for experimental pavement in Baltimore. Center 24 feet fly ash, and outer 6 feet on each side of it plain concrete, at Cooks Lane and Alson Drive in Baltimore (1950). Plain concrete had 3½ percent air and fly ash concrete 2½ percent. Strength low at early ages, equal at about 100-day age and exceeded control by 60 psi at later ages.

Permits lower water-cement ratio, has lower heat of hydration, and less potential efflorescence. Longer mixing period required. Good as filler in bituminous concrete but goes up stack, and therefore, stone dust preferred.

97. COMPTON, F.R. and MacINNIS, C. "Field Trial of Fly Ash Concrete." Ontario Hydro Research News, pp. 18-21, January-March 1952. See Bibliography No. 59, 238.

Compare two sections in construction of dam for Otto Holden Generating Station—one control and one with fly ash: (1) Used 30 percent substitution by weight in a mix of 508 pounds total cementitious materials. (2) Higher workability. (3) Decreased water 7 percent. (4) Developed lower heat with fly ash. (5) Strength low up to 15 days, then above control mix. (6) Cores substantiate cylinder strengths, with latter cured in well in concrete of dam to simulate mass curing.

98. CORSON, G. and W.H. "Fly Ash Concrete Paving Demonstration—Baltimore, Maryland." Mimeographed report of Corson Inc., June 1952. See Bibliography No. 94, 95, 96, 235.

Used about 1½ pounds of fly ash per pound of cement replacement in about 400 feet of two lane pavement at Cooks Lane and Alson Road. The outside 6 feet on each side were plain portland cement concrete. Work was done in October 1950. Used fly ash from Westport Station of the Consolidated Gas Electric Light and Power Company, Baltimore. This had 5 percent ignition loss, and a fineness of 3,010 square centimeters per gram. Strength after 28 days improved and began exceeding strength of plain mix.

Concludes demonstration proves that fly ash is practical and economical to use.

99. ERYTHROPEL, H. "A New Industrial Brick of Superior Quality Made with Coal Fly Ash." (Une Nouvelle Brique Industrielle de Qualité Supérieure a Base de Cendres Volantes de Houille.) Betonstein Zeitung (German) pp. 41-45, February 1952. Abstract in Revue des Matériaux de Construction, No. 457, October 1953.

Utilizes fly ash from a Ruhr power plant to make bricks of superior quality. Uses same manufacturing process as used in bricks made of calcareous and silicious base. Obtains density of 1, compressive strength of 60 kilograms per square centimeter (850 psi), using 10 percent lime for binder. Gives description and grain size of fly ash and of plant making 90,000 bricks per day utilizing 160 tons of fly ash. Gives properties and appearance of bricks. Used in load bearing walls of several stories in height.

100. MIELENZ, R.C., GREENE, K.T., BENTON, E.J. and GEIER, F.H. "Chemican Test for Alkali Reactivity of Pozzolans." Proceedings, American Society for Testing Materials, Vol. 52, pp. 1128-1144, 1952.

Outline chemical test that can be conducted in 2 days, and show correlation with expansion bar test. Conclude that a net reduction in alkali, in the solution, of 180 milliequivalents per liter or greater, indicates that the pozzolan will control alkali-aggregate reaction during hydration of cement. This corresponds approximately to a reduction in expansion in the mortar-bar text of 75 percent or more in 14 days. Give test correlation data on the two tests for 63 pozzolans. Fly ashes tested give a lower reduction than the recommended 180 milliequivalents per liter (-9 and 54), yet give a reduction in expansion bar tests of 63 and 41 percent, respectively.

101. MINNICK, L. JOHN. "A Manual of Fly Ash as Related to Its Proper Use in Concrete." G. and W.H. Corson, Inc., Plymouth Meeting, Pennsylvania, November 14, 1952. See Bibliography No. 53, 70, 153, 271.

Discusses: (1) Analyses of various fly ashes. (2) Pozzolanic property of fly ash. (3) Early strength improvement with fly ash. (4) Optimum fly ash requirement in concrete. (5) Effect of fly ash on water content. (6) Design of fly ash concrete mixes. (7) Miscellaneous notes.

102. MORGAN, R.E. "Utilization of Fly Ash." U.S. Department of the Interior, Bureau of Mines, Information Circular 7635, June 1952.

Defines fly ash. Used: as portland cement replacement in concrete; to replace fine aggregate in concrete; as mineral filler in bituminous concrete; in manufacture of brick, and with slag to make bricks; for sand blasting; for foundry core ingredient; as filler for fertilizer; as filler for paint and putty; as substitute for pumice in mechanic's soap. Transportation and handling present problems. Bibliography (annotated) of 37 items.

103. PALMIERI, MARIO. "The Weathering Resistance of Fly Ash." Concrete, Vol. 60, pp. 32-35, September 1952. See Bibliography No. 85.

Uses slow freezing and thawing test, and concludes that fly ash concrete has better resistance than control. Starts tests after 28-day moist curing.

104. PAWLIK, K. "'Ytong' Lightweight Concrete from Fly Ash." Mitteilungen ver Grosskesselbesitz, Vol. 20, pp. 215-217, 1952. Abstract in Fuel Abstracts, Vol. 12, No. 5, paragraph 4688, November 1952.

This steam hardened lightweight concrete (of Swedish origin) is manufactured in Germany, using fly ash from a power station, combined with blast furnace slag. The author describes the plant layout, production methods, and the properties of the products.

105. POHL, G. "Using Fly Ash for Hydraulic Cement." Mitteilungen ver Grosskesselbesitz, Vol. 20, pp. 213-214, 1952. Abstract in Fuel Abstracts, Vol. 12, No. 5, paragraph 4685, November 1952.

Different cements are described having varying proportions of fly ash. Particulars of their characteristics and properties are given.

106. PORTLAND CEMENT ASSOCIATION (Structure and Railways Bureau). "Evaluating Powdered Admixtures for Concrete." Concrete Information Leaflet, April 1952. See Bibliography No. 1, 6, 10.

Admixtures have various effects on concrete. An admixture should be considered only as one way to achieve desired results, and its cost should be compared with other methods of obtaining same results. Admixtures requiring increase in water-cement ratio reduce the quality of the concrete, which may not be offset by beneficial effect of use of admixture. Admixtures may have following beneficial effects: (a) physical effect, (b) cementitious properties, (c) pozzolanic properties.

Watery concrete can be stiffened by addition of more cement, reduction of water-cement ratio, or by addition of powdered admixture. Effect of admixture, therefore, depends on character of original mix. Value of admixture should be determined on basis of desired properties. Tests made at Portland Cement Association rate admixtures on basis of strength and workability. Includes table of indices which contains data on two fly ashes. Increase of water, frequently needed with use of admixtures, does not necessarily improve watertightness of concrete. Limiting of mixing water, care in construction, and adequate curing still essential for good concrete results.

107. ROESLER, H. "Experience With Pozzuolana Cement." Mitteilungen ver Grosskesselbesitz, Vol. 20, pp. 210-212, 1952. Abstract in Fuel Abstracts, Vol. 12, No. 5, paragraph 4689, November 1952.

Addition of 30 percent fine fly ash strengthens cements used, precludes the need for additional water, and renders shrinkage normal. Compositions and characteristics are tabulated.

108. SCHOLER, C.H. and SMITH, G.M. "Use of Chicago Fly Ash in Reducing Cement-Aggregate Reaction." Proceedings, American Concrete Institute, Vol. 48, pp. 457-464, February 1952. See Bibliography No. 74, 174.

Using Wisconsin and Kansas aggregates, and Chicago and Kansas cements and the alternate wetting-and-drying cycle (Exposure No. 2 for which a limit of 0.07 percent at end of 1 year has been established), find: (1) Fly ash, used as 20 percent by weight replacement, is sufficient to inhibit reaction, but 30 percent is better. (2) Fly ash in these quantities reduces early strengths, but after undergoing Exposure No. 2 (simulates outdoor weathering), strengths exceed control specimens. (3) Use of fly ash does not modify usual characteristics of fresh concrete, but improves workability and finishing properties. (4) Fly ash requires additional air-entraining agent to maintain given air content. Exposure No. 10 correlates highly with Exposure No. 2.

109. STERNE, WILLIAM P. "Pozzolans for Oil Well Cements." Oil and Gas Journal, Vol. 51, pp. 72-76, July 7, 1952.

Fly ash for oil well work has following advantages: (1) Low heat of hydration and volume change. (2) Improved tensile and compressive strengths. (3) Increased sulfate resistance. (4) Reduced leaching of soluble materials. (5) Reduced permeability. (6) Saving in cement and cost. (7) Use 50 percent replacement. (8) Lessens cracking. (9) Lowers pressure required in oil well sealing due to decreased density. (10) Method developed by Halliburton Company.

110. U.S. BUREAU OF RECLAMATION. "Durability of Concrete Containing Canyon Ferry Aggregates and Pozzolans." Concrete Laboratory Report No. C-609, January 31, 1952. See Bibliography No. 132, 155.

Freezing and thawing test method used: 3- by 6-inch cylinders in tight rubber sleeves, placed 1½ hours in brine at 8°F (center of specimen gets down to 10°F), then followed by circulation of warm brine at 73°F for 1½ hours, producing a temperature of 70°F at the specimen. About 50 cycles per week. Measure length change and weight loss. Failure is the number of cycles it takes to produce 25 percent loss in weight. Performance rating at failure for concrete fog cured for 28 days: below 150 cycles—poor; 150 to 300 cycles—fair; 300 to 500 cycles—satisfactory; 500 to 1,000 cycles—good; 1,000+—excellent.

Used both fly ash and pumicite in concrete mixes with Canyon Ferry aggregates and find: (1) In plain concrete 15 percent fly ash replacements increased freezing and thawing resistance over control, but higher replacements decreased resistance. The increased resistance is more pronounced with longer curing periods. (2) In air-entrained concrete continuously fog cured for 6 months, 30 percent fly ash replacement increased resistance to freezing and thawing. (3) Fly ash concrete, fog cured for short periods (7 and 14 days) followed by controlled laboratory drying (70°F and 50 percent relative humidity), or outdoor exposure, reduced durability of plain and air-entrained concrete in proportion to amount of pozzolan used, the larger amounts causing the larger reductions. (4) Microscopic shrinkage cracks on drying may be cause of reduction of resistance, due possibly to increase in fineness of particles in mix, or possibly due to starting freezing and thawing cycles before sufficient fog curing time to develop required strength to resist freezing action. (5) Scholer Exposure No. 2 (wetting-and-drying) indicates no deleterious expansion should be expected from the combination of concrete ingredients used in these mixes.

111. U.S. Bureau of Reclamation. "Pozzolans and Cement Pozzolan Reactions." Petrographic Laboratory Report No. Pet.-102, December 29, 1952.

"Pozzolans are silicious or aluminous substances which are not cementitious in themselves, but which contain ingredients that react with calcium hydroxide at atmospheric temperatures in the presence of water to form cementitious compounds." Pozzolans are not competitive with cement as they expand use of good concrete. Pozzolans in many cases reduce significantly alkali-aggregate reaction, but study of specific cement-pozzolan reactions for each case is needed inasmuch as certain pozzolans release alkalis in presence of calcium hydroxide. The report discusses properties of many pozzolans and the chemical and physico-chemical reactions, and reaction products involved in the hydrating of cement and pozzolans.

Increased expansion is observed if a highly opaline pozzolan is used to replace 10 percent or less of the cement. It represents deleterious attack of cement alkalis upon the opal, which results in alkali-silica gel capable of absorbing water and developing swelling pressures (in high alkali cement). This depends on ratio of alkali to reactive aggregate. Effectiveness of pozzolans lies in production of combinations of sodium and potassium which do not absorb water and swell when enclosed in mortar.

Classify pozzolans into natural, and industrial waste products. Natural pozzolans may in most cases be improved by calcination and fine grinding. Industrial wastes—only fly ash has been used as a pozzolan so far.

Fly ash is the finely divided residue resulting from the combustion of coal which is transported from the boilers by flue gases. Very important property of fly ash is its spherical particle shape which helps reduce water requirements and improves workability by reduction of intergranular friction. Discuss properties, and chemical composition of fly ash. Even though fly ash is affected by many variables, statistical studies of the significance of a given variable can be made more readily for fly ash than for natural pozzolans, the variables of which are almost infinite. Tests of 35 fly ashes indicate decrease in quality with increase in ignition loss—carbon being the major contributor to loss on ignition. Specifications usually contain limits on MgO and SO_3.

Discuss concepts concerning cement-pozzolan reactions.

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112. ADAMS, ROBERT F. "Fly Ash Concrete in Large Dam Construction." Civil Engineering Corps Bulletin, Vol. 7, No. 8, pp. 11-14, August 1953. Abstract in Proceedings American Concrete Institute, Vol. 50, p. 268, November 1953. See Bibliography No. 45, 52, 76, 83, 91, 110, 128, 136.

The use of fly ash by the Bureau of Reclamation in the construction of Hungry Horse and Canyon Ferry dams is described. Advantages pointed out in the use of fly ash in mass concrete are economy, improved workability, lower drying volume change, reduced permeability, lower heat generation during hydration, reduced alkali-aggregate reaction, and equal or greater strength than control after about one year. Fly ash comprises about 30 percent by weight of the cementitious material in Hungry Horse Dam and about 25 percent in Canyon Ferry Dam.

113. ANON. "Special Cements." (Les Ciments Speciaux). Information Sheet, Societé des Matériaux de Construction de la Loisne (France), 2 pp., February 18, 1953.

Describe two special cements containing fly ash. Cements P-M. F. No. 1 and P-M. F. No. 2 which are pozzolanic cements, but are not the simple pozzolanic cements that normally develop slow hardening, and which has restricted their use in France to limited special projects. These two special cements, in addition to having all the desirable properties of the best pozzolanic cements, have a hardening curve closely approaching portland cement.

In 1 to 3 mortars, although the 2-day strength is lower than regular portland cement, it rises and becomes very close to the portland mortar strength at

7 days, and catches up with it before 28 days—exceeding it after that. At 3 months, the strength exceeds significantly that of super-cements.

Because of their high plasticity, very workable concrete is obtained without excess mixing water, resulting in very dense concrete with very high impermeability.

As a result of their composition, which gives them a lime content lower than any other cement, they present a high resistance to chemical attack. They are the proper cements to use in aggressive natural surroundings, in sea water concrete, in underground or foundation concrete, in all hydraulic structures, in mass concrete and in all masonry work.

The strength of these cements could have been increased 25 to 30 percent at 2 days, and 20 to 25 percent at 7 days, by the addition of 1 percent calcium chloride, or other soluble accelerator salt. But the reason it has not been done is that this would be deceiving the user. The use of such accelerators should be restricted to freezing weather and cannot be used effectively except by dissolving in the mixing water. It is the user who should decide on their use, taking into consideration the increased shrinkage they bring about. The user should know whether his cement is doped up with accelerators or not, as the risk of serious errors is great.

		Strength of 1 to 3 Mortar (psi)				
Laboratory		2 Days	7 Days	28 Days	90 Days	6 Months
Arts et Métiers	P-M. F. No. 1	1,320	3,750	6,250	8,500	10,300
Arts et Métiers	P-M. F. No. 2	1,910	4,200	7,250	9,500	10,500
Laboratoire du Bâtiment et des Travaux Publics	P-M. F. No. 2	1,570	3,940	6,700	8,300	10,100

114. ANON. "Fly Ash—Its Effects When Used in Plastic Concrete and Concrete Products." Rock Products, Vol. 56, pp. 186-188, February 1953.

Fly ash is a pozzolan. Should not have more than 12 percent carbon and should have specific surface higher than 2,500 square centimeters per gram. Requires less water than cement except when high in carbon. Gives more workable mix. Used as addition, improves strength, but as substitution, 20 to 25 percent, reduces early strength, but develops higher strength than plain concrete at 180 to 360 days. Can be used to substitute part of sand. Can be used also to correct for deficiency in fines. Moist storage at 70°F, dry air storage at 70°F, and storage in molds at 45°F, all give same strength.

Fly ash reduces permeability of concrete, reduces heat of hydration, resists sulfuric acid attack, reduces alkali-aggregate reaction when it has pozzolanic properties, and with air-entrainment, it improves resistance to freezing and thawing, and lowers shrinkage of concrete.

Used in pipe or block as compared to plain concrete: (1) Equal or better plasticity. (2) More uniform, smooth surface texture. (3) Less sticking to molds and pallets. (4) Equal or better strength. (5) Less abrasion of wearing parts of machinery. (6) Lowers cost of materials. (7) Increases production ratio. (8) Works well for autoclaved products. (9) Handles like bulk cement.

115. ANON. "Six Dams on the Raquette." Engineering News-Record, Vol. 151, pp. 30-32, September 17, 1953.

General description of project and dams. Concreting operations with paver. Use 5-bag mix with one bag replaced by fly ash. Fly ash comes from Niagara Steam Plant of Niagara Mohawk Power Company at Oswego, New York, owner of dams.

116. ANON. "East's First Fly-Ash Concrete Dam." Engineering News-Record, Vol. 151, pp. 35-36, September 17, 1953.

Liberty Dam (Baltimore), first dam in East to use fly ash. Saving of 50 cents per cubic yard of concrete. Fly ash cost $5 per ton placed in dam and came from a power plant 22 miles away. Used with Type II cement. Specifications limit carbon to 10 percent. Obtained lower heat of hydration. Increased workability, reduced segregation and bleeding, and increased later strength. Mix 3 bags cement and 92 pounds fly ash.

117. BOLLEN, R.E. and SUTTON, C.A. "Pozzolans in Sand-Gravel Aggregate Concrete." Proceedings, Highway Research Board, Vol. 32, pp. 317-328, 1953. See Bibliography No. 87.

Using fly ash in sand-aggregate concrete in laboratory tests, and experimental pavement placed in August and September 1950, find: (1) Reduces excessive expansion effect of reactive aggregates. (2) Lowers water requirement (3) Increases workability. (4) Requires more air-entraining agent, and this requirement correlates with carbon content. (5) Lower compressive strength at early ages but higher at later ages. (6) Reduces expansion on Scholer test (Exposure No. 2) and on freezing and thawing test. (7) In field, fineness presented handling difficulties—but not insurmountable. (8) Little bleeding. (9) In hot dry weather some difficulty in finishing and some rubberiness. (10) In other weather it was easier to handle and finish than plain concrete. (11) Beam strength low at early ages but high at later ages. (12) More durable than plain concrete on freezing and thawing test exposure (prior curing: 7 days moist, 21 days in laboratory air at 70°F, then 2 days in water). (13) Replacement with 30 percent fly ash completely inhibited expansion in scaled containers at 100°F. (14) Fly ash lowered absorption of cores taken from pavement.

118. BRANDT, J. "Lightweight Concrete from Coal Fly Ash." (Un Beton Cellulaire a Base de Cendres Volantes de Houille). Betonstein Zeitung (German) p. 209, September 1951. Abstract in Revue des Matériaux de Construction, No. 457, October 1953.

Uses process developed by Christiani and Nielsen for manufacturing lightweight concrete. Gives properties. Known commercially as Celonit. Outlines manufacturing process. No shrinkage due to steam curing.

119. BROOKE, EDMUND H. "The Merits and Problems of Using Fly Ash as Partial Replacement of Portland Cement." National Concrete Masonry Association. Technical Report No. 41, 3 pp. March 16, 1953.

Summarizes Hungry Horse experience in economies obtained by use of fly ash. Carbon content very important for block manufacturer.

Fly ash particles consist of: (1) White ash-like phase of very finely divided particles. (2) Red particles high in iron and very finely divided. (3) Black particles of carbon or carbon coated ash. Usually larger in size than the other two phases.

Fly ash has pozzolanic properties and contains soluble salts such as sulphates and alkalies that may cause efflorescence in masonry units.

Fly ash concrete has high ultimate strength but low early strength. By using fly ash in quantities more than replacement, higher early strengths are possible.

Tests by Professor O. Neil Olson, with 20 percent cement replacement by weight in cinder blocks, developed 3-day strengths of 1.04, and in four months of 1.21, as compared to control.

In tests made by engineers of Lehigh Portland Cement Company, in which fly ash was used as an addition, in amounts equal to 12 percent of cinder by volume, it gave increased strength and 4 percent increased yield. This increase in strength was obtained at from one-half to one-third of the cost of obtaining the same strength increase by use of additional cement.

Concludes that: (1) Concrete products producers can benefit from use of fly ash. (2) Quantity to be used should be determined by tests at individual plant. (3) To obtain high early strength, the fly ash must be added to the mix in larger volume than the cement replaced.

120. CHICAGO CONFERENCE COMMITTEE ON CONCRETE TESTS, Report No. B.R. 163, Chicago, "Tests of Certain Cements and Cement Blends Regarding Their Suitability for Concrete Construction." June 1953. See Bibliography No. 166.

Made various mixes using Type I and Type II cements, plain and with air entrainment, with fly ash as replacement and as admixture, and also with natural cement replacement. Used for fly ash volume basis, $\frac{1}{6}$ replacement plus $\frac{1}{18}$ admixture, or $\frac{1}{6}$ admixture.

Find that both air-entrained and plain mixes cured at 70°F had same compressive strength. At 7 days, replacement mixes had low strength but became equal to others at 28 days. Low temperature curing lowered strengths.

Freezing and thawing indicated higher resistance with air entrainment. No improvement of freezing and thawing resistance with replacement mixes was found. Volume change and abrasion tests were inconclusive. Heat of hydration of Type II with replacement was lower than others. Type II with air entrainment showed improved resistance to sulfate whether as sodium sulfate or H_2SO_4.

Recommendations: (1) Use air entrainment for highway work, as fly ash lowers cost (when there is no urgency to get quick strength for opening to traffic). (2) Heavy concrete sections may have heat reduced by use of substitution mixes, especially Type II with fly ash. (3) For sewer work, use Type II or blends with fly ash, but not Type I alone. Type I with fly ash would be satisfactory. (4) All concrete should contain 3 to 5 percent air. (5) Cure in winter at 70°F for 3 days with straight cements and 5 days with blends, then protect from freezing until concrete develops $\frac{2}{3}$ of its specified strength.

121. FOUILLOUX, P.M. "The Use of Fly Ash of High Pozzolanic Quality in Cement Mills." (De l'Utilisation en Cimenterie des Cendres Volantes a Hautes Qualités Pouzzolaniques). Le Nord Industriel et Commercial, p. 463, March 14, 1953. See Bibliography No. 211, 240.

Discusses pozzolanic cements manufactured with fly ash. The percentage of portland cement clinker is much lower than that used for the manufacture of regular "Pozzolan" cements. Strength properties of the fly ash cements are given.

122. HESTER, J.A. and SMITH, O.F. "Alkali-Aggregate Phase of Chemical Reactivity in Concrete." Proceedings, Highway Research Board, Vol. 32, pp. 306-316, 1953. See Bibliography No. 188.

Work done at Alabama State Highway indicates that at least five major factors must exist for alkali-aggregate reaction to develop: (1) Sufficient alkali to react with the silica. (2) Silica that is reactive with low concentrations of alkali. (3) Water available in amounts to continue the reaction. (4) Lime free to react with the alkali silicates, releasing the alkali back to solution, or enough alkali to be present to injure the concrete without regeneration. (5) Enough force to rupture the concrete after the damage by the alkali. The last two factors are the most controversial.

From tests made to check on these, conclude: (1) The progressive reaction of the alkali and aggregate in concrete depends on presence of lime to liberate the alkali from the alkali silicates before continuing the cycle. (2) Silica from pozzolans can tie up this lime and thus reduce the trouble caused by the release of the sodium and potassium hydroxides from their silicates.

123. LARSON, GUY H. "The Effect of Substitutions of Fly Ash for Portions of Cement in Air-Entrained Concrete." Proceedings, Highway Research Board, Vol. 32, pp. 328-335, 1953. See Bibliography No. 51, 138, 150.

Following the 1949 experiments, restituted loss of air due to fly ash by adding air-entraining agent, and finds: (1) That it reduces strength at 28 days, but increases it at about 1 year. (2) Improves resistance to freezing and thawing to a great extent, but does not completely bring it back. (3) Requires considerably more air-entraining agent. (4) Delaying start of freezing and thawing may change findings.

Discussion by N.H. Withey—Disagrees with author's results and quotes work done by others in support of his contention. Agrees that starting freezing and thawing cycles at later age will provide strengths at start of freezing and thawing comparable to the strengths at earlier ages of plain concrete. Suggests, however, higher fly ash replacement to include part of the sand, to obtain higher early strengths, at start of freezing and thawing tests.

124. McCLENAHAN, W.T. "Experience with Fly-Ash Blends in a Test Pavement Built in 1938." Engineering News-Record, Vol. 150, March 12, 1953.

Reports construction of ½ mile of pavement at North Side Sewage Plant in Chicago—already 14 years in service: (1) Skin coat has disappeared and coarse aggregate exposed. (2) "D" cracking in two sections of plain concrete. (3) Used different combinations of 18 to 50 percent substitution by volume and cement factors of 3.1 to 5.5 bags. (4) With 50 percent replacement and 6.55 bags per cubic yard total cementitious materials, obtains 4,300 psi at 28 days and 5,600 at 6 months. (5) Also uses fly ash on sewers with about 12 percent replacement by weight. (6) Where fly ash exceeds 30 percent replacement, plastic concrete tends to be "gummy". (7) Carbon content affects air entrainment—finds lack of uniformity of carbon from some sources. (8) Carbon does not probably affect durability of concrete, but may slow strength gain. (9) Doubts that fly ash combines with lime to form cementitious material.

125. PATSCHKE, E. "Mixed Binders from Soft Coal Ashes." Silika Technik, Vol. 4, pp. 365-373, 1953. Abstract in Chemical Abstracts, Vol. 48, p. 4201, April 10, 1954.

Soft coal ashes are collected in cyclones and electrostatic Cottrell dust precipators. For middle and east Germany, four types are abundant. Type 1 is a lime-$CaSO_4$ ash which is a poor hydraulic agent. Type 2 has average composition of hydraulic lime or natural cement. Type 3 has some sililarity to blast furnace slag. Type 4 is similar to the fly ash commonly used in U.S., but has not been used industrially in Germany.

126. PEARSON, A.S. and GALLOWAY, T.R. "Fly Ash Improves Concrete and Lowers Its Cost." Civil Engineer, Vol. 23, pp. 592-595, September 1953.

Consolidated Edison Company tried fly ash and was able to introduce it into New York City Building Code. Details chemistry of pozzolan—there is about 18 pounds of lime formed from each bag of cement in concrete, which is available to be combined with fly ash to form more stable compounds. Fly ash increases workability, lowers water requirements, increases later strengths, impermeability, and resistance to sulfates. Examples of buildings which expanded when subjected to sea water action. Use of 20 percent replacement in the mixes discussed.

127. SERVICE DE DOCUMENTATION DU CENTRE D'ETUDES ET DE RECHERCHES DE L'INDUSTRIE DES LIANTS HYDRAULIQUES. "Bibliography on the Use of Fly Ash." Revue des Matériaux de Construction (Paris), No. 457, pp. 293-294, October 1953.

Covers some of the publications which appeared in 1941 to 1953.

128. U.S. BUREAU OF RECLAMATION. "Hungry Horse Project, Final Construction Report." Vol. IV, 1946-1953. See Bibliography No. 45, 52, 57, 76, 83, 91, 112, 128, 136.

Used 32.4 percent fly ash by weight of cement for interior concrete, and 24.2 percent for other concrete.

129. U.S. BUREAU OF RECLAMATION. "Concrete Aggregate and Concrete Mix Investigations for Anchor Dam—Owl Creek Unit—Bighorn Basin Division—Missouri River Basin Project." Concrete Laboratory Report No. C-498, April 17, 1953.

Results of tests indicate essentially that: (1) Fly ash counteracts alkali reaction with this combination. (2) Concrete continuously fog cured shows good freezing and thawing resistance. (3) Concrete with fly ash, which was dried after short period of moist curing, shows lowered freezing and thawing resistance. (4) Fly ash reduced drying shrinkage. (5) Fly ash reduced permeability. (6) Cavitation resistance of 90-day mass cured concrete with 4-sack concrete mix, is increased with 15 percent fly ash, but decreased as fly ash is increased to 45 percent. At 28 days (mass cured), cavitation resistance is greatly reduced with fly ash of any amount. With 3-sack concrete mix, fly ash somewhat lowers resistance of all combinations. (7) Abrasion resistance, of both 28- and 90-day concrete (mass cured), is lowered with fly ash in both 3- and 4-sack mixes. (8) Freezing and thawing durability of fly ash concrete as good as plain cement, if fog cured for 6 months or more. Durability of air-entrained concrete, fog cured 28 days with or without fly ash, is either good or excellent. Freezing and thawing resistance of fly ash concrete fog cured 7 and 14 days and exposed outdoors gave lowered values.

130. U.S. BUREAU OF RECLAMATION. "Progress Report Concrete Mix Investigation for Palisades Dam." Concrete Laboratory Report No. C-672, May 19, 1953.

Gives recommended mixes. Recommends fly ash in tunnel concrete and other places where freezing and thawing exposure is not severe, but not in exposed concrete. Use Fisk Station fly ash in mixes. Water demand lowered about 10 percent by use of fly ash.

131. U.S. BUREAU OF RECLAMATION. "Effect of Fly Ash, Calcium Chloride, and Temperature on the Compressive Strength of Concrete Containing Entrained Air." Concrete Laboratory Report No. C-696, May 1953.

Using mixes containing fly ash and calcium chloride in concrete with Types II and V cements mixed and stored at 50° and 73°F, find: (1) Fly ash reduced effectiveness of $CaCl_2$ at 50° and 73°F with both cements. (2) The strength of concrete containing 30 percent fly ash by weight, 2 percent $CaCl_2$ with Type II cement cured at 50°F, showed increase in strength of 145 percent at 1 day and 42 percent at 3 days, as against 210 percent and 190 percent respectively for the concrete without fly ash. (3) The use of fly ash in 73°F concrete, containing 2 percent $CaCl_2$ reduced the 1-day strength about 50 percent. (4) Use of 30 percent fly ash in concrete without $CaCl_2$ reduced the compressive strength at 1 day about 15 percent. (5) Fly ash contributes to strength at early and late ages, but makes little contribution between ages 7 and 28 days.

132. U.S. BUREAU OF RECLAMATION. "Concrete Mix Investigations for Canyon Ferry Dam—Canyon Ferry Unit—Helena-Great Falls Division—Missouri River Basin Project." Report No. C-656, June 22, 1953. See Bibliography No. 110, 155.

Recapitulate mix investigations and first year concreting operations, with following conclusions: (1) Mix with 30 percent fly ash replacement has adequate strength. (2) Use of fly ash reduces water requirement and increases air-entraining agent requirement. (3) Fly ash replacement of 30 percent reduced 28-day strength, but 3 to 6 months' strength comparable to control. With 45 percent fly ash replacement, strength remained low throughout. (4) Fly ash concrete, mass cured for 1 year, had a high coefficient of correlation with 28-day fog cured. (5) Resistance of fly ash concrete to abrasion and cavitation was reduced. (6) Fly ash in 30 percent replacement reduced permeability of all mixes. (7) Fly ash tends to reduce freezing and thawing durability with short curing, but improves it with long moist curing periods. (8) Fly ash reduced heat of hydration in mix. (9) Fly ash increases thermal conductivity and diffusivity. (10) Drying shrinkage reduced about 20 percent by fly ash. (11) Fly ash increased autogenous shrinkage of rich concretes. (12) Fly ash increased the expansion of concrete continuously moist cured. (13) Fly ash contributed to higher thermal coefficient of expansion. (14) Fly ash in 30 percent replacement gave higher modified cube strengths than control. (15) Modulus of rupture of moist cured 30 percent fly ash concrete was increased, but was reduced in dried specimens. (16) Modulus of elasticity was increased slightly with 30 percent fly ash and decreased with 45 percent. Modulus of elasticity of dried specimens was 75 percent of that of moist cured specimens at 2 years.

133. U.S. BUREAU OF RECLAMATION. "Concrete Mix Investigations for Falcon Dam—Rio Grande International Storage Dams Project—International Boundary and Water Commission." Concrete Laboratory Report No. C-655, June 23, 1953. See Bibliography No. 113.

Used fly ash in preliminary mixes only and decided on other local pozzolan instead. As compared to control: (1) Fly ash required less water (Northwestern Station). (2) Freezing and thawing 590 cycles, 28-day fog cure, 25 percent loss. Freezing and thawing 1,390 cycles, 90-day fog cure, 25 percent loss. Freezing and thawing 3,040 cycles, 180-day fog cure, 25 percent loss. Freezing and thawing 2,270 cycles, 365-day fog cure only 20 percent loss. Not as good as control at 28 days, but better than control at later ages. (3) Strength not as good as control at all ages.

134. U.S. BUREAU OF RECLAMATION. "Progress Report—Investigation of the Properties of Concrete for Use in the Design and Construction of Yellowtail Dam—Yellowtail Unit—Missouri River Basin Project." Concrete Laboratory Report No. C-705, September 8, 1953.

Results of tests indicate essentially that: (1) Using 30 percent fly ash replacement, concrete strengths are 15 to 20 percent higher than with cement alone, under 1 year mass curing conditions. (2) Fly ash reduced early strength, but after 180 days it equaled plain concrete or exceeded it. (3) Use of 30 percent fly ash reduced water requirement 6.5 percent. (4) Use of 30 percent fly ash approximately doubled Vinsol resin requirement. (5) Fly ash reduced drying shrinkage of concrete. (6) Autogenous shrinkage was higher for high cement-fly ash content, whereas in very low cement content, it showed expansion. (7) Fly ash increased modulus of rupture for sealed and moist cured concrete, but decreased it for concrete dried after 90 days moist curing. (8) Specific heat, thermal conductivity, and diffusivity are about average for 3-sack mix with 30 percent fly ash. (9) Wetting and drying durability (Scholer Exposure No. 2) showed 0.01 percent expansion against failure criterion of 0.07 percent. (10) Fly ash reduced freezing and thawing durability at early age, but after 90 days fog curing, durability equal to or greater than control. (11) In leaner mixes, fly ash reduced bleeding. (12) Durability in freezing and thawing reduced, if fly ash concrete is subjected to long drying period outdoors, after 7 and 14 days of fog cure. (13) Fly ash increased modulus of elasticity (flexural) for sealed and continuously moist cured specimens about 12 percent, but slight reduction on drying after 90 days fog cured specimens. (14) Compressive strength of modified cubes increased 5 percent with fly ash at 1 year. (15) Fly ash more effective in leaner mixes.

135. U.S. BUREAU OF RECLAMATION. "Laboratory Investigations of 81 Fly Ashes." Concrete Laboratory Report No. C-680, September 11, 1953.

Gives detailed results of tests of 81 fly ashes from various sources, used in combination with five Type II cements. From these tests, the comparisons with Davis dam specifications are made and some changes recommended.

136. U.S. BUREAU OF RECLAMATION. "Laboratory and Field Investigations of Concrete—Hungry Horse Dam—Hungry Horse Project." Concrete Laboratory Report No. C-699, December 4, 1953. See Bibliography No. 45, 52, 76, 83, 91, 112, 128.

A very comprehensive report of laboratory studies, field control, and tests of cores. Conclusions: (1) Strength gain of concrete containing fly ash is not as rapid as plain concrete, but continues at a more uniform rate for a longer period. At about 1 year, concrete with 30 percent fly ash has about same strength as plain concrete. (2) Fly ash increases modulus of elasticity of concrete for same compressive strength. (3) For lean mixes, fly ash reduces water requirement, but for richer mixes, it does not affect it. (4) Fly ash generates 40-50 percent as much heat as cement of equal weight. (5) Fog-cured (continuously) specimens with fly ash show slightly more expansion than without. (6) Fly ash tends to decrease drying shrinkage (fog cured 90 days). (7) Fly ash increases autogenous shrinkage of rich mixes at later ages, but compares favorably with lean mixes containing no fly ash. Fly ash retarded autogenous shrinkage at early ages. (8) Concrete with fly ash has higher thermal expansion coefficient than plain concrete. Brand of cement may be more of a factor. (9) Good freezing and thawing resistance was obtained with 40 percent fly ash (fog cured and dried in 50 percent relative humidity). (10) Fly ash greatly reduces permeability of concrete. (11) Early strength of concrete with fly ash is reduced in proportion to amount added, but at 1 year, it catches up with plain concrete. (12) Fly ash is unique among pozzolanic materials in reducing water content of concrete when used on an equal weight replacement basis. (13) Value of fly ash in reducing alkali reaction is low compared to opaline silica. (14) Long-time strength higher than plain concrete (moist cured). (15) Optimum fly ash content, having high fineness and low carbon, is 30-40 percent. (16) At early ages, fly ash concrete (fog cured) has a reduced freezing and thawing durability. At later ages, (6-12 months) durability of non-air-entrained fly ash concrete is reduced, but is increased with air entrainment. (17) Air meter of ¼ cubic foot capacity is satisfactory for 1½ inch maximum aggregate. (18) Hand picking provides as good a sample as wet screening if done carefully. (19) Transportation on dam reduced air content 0.6 percent (Hungry Horse). (20) Vibration removed only small amount of air. (21) Fly ash concrete had considerable variation in air content. (22) Control cylinders continued to gain strength through 2 years of age. (23) Fly ash from different sources required different amounts of air-entraining agent. (24) Petrographic examination of fly ash particles in concrete cores disclosed no evidence of reaction with other ingredients of mix. (25) Very little fractured aggregate at breaks in concrete. (26) Strength of 10- by 20-inch cores at 12 months approximately equals strength of 6- by 12-inch cylinders at 80 days.

137. WASHA, G.W. and WITHEY, N.H. "Strength and Durability of Concrete Containing Chicago Fly Ash." Proceedings, American Concrete Institute, Vol. 49, 701-712, April 1953.

Using Wisconsin aggregates and Chicago cement, ran tests and find: (1) Fly ash must be greater than cement it replaces to maintain 28-day strength (between 1½ to 2 times). (2) At 1 year, a 20 percent replacement by weight exceeded control strength. (3) Under adverse curing conditions (dry or cold), cement hydration is retarded about as much as pozzolanic activity. (4) Fly ash has no effect on freezing and thawing resistance of air-entrained concrete. (5) Fly ash increases sulfate resistance of concrete with Type I cement, but does not affect Type II, which is already resistant to such action. (6) Mixes containing 70 to 188 pounds of fly ash per cubic yard, required 1 to 2½ gallons less water for a given slump. (7) Fly ash concrete requires larger amounts of air-entraining agent to maintain given air content.

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138. ANON. "Effects of Fly-Ash Replacement of Cement." Concrete, Vol. 62, No. 3, pp. 38 and 41, 1954.

Summarizes the two investigations by Guy H. Larson and discussion of Larson's results by N.H. Withey.

Essentially that fly ash reduces the entrained air developed normally with air-entraining cement and it takes about three times as much air-entraining agent to restore it. With restored air entrainment, water requirement is reduced and resistance to freezing and thawing is improved, but not to equal control. Suggests that delaying freezing and thawing to later ages to permit pozzolanic action to take place might improve the durability further.

Withey claims tests made by Washa at Wisconsin showed equal durability with 500 cycles of freezing and thawing, and also suggests that fly ash replacement should be held to a maximum of 20 percent. Suggests that chert in Larson's tests might be responsible for the apparent adverse results.

139. ANON. "The Use of Pulverized Fuel Ash in Concrete." Editorial Notes, Concrete and Constructional Engineering (London), Vol. 49, No. 9, pp. 273-274, September 1954. See Bibliography No. 157.

Discusses tests made by British Electricity Authority to check findings in U.S.: (1) Fly ash has some cementitious properties because silica can react, over a period of several months, with hydrated lime in concrete to form cementitious compounds. (2) Fineness varies, but is of same order as cement. (3) Carbon content also varies with a range from 3 to more than 12 percent. (4) Reduced strength at early ages, but may equal control at one year. (5) If cement is replaced by twice its weight of fly ash, the 28-day strength is not reduced but nevertheless, the workability and resistance to chemicals of the concrete is improved. (6) Thinks 8 percent carbon should be top limit. (7) No durability data available, but its slow-hardening properties should be of concern where fast form stripping is needed. (8) Its advantageous use should be in mass concrete because of its lower evolution of heat. (9) For small job use, it could be blended with the cement at the mill, but its price will rise, thus defeating its normal economies.

140. ANON. "Fly Ash Use as Concrete Additive Questioned by Building Inspectors." Engineering News-Record, Vol. 152, No. 12, p. 22, March 25, 1954.

Use of fly ash as cement replacement was questioned by Long Island inspectors. Portland Cement Association and local sand and gravel company also opposed its use, claiming that if used, it should be in addition to the cement and not to replace it, and that any economic advantage by its use is lost in the increased delay for form stripping. Fly ash proponents on the other hand claimed that fineness and spherical shape of particles impart "ball bearing action" which results in greater workability, and that the chemical action between the fly ash and hydrated lime in the concrete renders it superior in compressive, tensile, flexural, and bond strength.

141. BLOEM, DELMAR L. "Effect of Fly Ash in Concrete." National Ready Mixed Concrete Association, Publication No. 48, January 1954. See Bibliography No. 77, 142.

Summarizes their studies to date on fly ash, and includes a selected bibliography—concludes: (1) Performance is related to fineness, carbon content, and silica content. (2) Improves workability with no adverse effects on water requirements. (3) Contributes to strength—low at early ages but increases at later ages—greatest benefits to leaner mixes. (4) Low temperature or lack of moisture during curing has no more detrimental effect than in plain concrete, but advantage of increased strength at later ages is lost. (5) Fly ash suppresses air entrainment unless an increase in air-entraining agent is made. (6) Does not increase or reduce freezing and thawing durability—evidence inconclusive. (7) Fly ash improves sulfate resistance. (8) It inhibits alkali reaction. (9) Fly ash has no effect on shrinkage. (10) It may reduce permeability at later ages.

142. BLOEM, DELMAR L. "Effect of Curing Conditions on Compressive Strength of Concrete Test Specimens." National Ready Mixed Concrete Association, Publication No. 53, December 1954. See Bibliography No. 77, 141.

Using mixes with Type I, Type IS, Type I with fly ash replacement of 1.5 pounds per pound of cement, and Type I with 2 percent calcium chloride, and field curing at 37°, 73°, 100°F for various periods as against standard curing, and also curing in 37° and 100°F water, finds: (1) All deviations from standard curing lower strength, and affect special mixes more than mixes with Type I cement, except for combination with fly ash. (2) Fly ash concrete equaled or exceeded Type I alone in standard curing and 100°F water curing, but was only equal or slightly lower for 73°F air, or 37°F air or water curing. (3) Cautions against extending results of this particular fly ash to other fly ashes.

143. BORNER, HANS and ALT, HERMANN. "Three Years of Building with Ytong."

Tonindustrie Zeitung (in German) Vol. 78, No. 3/4, pp. 43-47, February 1954.

A lightweight concrete known at "Ytong" is made with fly ash, slag, and lime. Discuss properties, covering strength, density, expansion and shrinkage, absorption, heat conductivity, fire resistance and thermal expansion, resistance to frost action, acoustical properties, and corrosion. The use of Ytong with reinforced concrete in buildings, and as precast slabs and structural units is described.

144. CHARRIN, V. "Natural Pozzolanas and Artificial Pozzolanas Such as Fly Ash and Burnt Schists of Autun." Chaleur et Industrie, Vol. 35, p. 182-4, 1954. Abstract in Building Science Abstracts, Vol. 27, No. 10, paragraph 1517, October 1954.

An evaluation, of the natural pozzolanas of Auvergne, Marne, and Ardennes, and of such pozzolanic materials as power station fly ash and the residues from low temperature carbonization of bituminous schists of Autun with respect to their constructional uses, is given. In the case of fly ash used as admixture, 30 to 50 percent, the workability of the resulting concrete is improved. The natural pozzolana are usually suitable after preliminary calcination.

145. COLLINS, A.R. "The Use of Pulverized Fuel Ash with Portland Cement." Cement and Concrete Association, Great Britain, Technical Report No. TRA/150, 6 pp., Revised Edition, October 1954.

Finds difficulties in using fly ash in practice because of its large variability. Thinks that each batch should be tested prior to use, for loss on ignition and perhaps moisture content. Its use in cement mixtures should be discouraged except in work with experienced contractors.

146. DAVIS, RAYMOND E. "Pozzolanic Material—With special Reference to Their Use in Concrete Pipe." American Concrete Pipe Association, Technical Memoramdum, September 1, 1954. See Bibliography No. 3, 4, 9, 13, 19, 60, 61, 79.

Gives definition of pozzolans and their action, and history. Pozzolans improve permeability of concrete pipe, with continuous moist curing, and reduce leaching, and increase resistance to sulfates and weak acids. Calls attention to variability of fly ashes. The lower the carbon, and the higher the specific surface, the lower the water requirement, the higher the strength, and the lower the permeability. Fly ash leads to lower water requirement in concrete than any other pozzolan.

Discusses action of pozzolan as replacement or as addition, with optimum of about 35 percent for fly ash. Sand can be reduced if considered as fines and fly ash substituted. Water reducing agents more effective in pozzolan concrete than in plain concrete. Fly ash improves workability, and reduces tendency to bleeding. The early strength of pozzolan concrete is lowered but later strengths are higher. Pozzolans reduce segregation in packer head pipe, in tamper pipe, and in centrifugal pipe also. Pipe should be wetted before laying to recover from shrinkage due to drying.

147. FUCIK, E. MONTFORD. "Benefits to Guayabo Project Justify Cost of Adding Fly Ash to Concrete." Electrical World, Vol. 142, pp. 30-31, October 11, 1954.

Using 25 percent fly ash replacement by weight in a one barrel per cubic yard mix, finds that it: (1) Reduces alkali reaction. (2) Reduces concrete temperature rise. (3) Minimizes cracking of concrete due to shrinkage. (4) Improves workability. (5) Slows initial set.

Fly ash which was used met both U.S. Bureau of Reclamation and American Society for Testing Materials specifications. The 7-day strengths were lower than those for plain concrete, but the 28-day strengths were equal. The fly ash mixes required 4 to 6 times the amount of Vinsol resin to obtain the 3 percent air requirement. Fly ash concrete was not used in exposed structural concrete.

148. GENERAL SERVICES ADMINISTRATION. "Federal Specification—Cement; Portland-Pozzolan." SS-C-208b, April 9, 1954.

This is used with Federal Test Method Standard No. 158, May 1, 1957.

149. JARRIGE, A. "Some Technical and Economic Aspects of the Fabrication and Use of Lightweight Concrete, and the Use in Construction of the Waste Products of Coal Utilization." (Quelques Aspects Techniques et Économiques de la Fabrication et de l'Emploi des Bétons Légers et de l'Utilization des Déchets de l' Exploitation Houillère dans la Construction.) Revue des Matériaux de Construction, No. 471, pp. 343-352, December 1954 and No. 472, pp. 3-8, January 1955. See Bibliography No. 216, 243, 244.

Reviews lightweight concrete construction: (1) Use of insulating materials and the building of cavity walls is an important recent progress in building construction. (2) The cost is affected by the cost of production of the materials, their transportation, and the labor of incorporating them in place. (3) Lightweight materials offer the double advantage of east of handling and insulation. (4) The incorporation in concrete of lightweight aggregate, produced artificially near the site, is often economical. (5) Aerated concrete, because of its price, is used only in limited applications: reinforced roof slabs and curtain walls. (6) Shale as a by-product of coal mining makes better brick than clay. (7) Shale when heated and expanded makes good lightweight aggregate. (8) Burned shale from old dumps can be used in foundation concrete. (9) Fly ash which has pozzolanic properties, permits reduction in cost of concrete and improves its quality. It can be used to make brick and aerated concrete.

The Americans, in trying to find means to dispose of fly ash from power plants, were able to take advantage of its pozzolanic properties. In the last 10 years, it has passed the experimental stage and has found industrial applications. Principal advantages in concrete: (1) Increase of compressive strength after a period of time. (2) Reduction in heat of hydration. (3) Improved workability. (4) Increased impermeability. Consequently, if one sets in advance the level to be attained for these characteristics, it spells economy.

Fly ash in concrete acts at the beginning as an inert material, followed by the pozzolanic action which increases the strength. All fly ashes are not equally as suitable with all cements and preliminary tests should be made. Past experience indicates the following conditions for best results: (1) Alumina plus silica in excess of 50 percent. (2) Magnesia and SO_3 under 3 percent each. (3) Carbon content under 7, 10, or 12 percent depending on the authority. (4) The fineness should be such that less than 12 percent is retained on the No. 325 sieve. Americans insist on the importance of the fineness of fly ash. (5) The present practice is to replace 20 to 30 percent of the cement, although this can reach 50 percent. (6) It is recommended that it be thoroughly blended with the cement in silos. (7) Most important applications are in mass concrete, water front structures, pavement, precast concrete, in power plants producing the ash, concrete products, and grouting.

American experience stimulated the French to study their fly ashes. In 1946, in order to get rid of fly ash, contractors on power plant projects were instructed to use it in concrete. The replacement varied from 30 to 100 percent of the sand with cement remaining constant. The mortar became very hard in a few months, but that without sand became very porous. The raw fly ash in these projects had in general the following properties:

	Percent
SiO_2	45.2-46.9
Fe_2O_3	6.1- 9.0
Al_2O_3	26.7-28.5
CaO	2.6- 4.3
MgO	1.3- 2.0
K_2O	2.8- 3.0
Na_2O	0.2- 0.9
Loss on ignition	1.4-13.5
Retained on No. 200 Sieve (this is the French sieve, 4,900 openings)	20 -75

Early French tests, using 25 percent fly ash with portland cement, confirmed American experience, that is, early loss in strength followed by higher ultimate strength. With slag cements, the strength at 7 days was above that for the slag cement alone. In 1952, the Centre d'Etudes et de Recherches de l'Industrie des Liants Hydrauliques confirmed the fact that certain raw fly ashes had definite pozzolanic properties.

Further intensified studies led to the statistical realization of the value of fly ash in concrete resulting in the fabrication of special cement P-M. F. in the plant at Loisne.

Other investigations have shown that by pulverizing the fly ash or separating its coarse particles, the replacement of fly ash can be increased to over 25 percent.

In mines, fly ash is being used to replace 30 to 50 percent of the sand, in which case a part of it adds to the cementing action, and the rest plays an inert role.

The finer the fly ash, the higher the ultimate strength, other things being equal. For untreated fly ash, at age of 3 months, the strengths equal control. For concrete containing 34 percent fly ash (50 percent of the cement) the strength is higher than would have been obtained by use of cement alone at 6 months. With higher fly ash contents, the strength is lower. The best increase in strength, 19 percent, is obtained with 14 percent fly ash (16 percent of the cement).

M. Chappelle has developed a rapid test to measure the pozzolanic activity of a fly ash instead of waiting six months to measure the strength of the concrete in which it is used. It is based on boiling the fly ash and determining the amount of lime fixed by the fly ash in a certain length of time.

The higher the fineness, the better the results: (1) The finer the particles, the higher the chemical action. This is a well known principle and if this is the case, then sieving out the coarser particles would provide a finer product. (2) However, some feel that the exterior of the particles is vitreous and less active than the interior, and therefore, there is an advantage in grinding to expose the inside of the particles. When grinding is done with the cement clinker, a homogeneous mixture is obtained. (3) Particles that are not ground constitute a porous material which has a higher water requirement than the cement, which is a reason for lowered strength. Grinding removes this cause, the water requirement is reduced, and the strength increases.

Obviously, grinding increases costs, and it would be best to use the fly ash as it comes and accept what improvement it provides, but if the demand for the special treatments develops due to the additional improvement in properties, then it will come into being.

Not much difference is apparent in chemical compositions. It might be that petrographic studies might find differences between similar chemical compositions, as the compounds formed are not only the result of the chemicals present, but also of the heat environment in which the ash is formed.

The materials included in the loss on ignition test, do not appear to be harmful from the chemical viewpoint, but interfere as inert materials, thus reducing the activity of the ash. They also have special affinity for water, thus increasing the water demand. It is not difficult in practice to keep the loss on ignition under 10 percent, if one does not consider the adjustment periods of starting, slowing, etc., of the plant operation. Most French fly ash has less than 7 percent loss.

Fly ash reduces cost of concrete by replacing cement and for the most part, it does not cost in France more than 30 percent of the cost of the cement it replaces. In America, a superior concrete is obtained at a saving of 5 percent. Economic use is limited by the distance from the source.

Two disadvantages are evident: (1) The low early strengths. (2) The additional material to be batched. In the first case, use is limited to service that does not require high early strengths, or in prefabricated units which are steam cured and thus attain early strength or can be stored until they reach proper strength. In the second case, blended cement at the cement plant would eliminate the extra handling. However, on large projects, such as dams, there is advantage in mixing at the site in order to adjust the proportions as needed for proper control. There is room for both operations and for a long time, there will be advantage in cooperation between cement plants, power plants, and users of cementitious products.

150. LARSON, GUY H. "Field Substitution of Fly Ash for a Portion of Cement in Air-Entrained Concrete." Proceedings, Highway Research Board, Vol. 33, pp. 259-264, 1954. See Bibliography No. 51, 123, 138.

Uses Type IA cement, in experimental pavement built September to November 1949 in Wisconsin—mixes: (a) plain concrete with air-entraining cement, (b) with 21 percent fly ash replacement, and (c) with air content of fly ash concrete restored to same level as in plain concrete.

Finds: (1) Increase of strength at later ages by use of fly ash. (2) Restored resistance to freezing and thawing which had been reduced in case (b). (3) Results from cores at 3-year age showed no adverse effect to natural weathering of all three concretes.

151. LILLEY, A.A. "Soil-Cement Roads: Experiments with Fly Ash." Cement and Concrete Association Great Britain, Technical Report No. TRA/158, 4 pp., October 1954.

Finds from tests, that fly ash does not contribute to the strength of the soil or soil-cement mixture, and that it is not possible to substitute fly ash for cement in such mixtures. The quality of the mixture is not improved by addition of fly ash.

152. LITTLEJOHN, CHARLES E. "The Utilization of Fly Ash." Bulletin No. 6, Engineering Experiment Station, Clemson A and M College, Clemson, South Carolina, 1954.

A very thorough review but mostly from chemical slant with 208 item bibliography, a few of which overlap civil engineering field. Discussed: (1)

Chemical and physical properties of fly ash. (2) Collection. (3) Disposal as waste. (4) Uses as developed by Detroit Edison Company. (5) Use in building industry. (6) Gives good summary of advantages in concrete. (7) Discusses metals, alloys and chemicals derived from fly ash, including rare element germanium. (8) Gives use of fly ash as catalyst.

153. MINNICK, L. JOHN. "Investigations Relating to the Use of Fly Ash as a Pozzolanic Material and as an Admixture in Portland Cement Concrete." Proceedings, American Society for Testing Materials, Vol. 54, pp. 1129-1164, 1954. See Bibliography No. 53, 70, 101, 271.

Summarizes investigations by various laboratories. Gives test results of 20 fly ashes by various cooperating laboratories to see how they meet proposed American Society for Testing Materials Specification. Table XX summarizes proposed specification requirements and shows which fly ashes do not meet. Concludes that for tests finally adopted, reproducibility was obtained except in reduction in mortar bar expansion—this test originated by U. S. Bureau of Reclamation, who obtain reproducibility in their laboratory.

Some evidence that low carbon, high fineness fly ash induces higher early strength than high carbon coarser fly ash. Corps of Engineers tests show that higher strengths are obtained for ignition loss under 3 percent, but author suggests that it was the source that may have contributed the high strength rather than low carbon. No satisfactory correlation between tests on mortar and on concrete, but mortar test more sensitive to type of fly ash, and therefore, mortar tests should be included in specifications. Does not feel that air entrainment and ignition loss are definitely related. Very little relationship between shrinkage and loss on ignition. Pozzolanic activity tests with lime good, and possibly autoclave with portland cement should be included also. Finds correlation between SO_3 and compressive strength, and also between MgO and strength.

There are many unanswered questions that still face the engineer in connection with the use of fly ash in concrete, just as there are many unanswered questions in connection with concrete itself.

Discussion by Bryant Mather. Shows relationship between amount of air-entraining agent required and carbon content.

154. MORAN, WILLIS T. "Admixtures for Concrete." American Concrete Institute Committee 212, Proceedings, American Concrete Institute, Vol. 51, pp. 113-148-6, October 1954. See Bibliography No. 71, 72.

Uses the American Society for Testing Materials definition for admixtures, and subdivides field into 11 categories. Fly ash fits into several of these categories as follows: (1) In pozzolanic class—as addition improves workability, impermeability and resistance to chemical attack. (2) Alkali-aggregate expansion inhibitor—degree depends on specific fly ash and other ingredients used in the mix—some combinations work well and others not so well. (3) Damp proofing and permeability reducing agent—better results in lean mixes than in rich. Cement does more good in this category than finely divided powders such as fly ash. (4) Workability agent—as finely divided powder, fly ash is one of the materials recommended. (5) Grouting agent—added to cement grout, improves pumpability, reduces settlement and cost, and also retards setting time.

Theoretical discussion on bleeding and plasticity as a result of additions of finely divided powders such as fly ash.

Discussion by W. T. McClenahan. Takes issue with classifying fly ash as admixture, and with method suggested by Committee in figuring water-cement ratio when using fly ash. He maintains that fly ash is part of cementitious material, and should therefore be considered as such, not only in classifying it but also in figuring water-cement ratio. Prefers volume proportioning to weight.

155. U.S. BUREAU OF RECLAMATION. "Technical Record of Design and Construction, Canyon Ferry Unit, Montana, Missouri River Basin Project," Vol. 1, 1949-1954. See Bibliography No. 110, 132.

General discussion on use of fly ash in this dam.

156. U.S. BUREAU OF RECLAMATION. "Pozzolan Investigations—Falcon Dam." Concrete Laboratory Report No. C-734, April 5, 1954. See Bibliography No. 98.

Tested some 30 pozzolans, among which were fly ashes. Find strength attained with fly ash satisfactory, but did not reduce alkali reaction as well as some other pozzolans.

157. WARD, J.M. "Pulverized-Fuel Ash as a Partial Replacement for Cement in Concrete." Cement and Lime Manufacture (British), Vol. 27, No. 4, pp. 53-59, July 1954. See Bibliography No. 139.

Tests made by British Electricity Research Laboratories. Chemical composition of fly ash from various stations seems constant, but ignition loss varies considerably. Samples taken for this survey indicate that 98 percent of the samples had ignition losses below 16 percent, and 76 percent below 8 percent. In mixes with 20 percent by weight replacement, strengths matched control at 3 months, while at 28 days they varied from 75 to 85 percent of controls. Results of tests using fly ash with ignition losses ranging between 5 and 12 percent were similar and indicate that in this range, the carbon content is without appreciable effect on the strength of the concrete. A 20 percent replacement with a specially coarse ash resulted in lower strength at 6 months than with same replacement of ashes with fineness of most British ashes.

During handling, the impression was gained that fly ash concretes were more workable, but this was not confirmed by measurements.

Fly ash can be used in concrete in large projects under strict control. The advantages are lower heat of hydration, lessened bleeding and segregation, and higher resistance to sulfate waters. Difference in strength between fly ash concrete and plain concrete, at ages up to 3 months, can be reduced by using less water as a result of increased workability. It is also possible that this difference could be reduced by adding more fly ash than the cement it replaces.

In small buildings, use of fly ash is preferred as a blend in the cement at the cement plant, due to poor control on the job.

158. WEINHEIMER, C.M. "Fly Ash Disposal—A Mountainous Problem." Electric Light and Power, Vol. 32, No. 5, pp. 90-93, April 1954. See Bibliography No. 31, 56.

Estimates fly ash produced in 1953 at 6,100,000 tons and forecasts possibility of its becoming 16,800,000 by 1963. Dumping near utility is cheapest method, but such locations are getting used up fast. Industry is developing uses for fly ash as admixture in concrete, as a pozzolanic material, and as a blending material for blended cement, and is trying to get favorable freight rates to extend area in which it can be shipped economically. Investigations have been conducted for use of fly ash in soil stabilization with lime, as a raw material for cement and fired brick, as the main ingredient in lightweight aggregate, as a mineral filler in bituminous concrete and asphalt building products, as an ingredient in grouting, and as a source of germanium.

A good market for fly ash disposal should produce revenue, or at least be disposed of with no cost to the producer, must insure a large tonnage, be nonseasonal, and contribute beneficial results to the economy of the country.

Discusses economics of dumping and says that it takes 1.25 to 1.50 cubic yards of dumping space for every ton of fly ash. Average cost of dumping in 1948 was 66 cents per ton with a minimum of 14¼ cents and a maximum of $1.50. By 1954, he estimates the average cost to have risen to 95 cents per ton. In a competitive market, a charge of 22½ cents for pulverizing coal may cause a switch to some other fuel. Fly ash loads pulverized coal with approximately 7.7 cents per ton for disposal. Range of compositions of fly ashes from wide areas:

CHEMICAL COMPOSITION OF FLY ASH

	Percent by Weight	
Ingredient	Minimum	Maximum
Silica, SiO_2	34.01	47.54
Alumina, Al_2O_3	17.50	30.39
Iron Oxide, Fe_2O_3	6.62	26.43
Lime, CaO	0.99	9.68
Magnesia, MgO	0.55	1.63
Sulfur Trioxide, SO_3	0.23	3.59
Loss on Ignition	1.49	19.51
Specific Gravity	2.18	2.63
Fineness Blaine Square Centimeters per gram	2,900	5,400
Passing No. 16 Sieve, %	99.40	100.00
Passing No. 325 Sieve, %	62.4	89.1

Two outlets appear to meet the requirements for a good market. Lightweight aggregate for making block and lightweight masonry units made by autoclaving admixture of fly ash, lime, and an air-entraining agent.

The rate of increase of fly ash seems to be higher than the growth of the markets that are being developed.

159. WILDE, J.R. and STACE, V.A. "Fly Ash: Asset or Liability." Electrical World, Vol. 142, pp. 42-47, April 12, 1954.

Discussion of problems encountered in selling fly ash: (1) Handling and storage facilities required. (2) Largest use so far has been as bituminous filler amounting to 25 percent of Detroit Edison output. (3) Used in concrete and concrete products, paint, putty, rubber, insecticides, etc.

1955

160. ALEXANDER, K.M. and WARDLAW, J. "Limitations of the Pozzolana-Lime Mortar Strength Test as Method of Comparing Pozzolanic Activity." Australian Journal of Applied Science, Vol. 6, No. 3, pp. 334-343, 1955.

Test 5 pozzolanic materials among them fly ash, to determine activity using: (1) Compressive strength and modulus of rupture of lime mortars stored for a fixed period at constant temperature. (2) Tests of lime mortars using weighted mean of strengths with curing at 70, 110, and 160°F.

Conclude that the value of a pozzolan cannot be completely known until it is tested as an ingredient in the actual concrete mix in which it will be used, and under the actual conditions of exposure.

161. ANON. "The Use of Fly Ash in Concrete." Civil Engineering and Public Works Review (London), Vol. 50, No. 583, pp. 70-71, January 1955.

In Great Britain, about 2 million tons of fly ash per year are produced, and expect it to increase to 4 million tons by 1960. Following experience in U.S., they are beginning to use it. Find following uses: (1) Bricks made of 80 to 90 percent fly ash and 10 to 20 percent clay. (2) Concrete with 20 percent cement replacement. Has lower early strength but higher ultimate. Replacement of some sand in addition to cement replacement brings early strength up. (3) Building block which are expected in time to absorb a high proportion of fly ash. (4) Lightweight aggregate—by sintering fly ash. This can be done locally near the power plant producing the fly ash and hauled at low cost to neighboring construction jobs.

162. ANON. "Power Station Waster Makes New Building Material." Civil and Structural Engineers Review (London), Vol. 9, No. 6, pp. 280-282, June 1955. Abstract in Engineering Index, p. 216, 1955.

Discusses development of a two-through cavity concrete block. Solution to high shrinkage of fly ash concrete is solved by using blocks with in-filling. Describe process of manufacture of fly ash concrete, and special machinery for block production.

163. ANON. "Power Station Waste Forms Basis of New Industry." Civil and Structural Engineers Review (London), Vol. 9, No. 11, pp. 516-518, 1955. Abstract in Engineering Index, p. 162, 1956.

Work in Great Britain on production of bricks and concrete products from fly ash. Some 2,000,000 tons available from power plants burning pulverized coal. Fly ash is similar to volcanic ashes used by Romans, but unlike them needs no crushing or pretreatment.

164. ANON. "Commercial Uses for Fly Ash." Coal Utilization, Vol. 9, No. 1, pp. 21-24, January 1955. Abstract in Engineering Index 1955.

Principal commercial uses: Salt water resistant structures, dams, roads, concrete and cinder blocks, ready mixed concrete, lightweight aggregate, and concrete pipe.

165. ANON. "Pulverized Fuel Fly Ash Concrete." Prefabrication (London), Vol. 2, No. 17, pp. 232-233, March 1955.

Efforts to counteract the high shrinkage rate in fly ash concrete block have resulted in a special patented design known as the "Two Through" cavity block.

166. BEARD, EARL. Mimeographed table of Type 1 Portland Cement Mixes, and Equivalent Fly Ash Blended Mixes, 1955. See Bibliography No. 120.

Table showing plain Type I mixes having strengths from 2,000 to 4,000 psi, and 4 to 6 bags of cement with corresponding equivalent mixes using fly ash as part of the cementitious material.

167. BUTTERWORTH, B. "The Problem of Pulverized Fuel Ash Disposal." National Housing and Town Planning Council Journal, Vol. 10, No. 1, pp. 26-29, 1955.

Finds among uses the manufacture of lightweight concrete blocks, fire bricks bonded with clay, and sintered aggregate for concrete.

168. CHICAGO FLY ASH COMPANY. "Suggested Specifications for Strength Concrete Using Fly Ash." Chicago Fly Ash Company, July 26, 1955. See Bibliography No. 183, 234.

Suggest following: (1) Fly ash shall conform to American Society for Testing Materials Designation C350 except modified to permit a maximum SO_3 of 5.0 percent. (2) Use not less than 20 pounds per sack of portland cement nor more than 150 pounds per cubic yard of concrete. (3) Maximum slump, 4 inches. (4) Top size aggregate, 1½ inches. (5) Sand in mix, maximum 45 percent. (6) Air, 3 to 6 percent. (7) Compressive strength at 28 days, 3,000 psi, standard cured.

169. FERET, LOUIS and VENUAT, MICHEL. "The Addition of Fly Ashes to Cement." (De l'Addition de Quelques Cendres Volantes au Ciment). Revue des Matériaux de Construction, No. 475, pp. 87-98, April, 1955. See Bibliography No. 226.

Report detailed test results on four fly ashes with a portland cement and a slag cement, using replacements of 20, 40, and 60 percent by weight of total cementitious material. Also used sand ground to fly ash fineness in same manner and proportions. One of the fly ashes was very coarse. Find: (1) The three fly ashes gave reduced early strengths with portland cement but higher ultimate, the age of equal strengths varying with amount of substitution. The sand substitution gave strength lower than the fine fly ashes, but higher than the coarse fly ash. (2) With slag cement, the strength of the fly ash mixtures remained below the control. (3) On grinding the coarse fly ash, its behavior became similar to the other fly ashes. (4) No definite effect due to fly ash on shrinkage. (5) Caution extending these results to other fly ashes as there are definite differences and each source should be tested before use.

170. GILBERT, J.R. and STEELE, B.W. "Selection of Cement Content for Large Dams." Proceedings, Fifth International Congress on Large Dams, Vol. IV, Paper R. 8, pp. 73-103, Paris, 1955. See Bibliography No. 192, 233, 247, 265.

Choice of type of dam depends on site characteristics and comparative cost. Concrete must have placeability, durability, impermeability, and strength. In arch dams where sections are relatively thin, exposure and strength govern. In buttress dams, upstream face requires strength, impermeability, and durability. In gravity dams, savings in cement can be effected by using lean mixes on inside, and richer and more durable mixes for the few feet of outer exposed surfaces. Manufacture of concrete is an intricate and involved procedure, and must be carefully planned and inspected to obtain optimum results.

In modern planning, air entrainment improves placeability, reduces bleeding and water demand, and increases durability. This permits increased efficiency in construction, and speeds up operations, thus resulting in lowered costs. Aggregate planning is important because uniform rigid quality permits reduction in cement, which cuts costs and reduces heat of hydration. Temperature control planning is important for control of crack formation in mass concrete dams. Pre-cooling and forced cooling, together with cement characteristics, are essential items in planning this phase.

Give example of control at Pine Flat Dam where low Type II cement content, close gradation of aggregates, and temperature control within 30° F were used. In some cases, special cements and cement replacements are used to reduce costs and minimize potential temperature rise. As a result, the

Corps of Engineers initiated an investigation for evaluating various cements and cement replacements on the properties of concrete.

Routine tests consisted of determination of fineness, bleeding, setting time, autoclave expansion, consistency, compressive strength, freezing and thawing, shrinkage and permeability. Freezing and thawing tests were made in an automatic fast cycle machine, in which center of specimen was cooled to 0° F in 1 hour and then warmed to 42° F. Fundamental flexural frequency was determined at frequent intervals, and durability factors calculated at end of 300 cycles. Fly ash was one of the replacements used and was proportioned by solid volume. Water-cement ratios of 0.5 and 0.8 were used to simulate outside and mass concretes, respectively. Materials were rated at constant water-cement ratio and variable cementing materials in Phase 1. Second phase will use constant cementing materials and vary the water content, and the mixes will be rerated on the new basis. Phase 3 will evaluate the materials in full scale mass concrete mixes. Gives test data for Phase 1.

171. JAIN, L.C. and PATWARDHAN, N.K. "Pulverized Fuel Ash as a Pozzolanic Material." Irrigation and Power, Journal of the Central Board of Irrigation and Power (India), Vol. 12, No. 3, pp. 460-471, July 1955.

Review the American and Australian experiences with fly ash, as available in the literature, and conclude from that: (1) Fly ash can be used as a pozzolanic material in concrete and concrete products. (2) Its use as an admixture will result in considerable saving in cement. (3) Exact economy will depend not only from knowledge of required mix in each individual case, but also from existing prices of cement, sand, and fly ash. (4) In addition to economy, the use of fly ash in concrete will impart benefits in quality and in desirable properties.

172. LOVEWELL, C.E. "Fly Ash in Concrete." Construction Specifier, Vol. 7, No. 1, pp. 44-47, Fall 1955.

In addition to fixing lime in hydration of cement, fly ash increases workability of concrete, and thus facilitates placing and finishing.

173. NAGAI, SHOICHIRO, OTSUKA, ATSUSHI, and ISHII, ATSUMI. "Properties of Fly Ash as Portland-Cement Admixture." (Japan), Yogyo Kyokai Shi, Vol. 63, pp. 573-579, 1955.

Authors examined four kinds of fly ash by chemical and electron microscope methods, tests of specimens for expansion in water and milk of lime, alkalinity, bending and compressive strength, and bleeding in the plastic concrete.

174. PEYTON, R.L., STINGLEY, W.M., and MEYER, R.C. "Effect of Pozzolans Added to Sand-Gravel Concrete Pavement." Proceedings, Highway Research Board, Vol. 34, pp. 301-320, 1955. See Bibliography No. 74, 108.

McPherson Test Road, built in summer 1949, has 46 sections using mixes with various cements, 3 pozzolans, of which one was fly ash, with and without air entrainment. Observations to date indicate that performance is not what would have been predicted from previous laboratory work. Test Road designed to find combinations that would inhibit map-cracking with sand-gravel aggregate concrete.

Findings to date: (1) Brand of cement has more effect on inhibiting map-cracking than pozzolans. (2) Only fly ash among 3 pozzolans shows less map-cracking than basic mixes. (3) Deterioration is present in air-entrained concrete to greater degree than non-air-entrained. (4) Durability of all concrete mixes by freezing and thawing, improved by air entrainment to a larger extent than in the fly ash mixes. (5) Field observations do not parallel preliminary laboratory tests. (6) None of the pozzolans have been effective in inhibiting map-cracking as much as limestone sweetening, but fly ash best of three. (7) Measured expansion in field slight for all concretes. (8) Depending on which method of evaluation is used, results appear contradictory. (9) Perhaps suitable combinations of limestone and fly ash may perform better than combinations tried in this road.

175. POWERS, T.C. "Basic Considerations Pertaining to Freezing and Thawing Tests." Proceedings, American Society for Testing Materials, Vol. 55, pp. 1132-1155, 1955.

Discusses mechanism of freezing and thawing, and shows that the standard laboratory tests do not subject the concrete to same conditions as field exposure—mostly by not providing a drying reprieve period between cycles. Suggests method that has drying period and uses measured expansion as criterion of damage.

176. PRICE, W.H. and CORDON, W.A. "Development of High Quality Concrete of Low Cement Content for Large Dams Built by the Bureau of Reclamation." Fifth Congress on Large Dams, Paris, Vol. IV, Question 19, Paper R. 4, pp. 57-71, 1955. See Bibliography No. 194.

Fly ash and air improve properties of mass concrete and lower cement content to as low as 2 sacks per cubic yard. Better workability, lower heat, less water, less segregation, lower permeability, greater resistance to leaching, and reduced expansion due to alkali-aggregate reaction.

177. U.S. BUREAU OF RECLAMATION. "Concrete Manual." 6th Edition, pp. 47-49, 1955. See Bibliography No. 122.

Pozzolans possess little or no cementitious value in themselves but in finely divided form in presence of moisture, react with $Ca(OH)_2$ at ordinary temperatures to form compounds possessing cementitious properties. "Pozzolans are normally not specified for concrete unless there are definite advantages in their use." Concrete containing pozzolan must be thoroughly cured, otherwise resistance to freezing and thawing will be reduced. Pozzolans control alkali-aggregate reaction effectively, but this generally diminishes if calcium chloride is present in a mix. Some pozzolans introduce adverse qualities into the concrete such as excessive drying shrinkage and reduced strength and durability. Pozzolans should be tested in combination with cement and aggregate to be used in specific project to determine advantages or disadvantages, quality of resulting concrete, and economy. If used in too small quantities, pozzolans may induce deleterious alkali-aggregate reaction. Pozzolans generally improve workability and reduce heat generated by hydration of cement. Some of them increase water demand, thus requiring additional cement to maintain water-cement ratio. Fly ash acts as a good pozzolan under certain circumstances.

178. U.S. BUREAU OF RECLAMATION. "Concrete Manual." 6th Edition, pp. 113-115, 1955. See Bibliography No. 121.

Fly ash is an industrial by-product pozzolan. "Some fly ashes significantly reduce the expansion of mortars caused by alkali-aggregate reaction, but others do not." "Fly ash has an unusual effect in that it does not increase the water requirement." Specific gravity controls weight-volume relationship between cement and pozzolan. Use of air-entraining agent can under certain circumstances compensate for increase of drying shrinkage and decrease of freezing and thawing durability. Fly ash has an advantage over most pozzolans in not requiring grinding or calcining, procedures which add to the cost of other pozzolans when needed.

179. VAN DER LEEUW, K.L.A. "The Use of Fly Ash as a Hydraulic Binder." (In Dutch), Cement (Amsterdam), Vol. 7, No. 3-4, pp. 57-58, April 1955.

Cites 14 references on use of fly ash as cement replacement in concrete. Many of these references are American sources. Not all fly ash is suitable for use in concrete, and should be investigated for fineness, origin, etc.

180. WOODFORD, T.V.D. "Fly Ash in Concrete." University of Kentucky Engineering Experiment Station Bulletin, Vol. 9, No. 4, pp. 18-25, June 1955.

Defines fly ash, gives history, defines admixture and how fly ash fits in as a pozzolan, and discusses pozzolanic action. Advantages of fly ash: increased workability, lower water requirement, increased later age strength, reduced bleeding and segregation, reduced heat of hydration of total mix, reduced cost. Stresses fact that enough cement has to be left in the mix to get the desired early strength. Describes briefly Dauphin Island Bridge, Chicago Sanitary District work, Hungry Horse Dam, and Power Plants in Chicago and New York. Concludes that fly ash improves concrete and lowers its cost.

1956

181. ANON. "Pulverized Fuel Ash in Building Materials." Building Research Station Digest (London), No. 92, 4 pp., September 1956.

Fly ash is used as a replacement of, or additive to cement in concrete; as ash mortar; unprocessed as aggregate or filler; sintered as concrete aggregate; in clay bricks containing fly ash; and as a filler for bituminous concrete and products.

182. BRINK, RUSSEL H. and HALSTEAD, WOODROW J. "Studies Relating to the Testing of Fly Ash for Use in Concrete." Proceedings, American Society for Testing Materials, pp. 1161-1214, Vol. 56, 1956, also in Public Roads, Vol. 29, pp. 121-141, February 1957. See Bibliography No. 200.

General discussion of use of fly ash in concrete reporting results of tests in Bureau of Public Roads laboratory, with principal findings: (1) Effect of replacement on mortar strength varies with cement and amount of replacement. Used 34 fly ashes (10, 20, 35, and 50 percent replacement by weight) and 3 cements, with graded Ottawa sand. (2) Greatest benefit in leaner mixes. (3) Carbon lowers strength because it increases water requirement and reduces active pozzolanic material. (4) Fineness by air permeability had no relation to strength. (5) Strength, however, varied with fineness as determined by percent passing No. 325 sieve—the finer, the better. (6) General relationship of water required and strength—the less water, the higher the strength. (7) No relationship between inorganic constituents and pozzolanic efficacy. (8) Reaction of silica with sodium hydroxide for determination of pozzolanic activity is not satisfactory because lime or $CaSO_4$ in fly ash interferes. (9) Lime absorption test was not significant for determining pozzolanic activity. (10) Lime-fly ash mortar tests cured at 130^0 F did not correlate with mortar strength tests. (11) Fly ash will inhibit alkali-aggregate reaction if used in sufficient amounts. (12) Suggest test methods and basis for specifications and give detailed test methods in appendix.

A discussion on several points is appended to the ASTM version.

183. CHICAGO FLY ASH COMPANY. "Chicago Fly Ash in Quality Concrete Mixes." AIA File 3-B-2, 1956. See Bibliography No. 168, 234.

A general discussion of liberation of lime in concrete and how fly ash combines with the lime to form stable compounds. Discusses properties of fly ash, its chemical activity and, the increased workability of concrete mixes. Covers mix redesign, workability, impermeability, resistance to sulfate, alkali reaction. Contains bibliography.

184. CHUBBUCK, EDWIN R. "A Study of the Effect of SO_3 in Fly Ash and Suitable Limits for SO_3 in Fly Ash." Semi-Final Report, Kansas State College, January 1956.

Using fly ash with varying SO_3 content (0.95-17.0) and Lone Star cements Type 1 with 3.00 percent SO_3 (high) and 1.25 percent SO_3 (normal), find solubility by ASTM C 265-51 T is small as compared to SO_3 content. Exposes beams to: (1) Exposure 2 (130° F drying 8 hours, then in water 16 hours at 75° F). (2) Exposure 10 (continuous water spray changing automatically from 130° F to 70° F and back again with 32 cycles per 24 hours). It takes 4 months for 3,000 cycles of exposure 10, which is considered equivalent to 1 year of exposure 2, and which is considered as the length of time required to evaluate expansion and map-cracking potential of concrete mixes. (3) Field exposure for 5 years. (4) Modulus of rupture and compressive strength.

Finds: (1) Apparently no harmful effects due to SO_3 contents of fly ash—control specimen (no fly ash) gave higher expansion. (2) Cannot place limits as result of conclusion No. 1. (3) SO_3 in fly ash not interchangeable with SO_3 in cement. (4) In general, expansion seems to decrease until fly ash SO_3 reaches about 5 percent; then it starts increasing. Only high SO_3 cement with high SO_3 fly ash gave expansion as high as control. In no instance was it objectionable, however.

185. FERET, L. "Addition of Fly Ash to Cement." Centre d'Études et de Recherches de l'Industrie des Liants Hydrauliques, Technical Publication No. 7, 30 pp., April 1956. (In French).

Resistance to compression and tension of cement mixtures containing 20, 40 and 60 percent fly ash were compared with mixtures where fly ash was replaced with inert material. Fine fly ash seems to have pozzolanic properties after several weeks. Shrinkage of the concrete is unaltered.

186. FULTON, A.A. and MARSHALL, W.T. "Use of Fly Ash and Similar Materials in Concrete." Edinburgh Institution of Civil Engineers, Paper 22 pp., January 1956. Abstract in Fuel Abstracts, Vol. 20, No. 1, p. 511, July 1956. See Bibliography No. 187, 254.

Factors relating to the effect of fly ash size and composition on water-cement ratio is outlined. Tables collate data on various samples of fly ash and the effect of fly ash constituents on the properties of the resultant concretes.

187. FULTON, ANGUS A. and MARSHALL, WILLIAM T. "The Use of Fly Ash and Similar Materials in Concrete." Proceedings, Institution of Civil Engineers, Vol. 5, Part 1, No. 6, pp. 714-730, November 1956. See Bibliography No. 186, 254.

Summary of work of Davis, U.S.B.R., and visits to dams in U.S. British requirements are different than U.S. and they do not use air-entrainment as freely, therefore the variation in carbon content of fly ash is not as important a problem. Fly ash under these circumstances shows more apparent improvement in workability. Stresses lack of popularity of fly ash among field forces in U.S. because it increases problems of control.

The authors' reaction to visit at Portland Cement Association in Chicago:

> "Not unnaturally, the American Portland Cement Association did not favor the substitution of fly ash for cement. Their view was that there were too many uncertainties and it was possible to get fly ash which would not behave as desired. Their chemist was of the opinion that fly ash did not improve the resistance to aggressive waters, his argument being that even though free lime did combine with silica, the calcium silicate so formed tended to be nearly as soluble as free lime."

Conclude that where delayed strength can be accepted, substitution of 20 percent by weight of fly ash will give a more workable concrete with improved resistance to weathering.

Discussion: Proceedings, Institution of Civil Engineers, Vol. 7, pp. 658-672, July 1957.

Bryand Mather. Claims that their account of Waterways Experiment Station work was garbled and gives corrections.

N. C. Smyth. Fly ash made possible the pumping of lean concrete up to 400 feet at Bold "B" Power Station, St. Helens. Gives precautions taken to "lubricate" pipe before starting of pumping of regular mix. Substitution of portion by equal weight of fly ash increased workability of lean mixes, and 5 percent fly ash addition, without cement decrease, gave adequate safety margin against stoppage of pipe line. Fly ash should not be used with low-lime cements. Reduction of heat generated was an advantage in reducing shrinkage stresses even though form stripping time had to be increased in cold weather.

J.A.C. Beake. Describes operation on one of the dams of North of Scotland Hydro-Electric Board in which 20 percent fly ash was used as a substitution for cement. Batching was in a fully automatic plant which is described in some detail. Fly ash seemed to have affinity for slightest moisture and caused "balling" which stopped flow at times. Most stringent measures to keep things dry were used. Fly ash particles were highly abrasive and caused excessive wear of mechanisms they settled on. Carbon content was erratic. Use of fly ash was fraught with pitfalls for the contractor—a lot of problems have to be solved before it becomes a good commercial proposition.

M. F. Kennard. Asks questions relative to effect of lower early strength on tunnel grouting and concrete requiring form stripping, and the delay caused in this operation. Also, how control of mixes is obtained with fly ash of variable water content.

William Young. At Lubreock Dam, maximum carbon content of 10 percent in the fly ash was specified. Also, 70 percent of the strength of plain concrete at age of 7 days was required. With 20 percent fly ash, an average of 75 percent of the 7-day strength and 78 percent of the 28-day strength were obtained. There was definite evidence of increased workability, but other problems developed.

Fly ash was delivered from a power plant 90 miles away by tarpaulin-covered truck. Tests made on the material in the truck were telephoned to the job, but it was too late by then, as the truck was already on the way. On the job visual comparison of color, against samples containing different carbon contents, was made. Mechanical difficulties necessitated slow tipping of truck bodies with resulting 20-minute emptying time for 6 tons. Machinery bearings gave trouble from fly ash dust. Clogging of chutes, corners, and gates were experienced in damp weather, more air and steeper chutes were required than for portland cement.

C.K. Haswell. Notes British experience—increased workability and reduced cost, which may overshadow authors' reduced heat of hydration and resistance to aggressive waters found of importance in Scotland. In America, savings in spite of long haulage were important in decision to use fly ash on Hungry Horse. Fly ash makes for easier pumpability of concrete. Carbon is not the only variable affecting strength—fineness is also a factor. Carbon content depends not only on coal burned in boilers, but also on rate of change of load. Shrinkage is a function of amount of water used. Savings depend on distance from source. Cost of disposing of fly ash should be subtracted from handling costs to arrive at net cost or saving. Feels that authors' conclusions regarding quantity of replacement and build-up strength are conservative. In England, also, the cement interests do not seem to take advantage of possible use of fly ash in cement manufacture.

A.C. Allen. Gives experience at Lednock Dam where it was found that increased carbon reduced strength and rate of strength gain. Strength loss was more than would be obtained had carbon been replaced by an equivalent inert material. Increase in carbon was generally accompanied by increase in iron oxide and combined sulfuric acid, and therefore decrease in useful alumina and silica. Fineness seemed to affect workability more than it did strength. It was not considered, as a result, as essential to have high fineness as to have low carbon. Method of measuring fineness does not seem appropriate, because carbon particles are of a different specific gravity than other ash particles. Practical advantages of using fly ash on this dam turned out to be the removal of laitance from the top of a concrete layer by water and brushes the day following placement, and the lower temperature rise which contributed to less thermal surface cracking. The substitution of fly ash from nearby plants for portland cement should prove attractive economically, but closer control will be required to obtain the same uniformity.

Closure. Thanked everybody and realized that use of fly ash could not be free from criticism at the outset, but grateful that so many agreed with the authors' general conclusions.

188. HESTER, J.A. and SMITH, O.F. "The Alkali-Aggregate Phase of Chemical Reactivity in Concrete—Part II." American Society for Testing Materials, Special Technical Publication No. 205, pp. 74-90, 1956. See Bibliography No. 122.

Field observations to supplement Part I, which outlined the chemistry involved. The previous conclusions applicable to the field study are: (1) Reaction between alkali and aggregate is greatly aided by the regeneration of the alkali by the lime. (2) Reactivity between comparatively low alkali concentrations and aggregates will proceed under favorable conditions. (3) From controlled mortar bars that were allowed to react for 46 months, it was found that total acid soluble silica in each bar varied directly with the alkali content and total expansion. (4) By addition of controlled amounts of finely divided silica, it is possible to reduce or eliminate expansion in concrete due to alkali-aggregate activity.

As a result of last conclusion, fly ash has been added to the list of silicious materials under laboratory investigation.

Several structures and pavements in Alabama already contain Barry fly ash having an average ignition loss of 4.34 percent, and average specific surface of 2,600 (Blaine). Of these structures, the Dauphin Island Bridge is the largest, and contains fly ash as a 20 percent by weight replacement for Type II cement. The caps and encasement concrete contains 4.96 sacks of cement per cubic yard, while the deck contains 5.76 sacks per cubic yard of concrete.

Compared to control mix without fly ash containing 6.2 sacks of cement, the fly ash concrete had better workability and practically no bleeding. Compressive strengths of over 9,500 psi were obtained at the age of one year for the fly ash concrete. From chemical analyses, it was found that the fly ash in the mixture increased the SiO_2 by 7.28 percent, and slightly reduced the Na_2O equivalent as compared to the original cement. This tends to tie up the free lime produced by the hydration of the cement before all the alkali from the cement is released.

Conclude: (1) Variations in effect of alkali-aggregate reaction in a structure containing reactive aggregate and same cement is primarily due to variations in type, sizes, and amounts of reactive materials in the aggregate, and differences in exposure to moisture and sunshine. (2) Not only high alkali cement, but also medium and low alkali cements seem to produce alkali-aggregate reaction in structures. (3) Low alkali cement takes longer to produce reaction, and when produced it is less severe than the higher alkali cements. (4) The white gel formed as a result of alkali-aggregate reaction is similar in composition for both high and low alkali cements. (5) Chemical and physical investigations of the fly ash concrete give indication of the rate of reaction between cement and fly ash. Fly ash produces beneficial results in workability, strength, and economy. (6) Pure hydrous silica gives best results of all pozzolanic materials investigated.

189. HOMSHER, J.G. "Developing Fly Ash Outlets." Edison Electric Institute, Purchasing Stores Committee, May 7-9, 1956.

Sent out questionnaires and received 32 answers. Expect total fly ash production of 13,700,000 tons annually, by 1963. Most of sales now are for concrete, concrete products, and bituminous filler. About 7.5 percent of present production sold, at prices ranging from $0.44 to $7.00 per ton. Discusses sintering and selling through brokers. Urges interchange of information. Forecasts 17,000,000 tons, eventual annual production.

190. KINNIBURGH, W. "Lightweight Aggregate from Pulverized Fuel Ash." Concrete and Constructional Engineering, Vol. 51, No. 12, pp. 571-574, December 1956.

Describes fly ash, and sintering process after pelletizing, to make it useful for block manufacture and lightweight concrete. Gives information of mixes and strengths.

191. LEA, F.M. and DESCH, C.H. "Pozzolans and Pozzolanic Cements." The Chemistry of Cement and Concrete, Chapter XIV, St. Martin's Press, Inc., N.Y.C., 1956.

Classify natural and artificial pozzolans, discuss pozzolanic reaction with lime, and give history and uses in Europe. Fly ash is used more in U.S. than abroad. As long as carbon remains under 10 percent, fineness is more important than carbon content. In concrete only 66 percent of strength developed at 28 days. Feel that 20 percent substitution is better than higher proportions. Require long period of wet curing. Workability about same as plain concrete. Heat of hydration is reduced. Expansion and shrinkage are little affected. Permeability is decreased at later ages. Frost resistance lower than plain portland cement concrete when freezing is started at 28 days, but if started at 6 months or later fly ash concrete equals plain concrete. Reduces entrained air. Abrasion resistance is lowered particularly at early ages. Inhibits alkali expansion. Increases resistance to sulfate and sea water attack. Impermeability and protective films of calcium silicate, products of the lime-pozzolan reaction, protect the more vulnerable alumina compounds.

192. MATHER, BRYANT. "The Partial Replacement of Portland Cement in Con-

crete." American Society for Testing Materials, Special Technical Publication No. 205, pp. 37-73, 1956. See Bibliography No. 170, 233, 247, 272.

Tests on various cements, pozzolans, and admixtures. Fly ash is included. Judges value of replacements on basis of equal water-cement ratio. Concludes: (1) Replacement with 35 percent natural cement improves structural concrete (0.5 water-cement ratio) and mass concrete (0.8 water-cement ratio), over control concrete. (2) Replacement with 12 percent uncalcined diatomite improves mass concrete and equals structural control concrete. (3) Replacement with 30 percent calcined shale improves mass concrete but worsens structural over control concrete. (4) Other 10 materials used as replacement lead to less desirable results.

193. NURSE, R.W. "Utilization of Fly Ash for Building Material." Journal Institute of Fuel, Vol. 29, No. 181, pp. 85-88, 1956. Abstract in Ceramic Abstracts, Vol. 39, No. 6, p. 116-11-h, June 1956.

Work done on brick containing 85 percent fly ash and 15 percent plastic clay, and sintering fly ash for lightweight aggregate. Gives data on fly ash as a pozzolan.

194. PRICE, WALTER H. "Fly Ash in Heavy Construction." Presented at Conference on Fly Ash sponsored by the Electrical World, Pittsburgh, July 30 to August 1, 1956. Synopsis in Electrical World, Vol. 146, No. 9, August 27, 1956. See Bibliography No. 176.

Summary on use of fly ash by U.S. Bureau of Reclamation, gives latest U.S. Bureau of Reclamation specification on fly ash and an extensive bibliography. Defines pozzolan and brings out fact that particles are silicious, in the form of glass spheres. Gives data on Bureau dams using fly ash and other pozzolans and also strength curves. Loss in handling about twice that of cement due to higher fineness. Apart from economic considerations, pozzolans in general and fly ash in particular have following advantages: (1) Combine with lime liberated during cement hydration to produce more stable products which are not as easily leached from the concrete and are more resistant to chemical attack. (2) Contribute to ultimate strength of concrete. (3) Produce lower heat of hydration. (4) Make concrete more impermeable. (5) Reduce alkali-aggregate reaction—30 percent or more fly ash replacement provides usually adequate protection for this purpose. (6) Fly ash adds to workability and reduces drying shrinkage.

High carbon introduces difficulties by lowering strength and increasing air-entraining agent requirement. Bureau specifications limit carbon by limiting loss on ignition to 5.0 percent, and reject fly ash that requires more than double the amount of air-entraining agent as compared with control mix.

195. ROTTER, W. "Utilization of Coal Ashes." Brennstoff-Warme-Kraft, Vol. 8, pp. 584-587, 1956. Abstract in Building Science Abstracts, Vol. 30, No. 7, paragraph 1166, July 1957.

When plotted on a ternary diagram for CaO-SiO_2-Al_2O_3 the composition of fly ash samples from Austria, Belgium, Germany and U.S. fall well within the area of brick clays. To produce a satisfactory burned brick, it is necessary to add 10 to 30 percent clay or loam and 8 to 20 percent water. The density of the brick can be varied over a wide range. Heat conductivity data for fly-ash brick are given and compared with porous concrete and kieselguhr insulating material for temperatures up to 800^0 C ($1,470^0$F).

196. SMITH, E.J.D. "The Sintering of Fly Ash." Journal Institute of Fuel, Vol. 29, No. 185, pp. 253-260, 1956. Abstract in Building Science Abstracts, Vol. 29, No. 12, Paragraph 2079, Dec. 1956.

Sintering curves are shown and discussed, and a robust but sensitive dilatometer for measuring onset of sintering is described and discussed. This dilametric method has been used to demonstrate influence of particle size on commencement of sintering, and the effect of thin condensed water soluble alkali deposits on the surface of the particles. The effect of the iron oxide content on the sinter point has also been studied.

197. TEBAR, DEMETRIO G. "Fly Ash as a Material of Construction." Consejo Superior de Investigationes Cientificas (Spain), Instituto Tecnico de la Construccion y del Cemento, Publicationes No. 175, 18 pp., 1956.

Gives an account of tests using Spanish fly ash mixed with portland cement. Use 30 percent replacement in concrete or as a primary material to manufacture so-called lightweight lime concretes.

198. THOMSON, HARRY F. "Verify Quality of Fly Ash Before Using." Pit and Quarry, Vol. 48, pp. 266, 293, January 1956. See Bibliography No. 199.

Brings out differences between individual fly ashes and discusses following: (1) Pozzolan and pozzolanic activity. (2) Limits on loss of ignition. (3) Fineness and spherical shape of particles and their effect on mix. (4) Inhibition of alkali-aggregate reaction. (5) Use as cement "stretcher." (6) Replacement of 20 percent by weight of cement will increase strength after 28 days. (7) Replacement of 1 pound of cement with 1½ pounds of fly ash, and re-design of mix gives 28-day strength equal to plain concrete. (8) Increase air-entraining agent requirement. (9) Air entrainment necessary if subjected to weathering. (10) Accelerated strength gain by use of higher curing—100^{0} F for 28 days equal to 90 days at 73^{0} F. (11) Lower water requirement for fly ash of low carbon and high fineness. (12) Tests are necessary to detect differences in properties and eventual cost of fly ash concrete.

199. THOMSON, HARRY F. "Role of Fly Ash in Precast Products." Pit and Quarry, Vol. 48, pp. 165-168, February 1956. See Bibliography No. 198.

Reviews role of fly ash in structural concrete, its early low strength and increased later strength with replacements of pound for pound. Calls attention to harmful effect of high carbon. Says that replacement of 1¼ to 1½ pounds per pound of cement will give 28-day strength equal to plain concrete. In precast products, curing at high temperatures, strength gain is faster, thus overcoming lowered early strength of fly ash mixes. Fly ash holds more water and thus permits better mix. In pipe, it decreases permeability and leaching. It gives a better finish, particularly in packer-head process for pipe making. Reduces cost and stretches cement, except in pipe where a minimum of 6-sack concrete is specified. Increases resistance to sulfate and weak acids—advantageous in sewer pipe and pipe in active soils.

200. TIMMS, ALBERT G. and GRIEB, WILLIAM E. "Use of Fly Ash in Concrete." Proceedings, American Society for Testing Materials, Vol. 56, pp. 1139-1160, 1956. Also in Public Roads, Vol. 28, pp. 142-150, February 1957. See Bibliography No. 182.

Concrete mixes using 4 fly ashes of the 34 used in mortar study, and two of the cements, find: (1) Low early strengths but higher strengths than control at 1 year, except in large replacements (volume replacements of 16⅔ and 33⅔ percent) with high carbon fly ash. (2) The same for flexural strength except that everything was higher at 1 year. (3) Non-air-entrained concrete with and without fly ash had poor resistance to freezing and thawing. (4) Good durability on freezing and thawing (200 slow cycles) with air-entrained concretes, with and without fly ash except for high replacement with high carbon fly ash. (5) Characteristics of cement affect durability and strength of fly ash mixes. (6) Fly ash concrete showed less drying shrinkage than plain concrete. (7) Calcium chloride attacked non-air-entrained concrete severely with and without fly ash. (8) Air-entrained concrete without fly ash had good resistance to calcium chloride, but less with fly ash (33⅓ substitution). (9) Amount of air-entraining agent to obtain a given air content increases with carbon content of fly ash.

201. TROXELL, GEORGE E. and DAVIS, HARMER E. "Composition and Properties of Concrete." McGraw-Hill, pp. 72-73, 1956. See Bibliography No. 140, 141.

Fly ash has been used successfully as a pozzolan. "For successful use of portland-pozzolan cement at normal temperatures, sustained moist curing is important." This is because moisture is necessary for the reaction between the pozzolan and the liberated lime. In massive structures use of pozzolan saves cement and reduces heat generated, and therefore, thermal volume change. Pozzolans also tend to lessen attack of aggressive waters containing salts and sulfates, tend to reduce permeability, especially in lean mixes, lessen harmful reaction of aggregate with alkalis, improve workability, and reduce bleeding and segregation. With lean mixes strength is often increased, while with rich mixes it is generally decreased. "Disadvantages lie in the relatively slow rate of strength development and the possibility that in exposed sections, if special attention is not given to maintaining moist conditions and temperatures sufficiently above freezing, serious deficiency in strength and low durability may result." Pozzolans should be tested with cement and aggregates for each specific job to ascertain suitability. Some pozzolans may result in undesirable effects, such as drying shrinkage, reduced strength and durability, and if used in insufficient amounts, may cause deleterious reaction with cement alkalis.

202. TROXELL, GEORGE E. and DAVIS, HARMER E. "Composition and Properties of Concrete." McGraw-Hill, pp. 210-211, 1956. See Bibliography No. 139, 141.

Some pozzolans counteract effect of alkalies in high alkali cement with reactive aggregates. "Some test data indicate that the amount of pozzolanic material required is about 20 grams of finely divided reactive silica per gram of alkali in the cement in excess of 0.5 percent." (Powers and Steinour paper).

203. TROXELL, GEORGE E. and DAVIS, HARMER E. "Composition and Properties of Concrete." McGraw-Hill, pp. 238-239, 1956. See Bibliography No. 139, 140.

"However, replacements of fly ash (a pozzolanic material), treated diatomaceous earth, certain water-quenched ground slags, or lime do not change the shrinkage characteristics to an appreciable degree." (This is in connection with a discussion on effect of admixtures on shrinkage of concrete.)

204. VAN DE FLIERT, C. "Fly Ash in Concrete." (In Dutch) Ingenieur, Vol. 68, No. 7, pp. 9-17, February 1956. Abstract in Engineering Index, p. 163, 1956.

Studied use of fly ash in concrete. Finds substitution of 10 to 30 percent of suitable fly ash favorable to workability, density, ultimate strengths, shrinkage, heat of hydration, resistance to aggressive liquids, etc.—possibility of using fly ash as partial replacement of cement or sand in normal and lean concrete.

205. WELCH, G.B. "Use of Fly Ash Materials in Concrete." Commonwealth Engineer, Vol. 43, February 1956 and March 1956. See Bibliography No. 170.

Report is in two parts: (1) Fly ash is fine residue recovered by precipitation from flue gases, which would otherwise be discharged from stacks, creating a dust nuisance. (2) It has been used in U.S. both as a cement replacement and as an admixture. (3) Fly ash consists of a large proportion of spherical particles of fused residue high in silica content. The pozzolanic action may be regarded as a combination of the silicious material with the calcium hydroxide liberated during the hydration of the cement to form cementitious compounds. (4) Use of fly ash replacement results according to U.S. work in improved workability, reduced segregation and bleeding of the plastic concrete, lowered heat of hydration, and improved durability, and sulphate resistance. Strengths are usually reduced at early ages, and prolonged curing is required to gain potential strengths. (5) In Sydney, Australia, 100,000 tons of fly ash are produced each year from 4 principal power stations—Pyrmont B, Ultimo, White Bay, and Bunnerong. (6) Fly ash samples from these stations were tested, together with a sample from East Perth Power Station in Western Australia, and from Chicago (Unit 17 Fisk Station). (7) Table compares chemical analyses with USBR and ASTM Specifications. All had loss on ignition below 10 percent except Bunnerong, which was 16.7 percent, while the Chicago fly ash showed 5 percent, East Perth 2.7 percent, and the other Australian stations 8 to 9.5 percent. (8) Normal cement was used for the tests on comparison of pozzolanic properties and low heat cement for the replacement and concrete tests—both cements being low alkali (about 0.50). Sydney beach sand, FM 1.75, was used for the general investigation and Nepean "standard sand" for the mortar replacement tests. Nepean river sand and gravel were used for all concrete tests. Tests made according to USBR methods. (9) Specific gravities ranged from 1.88 to 2.00, except East Perth, which had 2.49 and Chicago 2.39. Specific surface (Blaine) ranged from 2,360 to 4,400, with East Perth 3,630, and Chicago 3,600. (10) In mortar tests, replacement was 35 percent by absolute volume, tested at same consistency, and therefore, variable water-cement ratio with variations in water requirement. Storage of mortar cubes was in sealed containers at 100° F for 27 days after stripping, then air cured in laboratory till time of test. For mortar bar expansion, alkali was added artificially to mix, to get positive values of volume change. (11) Tests on Pyrmont B fly ash were on variable replacement basis to obtain compressive strength-age characteristics—for this, curing was at 70° F in water storage. (12) Tests were also made on treated fly ash—coarse particles separated, resulting in lower carbon, and in other cases ignited at 950° C to reduce carbon. (13) Concrete tests used 30 percent by weight replacement with normal water curing at 70° F. (14) No sharp line of demarcation between satisfactory and unsatisfactory fly ash—most investigators agree that advantages of fly ash decrease with increase in carbon, although this may have been overemphasized because of the usual occurrence of high carbon with low fineness in the past—Davis has indicated that satisfactory results may be expected with as high as 17 percent carbon if fly ash is sufficiently fine. Sydney fly ash has about 9 percent carbon as compared with less than 6 percent for Chicago. Sydney fly ash has about the same alkali content as U.S. (1.25-1.30 Na_2O equivalent), but it has, in general, higher silica, higher alumina, and lower iron contents than U.S. fly ashes. Significance of these factors is not known. (15) Fineness appears to be no less important than carbon content—Sydney fly ashes, although not having high specific surface values, compare reasonably well with better U.S. fly ashes. They have high percentages retained on No. 325 sieve, from 17 to 52 percent as against 12 percent for recommended maximum. (16) Specific gravities of Sydney flyashes are lower than the typical 2.2 to 2.5 reported for U.S., and do not exceed 2.15 even after sieving out coarser carbon particles, or igniting. (17) Water requirements are 110-130 percent as compared to about 100 percent for Chicago fly ash. (18) 28-day cubes do not show as good a gain ratio as Chicago, but activity was improved in the sieved fly ash. (19) Reduction in alkali-aggregate reaction was not reliable. (20) Mortar strength for 25 percent replacement by absolute volume was lower than control up to test ages (180 days), while with 14 percent replacement, it about equaled it. With 15 percent admixture, the strength exceeded control at all ages. (21) In concrete, the 10 percent replacement exceeds control at about 60 days, 20 percent at about 100 days, and higher replacements are below control at all ages. Mortar is more sensitive to variations in fly ash than concrete.

Conclude: (1) Sydney fly ashes are inferior to the better U.S. products. (2) Best Sydney do not comply with USBR specifications, with respect to percent retained on No. 325 sieve, water requirements, or compressive strength gain. (3) The better Sydney fly ashes showed marked pozzolanic activity, and equal strength might be anticipated with less than 12 months moist curing, and up to 30 percent cement replacement. (4) Improved workability and gain in strength are anticipated with the better fly ashes.

206. WITHEY, NORMAN H. "Use of Fly Ash in Block Mixes." National Concrete Masonry Association, Technical Report No. 56, 8 pp., March 22, 1956.

Fly ash may be defined as the finely divided powder collected by precipitators from flue gases of coal-burning boilers. Fly ash acceptable for use in concrete contains a total of at least 70 percent silica plus alumina and iron oxide.

These constituents are highly pozzolanic—reactive with lime. Tests conducted by G.W. Washa at the University of Wisconsin, on the effect of various amounts of fly ash in sand-gravel block mixes, and effects of various curing procedures on the flexural strength and toughness properties of block-type concrete indicate: (1) Curing temperatures above 160° F increase the early age toughness of the blocks. (2) With low pressure steam curing, 15 to 30 percent fly ash can be used in the mix. (3) With high pressure steam curing up to about 50 percent fly ash may be employed.

By the use of fly ash in block manufacture, it is found that the required strength can be obtained with improved finish and texture, better corners, better mold life, and improved plasticity of the relatively harsh block mixes.

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207. ANON. "Aggregate from Pulverized-Fuel Ash." Concrete and Constructional Engineering (London), Vol. 52, No. 5, pp. 255-256, July 1957.

Describes plant in England costing 260,000 pounds sterling, in which ash is pelletized then is sintered to form aggregate known as Terlite, weighing 52 pounds per cubic foot. Concrete made of 1 part cement and 8 parts aggregate with no fines, weighs 68 pounds per cubic foot and has a strength of 600 psi. A mixture of 1 part cement, 2 parts fine aggregate, and 3 parts larger aggregate weighs 92 pounds per cubic foot, and has a strength of 3,000 psi. Shrinkage on drying is about 0.025 percent, and it is found to be a good insulator and to resist fire. It is nailable and provides key for plaster.

Gives tests and recommended water-cement ratios.

208. BRECKENRIDGE, R.H. "Utilization of High Lime Fly Ash in Concrete." Reprint of paper given at 1957 American Concrete Institute Convention at Dallas, February 1957.

Fly ash was used up to 30 percent by volume replacement. Finds that 7-day strengths are in general low, 28-day strengths about same as control, and

90-day strengths higher. Workability is improved. Less water is required, improving water-cement ratio, and thus increasing strength. Used 5- to 6-bag mixes. Reduces cost of materials in mix.

209. BURTON, CONWAY. "Use of Fly Ash in Bituminous Mixtures." Chicago Testing Laboratory, April 5, 1957.

Using fly ash from Stateline Units 1, 2, and 3, and from Marysville Plant of Detroit Edison, limestone dust from Thornton, as filler materials, and aggregates and asphalt cement, made various mixtures and tested by Marshall method both by standard procedure, and after 14-day immersion in 120° F water. All give satisfactory mixes. Sources of fly ash made no difference.

210. FLACK, H. L. "The Freeze-Thaw Resistance of Concrete as Affected by Method of Test." Proceedings American Society for Testing Materials, Vol. 57, pp. 1077-1095, 1957.

Tests made at Bureau of Reclamation using several cycles including four ASTM methods, indicate essentially that: (1) Freezing and thawing resistance of fog cured specimens, directly proportional to length of fog cure. This is improved if fog curing is stopped at 7, 14, or 28 days, and specimens stored in 50 percent relative humidity atmosphere. (2) Air-entrained concrete under moist freezing and thawing tests absorbs less water than non-air-entrained concrete. (3) Large differences in results of freezing and thawing tests when performed in different media (air or water). (4) Less variability in slow water freezing and thawing test than in others. (5) In spite of variations in tests, all five test methods used, evaluated concretes in same relative order. (6) Regardless of method, air-entrained concrete was much more durable than non-air-entrained.

211. FOUILLOUX, P. "Pozzolanic Slag Cements of High Chemical Resistance and Normal Strength Gain." (Ciments aux Pouzzolanes à Haute Résistance Chimique et Durcissement Normal). Revue des Matériaux de Construction, No. 502, 191-196, July 1957. See Bibliography No. 121, 240.

Most fly ashes possess pozzolanic properties. In the United States, this has been known for many years and utilized in concrete mixes as substitution for cement in mass concrete in dams, notably in Hungry Horse, where 30 percent replacement by weight was used. But the pozzolanic properties of fly ash are not utilized to the utmost by substitution of equal weight for cement in concrete.

No matter how fine a fly ash may be, it is evident that a pozzolanic cement prepared at the mill, using fly ash interground with cement clinker, assure a more homogeneous mixture as well as an increase in the fineness of the amorphous silica grains, all of which has the effect of intensifying the pozzolanic action and accelerating its release.

It does not seem that American cement plants have yet shown any interest in producing pozzolanic fly ash-cements. This even though a qualified representative of the American cement industry, E.A. Ledyard, wrote in Rock Products, December 1947:

> "Since at this time, it is quite clear that portland-pozzolan cements are serving well a definite and important need,... it appears that the time is over-ripe when the portland cement industry should realize the importance of these implications and lend their support and talents to a complete and constructive study of the pozzolanic materials and portland-pozzolan cements.... Some who read this article may obtain the impression that the writer is not of the portland ce-

> ment industry, but this is not the case. He is of the industry and has the interest of the industry very much at heart. He is concerned chiefly with having the industry turn out the very highest quality products at all times, and feels that industry had done themselves no favor by not recognizing the potentialities of pozzolans and doing something about developing them."

This, even though fly ash with pozzolanic qualities are very abundant in the United States.

If, in spite of the interest of the Americans in utilizing fly ash, the American cement industry has not shown interest in the production of fly ash pozzolanic cements, it is because pozzolanic cements have the inconvenience of slow strength gain at early ages, irrespective of the quality of the pozzolan used, and the fineness of the grind.

Therefore, before the practical utilization of the pozzolanic properties of fly ash could be accomplished, it was necessary to find a procedure which would develop a strength gain curve approaching that of portland cement, thus making it the product useable in all common concrete, reinforced concrete, or prestressed concrete, and not only in mass concrete as used mostly heretofore.

The author tried to find a solution to this problem, with the restriction that calcium chloride, sodium sulphate, or other accelerators would not be used. The findings from this work are: (1) Pozzolans in general, and fly ash with pozzolanic properties in particular, do not show the slow strength gain in tertiary mixtures of pozzolan plus portland cement plus blast furnace slag, that they show in a binary mixture of pozzolan plus portland cement. That is, the pozzolanic action starts much earlier and with more intensity when the pozzolan is in the presence of proper mixtures of portland cement and slag than in the presence of portland cement alone. (2) It is possible to obtain mixtures of portland cement, pozzolan, and properly chosen slag, composite cements which possess all the best properties of pozzolanic cements, yet with a strength gain similar to the best portland cements, and with higher ultimate strengths.

This discovery was most surprising, inasmuch as slag in cement, used as a binary mixture (portland plus slag), shows slow strength gain. The patent resulting for this discovery was granted April 5, 1951, and La Société des Matériaux de Construction de la Loisne operating under license, placed on the market on October 3, 1951, pozzolanic slag cements, known as C.P.-M.F. No. 1 (160/300), and C.P.-M.F. No. 2 (250/275). In addition to higher early strength and very high ultimate strength, these cements develop very high resistance to aggressive waters.

The cements met with great success, judged by the large quantities being used. They have been accepted by the Public Works Ministry for use in salt water, and by the City of Paris. Official tests made at regular intervals indicate that a 1:3 mortar with C.P.-M.F. No. 2, develops strengths (kilograms per square centimeter):

2 days	149 (2,120 psi)
7 days	273 (3,870 psi)
28 days	438 (6,200 psi)
90 days	580 (8,250 psi)

In France, portland cement standards call for 7-day and 28-day mortar strengths as follows (first figure gives 7-day strength and second figure the 28-day strength):

Portland cement	160/250 (2,270/3,550 psi)
Portland cement	250/315 (3,550/4,450 psi)
High Early Strength P.C.	315/400 (4,450/5,700 psi)
Super cements	355/500 (5,050/7,100 psi)

Thus, C.P.-M.F. No. 2 not only meets the requirements of the best French portland cements, but by its continued strength gain, ultimately surpasses the strength of super cements. These strengths of the pozzolanic slag cements were obtained with 11.6 percent mixing water, which is higher than either the 10.75 percent used in standard portland cement tests, or the 11 percent used in high early strength cement tests, thus involving a higher water-cement ratio to the disadvantage of developed strength. With lower mixing water, the following strengths have been obtained with C.P.-M.F. No. 2:

7 days	296 (4,200 psi)
28 days	508 (7,200 psi)
90 days	666 (9,500 psi)
180 days	738 (10,500 psi)

In addition, the flexural strength is superior to that of portland cements.

Average strengths to compare with other cements are as follows:

	2 days	7 days	28 days
C.P.-M.F. No. 2	149(2,120 psi)	273(3,870 psi)	438(6,200 psi)
Fly Ash Pozzolan Cement 65 % clinker 32.5% fly ash 2.5% gypsum	102(1,450 psi)	188(2,670 psi)	332(4,700 psi)
Slag-Fly Ash Cement 65 % slag 32.5% fly ash 2.5% gypsum	59(850 psi)	98(1,390 psi)	204(2,900 psi)

Characteristics of C.P.-M.F. No. 2

Approximate density	0.80
Specific Gravity	2.84
Passing 15 microns	41.4 %
Passing 30 microns	77.5 %
Passing 45 microns	88.0 %
Initial set, 2 hours 40 minutes	
Final set, 6 hours	

These cements have high water retention and a high cementitious action, so that they can be used in concrete placed under water without any special precautions and without separating or segregating. Their cohesion and the filling of the voids with the colloidal gels, formed from the fly ash, assure the best protection against aggressive waters or drying action. The exceptional plasticity they give to concrete reduces segregation, bleeding, and cracking, and facilitates placing. These cements do not require a higher water demand (this is a superiority of fly ash over all other pozzolans) than portland cement of corresponding fineness, and in addition, fly ash imparts a very high impermeability to concrete.

Chemical analysis:

Silica	28.51%
Alumina	16.27%
Iron Sesquioxide	2.71%
MnO	0.67%
Lime	44.17%
Magnesia	2.38%
Sulfuric Anhydroxide	1.42%
Sulfide sulphur	0.31%
Alkalies (expressed as Na_2O)	0.96%
Ignition loss	2.12%
Unaccounted for	0.48%

These cements do not contain any accelerators, and are compatible with all admixtures known and used with portland cement. They provide to a higher degree all the well known qualities of good pozzolanic cements: (1) low heat of hydration (2) excellent resistance to aggressive waters. Their use is indicated in aggressive surroundings, in reinforced concrete where electrolytic action is feared, and in grouting.

It may not be out of place to point out that fly ash high in lime, produced by power stations burning lignite, does not possess any pozzolanic qualities, and that this high lime content permits their use with slag to manufacture a slag cement as a binary combination with the addition of gypsum. The author suggests, therefore, a modification of Lea's definition of pozzolans as follows: (underlined phrase added by author):

> Pozzolans are silicious materials, low in lime content, which possess in themselves little or no cementitious properties, having constituents which at ordinary temperatures, combine with lime, in the presence of water, to form insoluble compounds possessing cementitious properties.

It might also be useful to add to Davis' statements given at the ASTM San Francisco meeting in 1949, in his paper, "A Review of Pozzolanic Materials and Their Use in Concrete" (See Bibliography No. 60):

Davis' statement:

> "Though the predominating constituent of all of the recognized pozzolans is silica, many which exhibit satisfactory performance contain as little as 40 percent of this compound. All are relatively low in lime and magnesia, and many of those which are regarded as the better pozzolans contain as much as 5 percent, and some as much as 10 percent of the alkalies—soda and potassa. Some contain as much as 30 percent of alumina and some as much as 20 percent of iron oxide. It seems to be the case that the presence of at least a small percentage of the alkalies, in whatever may be their compound form, is beneficial rather than detrimental. It also seems to be the case that those which contain at least a moderate amount of alumina and some iron oxide are superior to those for which the silica is of a high degree of purity."

Author's suggested addition:

> "It seems that the presence in pozzolans of at least a small percentage of alkali is more likely to be favorable than unfavorable, and those that contain any appreciable percentage of alumina and of iron oxide are better than those that contain a very high percentage of silica."

Gives a table of various fly ashes showing the ratio $SiO_2/(Al_2O_3+SiO_2+Fe_2O_3)$

Cites various projects which have used this cement.

Discussion

L. Blondiau: Seeing the long time it takes to determine pozzolanic activity, it would be interesting to find a procedure for rapid determination of such activity prior to use. The ratio of lime to silica obtained from chemical analysis cannot be a criterion of this activity, contrary to the author's statements. In effect, if a part of the fly ash has a pozzolanic function, a large portion is inert. This inert portion reduces the ratio of lime to silica without any effect. This inactivity and the slowness of the reaction of the active portion can be determined in the fly ash cements by the Chatelier-Anstett test.

From the point of view of gain in strength, the addition of fly ash to portland cement or to slag cement does not contribute to high strength except by increasing the fines, facilitated by the presence of carbon (grinding aid). In effect, with fly ashes rich in carbon (ignition loss 31.5 percent) and others low in carbon (ignition loss 2.5 percent) one finds: (1) At constant Blaine fineness of 3,080, the strength at 28 days decreases with the addition of fly ash both in portland and in slag cements. (2) If one grinds for the same length of time, resulting in increased fineness due to the fly ash, the strengths at 3 and 28 days are lower than plain portland, and with a slag cement, the strength at 3 days is lower than plain slag cement in spite of a fineness of 4,070 in the latter, and of 5,275 fineness for the cement with 30 percent fly ash. At 28 days, the strengths are of the same order. These findings are the same for low carbon as well as high carbon fly ash additives, but the latter give a higher loss of strength. In all cases, the water requirement is higher with the addition of fly ash.

Closure: Author does not agree with Blondiau on any of the points: (1) The question of pozzolanic activity is not that simple, the portion he thinks is inert is not so in reality, but is just slower in acting. Pozzolanic activity of fly ash is composed of a small activity at the start, and a total activity which is higher. The difference between the two is the retarded activity. Grinding is not the only manner to accelerate the latter. (2) Permit me not to speak here of the Chatelier-Anstett test, I will publish my opinion of it some day. (3) The statement covering the facilitating of grinding by presence of carbon, is not supported by the facts. Fineness is not the only factor in the early activity of fly ash. (4) The slump cone is not a good measure of workability and has no meaning any more today. There are better methods of determining workability. Workability is not only plasticity but also absence of a tendency to segregate.

212. GARLONI, LOUIS J. "Method of Making Lightweight Aggregates." U.S. Patent No. 2,799,074, Official Patent Gazette, Vol. 720, No. 3, p. 462, July 16, 1957.

Makes fly ash pellets and then expands them.

213. GRANT, D.S., LYON, L.W., and FOULGER, F. "Utilization of Flue Dust or Fly Ash in Manufacture of Cement." Great Britain, British Patent No. 765,677, patented 1957. Abstract in Fuel Abstracts, Vol. 21, No. 5, paragraph 5418, June 1957.

Method of production of cement clinker, where clay and chalk are fired together in a kiln by a flame of pulverized coal, characterized in that fly ash is introduced with the pulverized coal into the kiln.

214. GUMZ, W. "Sintering of Fly Ash." (in German) Vereiningung der Groskesselbesitzer, Bulletin No. 48, pp. 160-165, June 1957. Abstract in Engineering Index 1958.

Tests on sintering belt and shaft kiln, with recommendations for sintering of fly ash in furnace, and utilization of fly ash and sinter as concrete aggregate, cement admixture, and in brick making.

215. HUGHES, T.H. "Sampling and Size Analysis of Pulverized Fuel and Fly Ash." Second Conference on Pulverized Fuel (London), Paper No. 9, 20 pp., November 1957. Abstract in Fuel Abstracts, Vol. 23, No. 3, paragraph 2789, March 1958.

Describes methods used in sampling and determination of particle size of pulverized fuel and its flue dust.

216. JARRIGE, A. "Fly Ashes and Their Utilization." (Les Cendres Volantes et Leurs Possibilités d'Utilsation). Annales Des Mines (in French) Vol. 146, pp. 649-672 and 707-725, October and November 1957. Abstract in Engineering Index p. 412, 1957. See Bibliography No. 149, 243, 244.

Discusses uses of fly ash in mortar, cement, glass, slag wool, pavements, impervious coatings, highway engineering, lightweight materials, etc. Gives mechanism of pozzolanic action and the influence of fly ash on various properties of mortar.

217. KANTOR, ANDREW J. "Fly Ash Sintering." Pit and Quarry, Vol. 49, No. 12, pp. 88-90, June 1957.

Describes the Koppers fly ash sintering method. Sintering is passing air through a layer of a material that will support combustion, and thus consolidate the particles by thermal bonding. Because of the fine powdery texture of fly ash, it is necessary to pelletize it prior to sintering. To do that requires the addition of a binder costing 15 to 25 cents per cubic yard of production. Fly ash containing 3½ to 10 percent carbon will support sintering and if carbon is lower, then additional carbon needs to be mixed to support burning. Experiments show that 1½ to 3 tons of fly ash can be produced per square foot of grate area per day. The sinter weighs 37 to 52 pounds per cubic foot. Lists equipment required and gives a rough estimate of $1.23 per cubic yard of sintered fly ash aggregate, not counting fly ash cost. Notes that other lightweight aggregate in New York City area sells at $3.75 to $5.15 per cubic yard. Can be used in block manufacture and in concrete.

218. KENNEDY, THOMAS B. "The Corps Searches for Better, Cheaper Concrete." Engineering News-Record, Vol. 159, No. 8, pp. 34-36, August 22, 1957. See Bibliography No. 170, 192, 233, 246, 247, 265.

Use 6 classes of materials as cement replacements, fly ash being one. Make mixes with 0.8 water-cement ratio simulating mass concrete, and 0.5 water-cement ratio simulating structural concrete. The mixes were rated on bleeding, permeability, durability, compressive strength at 3, 28, and 90 days, shrinkage at 180 days, and in mass concrete, on reduction in heat of hydration. From these ratings, best proportion for fly ash is 30 percent replacement. These are guides only as each project will be studied in the office and in the laboratory, for best replacement material and its proportions.

Field exposure is studied at Treat Island, Maine, and St. Augustine, Florida. From the Treat Island observations, the superiority of air-entrained concrete over non-air-entrained concrete has been demonstrated, and it has been established that properly porportioned 2-bag concrete can be made durable.

Grouting experiments using different mixtures and different width cracks, with fly ash in some of the mixtures, indicate that presence of fines is important, rather than what the identity of the fines might be.

219. MAZUR, S. "Fly Ash Concrete (with Lime or Portland Cement)." Materialy

budowlane, Vol. 12, No. 10, pp. 300-309, 1957. Abstract in Building Science Abstracts, Vol. 31, No. 1, paragraph 43, January 1958.

Listing only, no summary. Polish article.

220. Mc ALLISTER, ROBERT J. "Fly Ash Concrete for Shippingport Atomic Power Station." Proceedings, American Society of Civil Engineers, Separate No. 1215, April 1957.

Obtained uniform fly ash from Frank R. Phillips Power Station in Pittsburgh, and used it with Type IS cement. Fineness ranges from 2,600 to 3,700, with average of 3,330 square centimeters per gram. Average loss on ignition 4.72 percent (varied from 3.30 to 8.50). Laboratory concrete mixes did not show as high strengths as field made cylinders. Used 20 percent by volume replacement. Specified 3,000 psi concrete without air. Strength was found to remain lower than plain concrete until about age of 80 days. Fly ash handles like cement.

221. MONSON, CARL A. "Design of Concrete Mixture." Walter H. Flood and Company Laboratory Report No. 570189, March 19, 1957.

Used 3 mixes: (a) Type III cement, 7½ bags per cubic yard, (b) Type III cement, 6 bags per cubic yard plus 150 pounds of Chicago fly ash, and (c) Type III cement, 6½ bags per cubic yard plus 150 pounds of Chicago fly ash. Steam cured to simulate prestressed concrete practice (cylinders in room for 2 hours, then 16 hours in saturated steam at 140°F, followed by standard moist curing until tested), finds following in psi:

Mix	18 hrs	7 days	14 days
a	3,563	5,926	6,402
b	3,396	5,430	5,748
c	4,041	5,766	6,544

222. NICOL, A. "Mixtures of Blast Furnace Slag and Fly Ash with High Calcium Sulfate and Low Lime Contents." (Sur le Mélange Laitier-Cendres Volantes à Teneur Elevées en Sulfate de Calcium et Faibles en Chaux). Revue des Matériaux de Construction No. 501, pp. 157-164, June 1957.

Blast furnace slag and fly ash are waste products from which advantages can be gained. By utilizing their cementing potentialities through combining them with calcium sulfate in the presence of lime or portland cement clinker. Such combinations have already shown good results for the slag alone, and it seems possible to take advantage of fly ash to fix the lime of this combination. In addition, as fly ash has a low density, and absorbs a lot of water, it is possible to develop voids which would contribute to the formation of a "concrete" of a lightweight character utilizing very low cost materials.

With the four constituents for these mixes, the fly ash is considered as aggregate and the cementing materials consist of the slag, the calcium sulfate, and the lime. Lime is simpler chemically than cement clinker and is the reason it is chosen for this experiment.

Three types of "concrete" consisting of the following proportions by weight were made:

⅓ binder to ⅔ fly ash
½ binder to ½ fly ash
⅔ binder to ⅓ fly ash

The binder consisted of:

25 percent $CaSO_4.2H_2O$ and 75 percent slag
20 percent $CaSO_4.2H_2O$ and 80 percent slag
10 percent $CaSO_4.2H_2O$ and 90 percent slag

Used very low lime contents and expressed the lime as a percentage of the slag (1 percent and 0.5 percent), or simply used lime water for mixing purposes, in which case, the lime content fell between 0.08 and 0.16 of the weight of the slag. The tests were made on a slag of 2.96 specific gravity and specific surface of 3,500 square centimeters per gram, and a fly ash with specific gravity of 1.98 and specific surface of 3,520 square centimeters per gram. The water required for workability was 30 to 33 percent by weight of the total powder mixture. The water requirement increased with the increase in fly ash and $CaSO_4$.

Specimens were evaluated by their compressive strength, using cylinders of the same size as for testing neat cement paste. Specimens were cured, after stripping, on glass plates at a temperature between 61 and 64.4° F, and at constant humidity by covering with wet rags. In mixing slight increase in temperature took place, probably due to a calorimetric phenomenon accompanying the absorption of water.

Specimens showed 46 to 48 percent voids and dry densities of 1.16 to 1.27. Strength after normal curing varied from 92 to 202 kilograms per square centimeter (1,290 to 2,870 psi). Specimens cracked on the outside due to shrinkage. This was successfully reduced by keeping rags wetter. Explains chemistry.

Concludes: (1) With low lime contents in the presence of appreciable amounts of $CaSO_4$, slag and fly ash mixes give lightweight concrete of good strength. (2) Fly ash modifies the set by fixation of water and lime. (3) Too little lime produces deteriorations due to unused free alumina. (4) The mixture may be expansive and yet maintain sufficient strength. (5) Lime seems to have a double role, quantitative in certain reactions, and catalytic in accelerating other reactions in the larger mass. (6) Set may propagate from an active center of reaction as long as hardening has not completely taken place in these centers. (7) This explanation corresponds to two types of simultaneous hydrolysis during the early set, and at the same time leaves the slag-fly ash effect manifest itself over longer periods.

223. PETERS, H. "Use of Fly Ash in Concrete." Betonstein Zeitung, Vol. 11, No. 1, pp. 27-34, January 1957. Abstract in Revue des Matériaux de Construction No. 500, p. 24-D, May 1957.

Reviews literature on the subject. A summary of the conditions of use of fly ash in concrete and the qualities it imparts are given. Enumerates the properties of fly ash from lignite and coal and examines the results obtained through their use in concrete. Concludes that its use is advantageous.

224. RUSSELL, H.H. "Summary of Fly Ash Disposal Problem." Journal of Air Pollution Control Association, Vol. 7, No. 1, pp. 46-47, May 1957. Abstract in Engineering Index, p. 412, 1957.

Compilation of U.S. country-wide inventory of fly ash. Number of uses have been developed and a considerable amount of fly ash is being sold through such outlets, some of which are: Concrete aggregates, bricks, road materials, abrasives, filter materials, and soil stabilization. Gives ASTM Designation C350-54T including physical and chemical requirements, and suggests possible new uses.

225. SMIT, G.S. and EHRENBURG, J.P. "Using Fly Ash in Building Materials." Electro-Techniek (Dutch) Vol. 35, pp. 141-146, April 4, 1957. Abstract in Engineering Index, p. 160, 1957.

Gives properties of fly ash and reviews its use in cement and concrete manufacture, in limestone, cellular concrete and bricks. Contains 21 references.

226. VENUAT, MICHEL "A Study of the Properties of Fly Ash Cements." (Etude des Propriétés du Ciment aux Cendres Volantes). Revue des Matériaux de Construction, No. 506, pp. 309-317, November 1957. See Bibliography No. 169.

This investigation which is more detailed than the previous study by Feret and Venuat, should be of interest to all cement plants as the trend is to use less and less straight portland cement, when it can be replaced by a blended cement with 10 to 20 percent fly ash. This application reduces costs and increases the production of hydraulic cements. Two fly ashes were used as received, and after being ground to different finenesses. Replacements in the tests were 25 and 40 percent by weight except in the aggressive water tests, where the latter was increased to 50 percent. Water-cement ratio used in all instances was 0.50.

ANALYSES OF FLY ASH

	A	B
Loss on Ignition	1.49	4.87
SiO_2	50.66	47.50
Al_2O_3	30.15	30.01
Fe_2O_3	7.59	7.18
CaO	2.78	3.28
MgO	1.97	1.85
SO_3	0.23	0.35
Alkalies	5.62	5.19

Under the microscope both ashes appear similar: the majority of the grains are spherical and range in diameter from 3 to 150 microns. The small particles are close together while the coarse ones are in bubbles. Side by side with the spherical particles, one finds vitreous compact fragments, and irregular spongy pieces.

The X-ray diffraction gives only a small number of lines of very weak intensity. By transmitted polarized light, few grains polarize. The ashes, therefore, contain very few crystallized elements. By reflected light, one can distinguish grains, the strong reflective property of which must be due to iron—their distribution is irregular. Other grains, less reflective, must be alumino-silicates.

	A	B
Specific Gravity	1. 90	1. 98
Specific Surface		
Blaine square centimeters per gram	2,600	3,800
Apparent density	0.667	0.683

Grain size curves show fly ash B to be finer than A, and both are finer than ordinary French portland cement.

The ashes were ground in a laboratory ball mill to three different finenesses.

	As Received Square Centimeters per gram	Ground Square Centimeters per gram		
A	2,600	4,500	6,100	10,000
B	3,800	5,570	7,100	9,970

The influence of fineness on the specific gravity is remarkable. The specific gravity increases with the fineness and trends to approximately 2.7, in fact a plot of specific gravity versus fineness shows a fairly good correlation.

The grindability was measured and plotted against time. It was found that fly ash A grinds more easily than B, and about as easily as the average portland cement clinker.

The cement used had the following characteristics:

Loss on Ignition	1.90%
SiO_2	20.62%
Al_2O_3	5.18%
Fe_2O_3	3.02%
CaO	66.10%
MgO	0.78%
SO_3	2.28%
Free Lime	0.97%
C_4AF	9.2%
C_3A	8.6%
C_3S	62.7%
C_2S	11.9%
Specific Gravity	3.09
Water demand	27%
Time of set at 68° F:	
Initial	3 hrs 45 min
Final	6 hrs
Specific Surface, Blaine, square centimeters per gram	2,820

DETAIL OF THE 16 MIXES USED

Fly Ash	Percent Fly Ash	Specific Surface FA, Cm^2/g	Mixing Water %	Time of Set Initial Hrs	Time of Set Initial Min	Time of Set Final Hrs	Time of Set Final Min
		2,600	29.0	4		7	30
	25	4,500	29.0	4	45	7	15
		6,100	29.0	4	30	8	
		10,000	27.5	4	30	8	
A		2,600	31.0	4	15	9	
	40	4,500	30.0	5		9	15
		6,100	30.0	5		9	
		10,000	28.0	4	45	8	
	100		35.0				
		3,800	29.0	3	45	7	45
	25	5,570	29.0	4	15	7	30
		7,100	28.5	4	15	7	15
		9,970	27.0	4	15	7	45
B		3,800	32.5	4	45	8	45
	40	5,570	32.0	5		9	
		7,100	31.5	5		9	
		9,970	28.5	4	30	8	15
	100		42.0				

The above tabulation shows that the fly ash-cement neat mixtures require more water as the fly ash increases.

Time of set varies little—increases slightly with the increase in fly ash.

The strength tests show that fly ash substitution reduces the strengths at 28 days in proportion to the fly ash content. Very fine fly ash grinds (10,000 square centimeter per gram) and 25 percent substitution give essentially the same strength at 28 days as the plain cement. At the end of 1 year all mixes with 25 and 40 percent fly ash give higher strengths than the control. In the case of the finer grinds of fly ash B, this increase in strength is of the order of 15 percent for 40 percent replacement, and 25 percent for 25 percent replacement. For the same grinding energy as plain cement clinker, a 25 percent replacement gives equal strength at 90 days as plain cement. The same is true at 6 months for 40 percent replacement. Fly ash B is more active than A, and the strengths for equal fineness are therefore higher.

A plot of pozzolanic activity in terms of Feret's coefficient, shows that at 7 and 28 days the raw fly ash has negligible pozzolanic effect, but at 90 days, this is already appreciable. The pozzolanic effect is accentuated by grinding.

Curing tests made at 140° F, for fly ash B, give the following for a 25 percent replacement as compared to 68° F curing:

		Strengths in pounds per square inch					
		Plain cement (Control)		Blended cements			
				Raw Fly Ash		Ground Fly Ash 7,100 cm^2/gm	
Curing	Age	Flexural	Compressive	Flexural	Compressive	Flexural	Compressive
Water 68° F	7 days	780	5,450	653	2,650	890	3,610
	28 days	1,305	8,400	1,050	5,310	1,280	7,200
Water 140° F	8 hours	525	4,080	540	2,820	596	4,160
	24 hours	610	4,090	497	3,890	865	5,750
	48 hours	725	5,700	1,080	6,650	1,265	7,100
	7 days	980	6,700	1,305	6,650	1,575	8,200

For equal age, the mixes with ground fly ash give consistently higher strengths than plain cement. It takes 48 hours at 140° F for plain cement to exceed the strength of normal curing at 7 days. The length of time at 140° F to equal the 7-day strength under normal curing diminishes with the presence of fly ash and is proportional to its fineness. Thus, the use of fly ash in cement is particularly recommended for steam cured concrete—from block manufacture to prestressed beams.

The tests with specimens immersed in 5 percent $MgSO_4$ show absence of attack at end of 15 months.

For heat of hydration tests, a 1 to 3 mortar with a water-cement ratio of 0.50 was used. It was found: (1) The heat of hydration is lower for fly ash mixes than for plain cement. (2) This heat increases with fineness. (3) For the fly ashes used, the worst combinations were those of 25 percent fly ash replacement with a fineness of 10,000 square centimeters per gram. Their heat of hydration at 7 days is nearly equal to that of plain cement. The heat of hydration of fly ash B is slightly higher than that for A. It appears that in all cases, the heat of hydration is nearly proportional to the strength.

Measurements indicate that the use of fly ash reduces shrinkage in proportion to the amount of fly ash and to its coarseness. The high fineness of interground fly ash with clinker should therefore not cause excessive shrinkage.

Concludes: (1) The pozzolanic value of fly ash, weak at early ages and at 68° F, increases rapidly with age and becomes very important. (2) It is accentuated considerably by grinding and by heat: fly ash cements are therefore very sensitive to cold weather. (3) The addition of fly ash, even finely ground, should not cause an increase in shrinkage. On the contrary, finely ground fly ash does not give hope for a large decrease in the heat of hydration.

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227. AMERICAN SOCIETY FOR TESTING MATERIALS. "Terms Relating to Concrete and Concrete Aggregates." Designation: C125-58 Book of Standards, Part 4, pp. 588-589, 1958.

Admixture—A material other than water, aggregates, and portland cement (including air-entraining portland cement and portland blast-furnace slag cement) that is used as an ingredient of concrete and is added to the batch immediately before or during its mixing.

228. AMERICAN SOCIETY FOR TESTING MATERIALS. "Terms Relating to Hydraulic Cement." Designation: C219-55, Book of Standards, Part 4, p. 195, 1958.

Pozzolan—A silicious or silicious and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

229. AMERICAN SOCIETY FOR TESTING MATERIALS. "Sampling and Testing Fly Ash for Use as an Admixture in Portland Cement Concrete." Designation: C311-57T, Book of Standards, Part 4, pp. 676-683, 1958.

Gives: (a) sampling methods, (b) chemical tests, (c) physical tests (include air-entrainment tests).

230. AMERICAN SOCIETY FOR TESTING MATERIALS. "Portland-Pozzolan Cement." Designation: C340-58T, Book of Standards, Part 4, pp. 15-21, 1958.

Detailed specifications for Portland-Pozzolan Cement, which permit fly ash as a pozzolan.

231. AMERICAN SOCIETY FOR TESTING MATERIALS. "Fly Ash for Use as an Admixture in Portland Cement Concrete." Designation: C350-57T, Book of Standards, Part 4, pp. 616-618, 1958.

Detailed specifications for fly ash, as an admixture to promote workability and plasticity.

232. BERTHIER, R.M. "Free Lime: A Deleterious Agent in the Freezing of Concrete." (Le Rôle Néfaste de la Chauz Libre dans le Gel des Bétons). (France) Paper R. 99, Sixth International Congress on Large Dams, New York, September 1958.

Free lime results from hydration of portland cement. During freezing, this lime is in solution in the interstices of the concrete, particularly in cracks and microscopic fissures. As freezing starts, the lime solution increases in concentration, inasmuch as lime is more soluble in colder water. At thawing time the lime solution is in a state of super saturation, which oozes out wherever it can find an opening or fissure and deposits the lime on the sides of the fissure, thus exhibiting the characteristic lines outlining the exterior edges of the fissure.

The deposit reduces the cohesion between the sides of the fissures, and therefore, the strength of the concrete. Mortar is observed to swell above the aggregate edges, and a plane surface becomes irregular. In the experiments and the examples cited, the author uses a quick freezing and thawing cycle with freezing in air and thawing in lime water. Fixing the lime with pozzolans, in this case slag, reduces the lime deposits, and improves the resistance to freezing and thawing. Fine sand helps also, by dispersing the localized concentrations of lime. Stressing of concrete will also delay the segregation of lime.

233. BUCK, ALAN D., HOUSTON, B.J., and PEPPER, LEONARD. "Effectiveness of Mineral Admixtures in Preventing Excessive Expansion of Concrete Due to Alkali-Aggregate Reaction." U.S. Army Engineers, Waterways Experiment Station, Technical Report No. 6-481, July 1958. See Bibliography No. 170, 192, 247, 272.

Twenty materials, representing eight different classes of mineral admixtures, were evaluated, using both chemical and mortar-bar test methods, for their effectiveness in preventing excessive expansion of concrete due to alkali-aggregate reaction. The criteria of the chemical tests were examined, and the test results were compared with the mortar-bar test results. All results were compared with those obtained by two other laboratories. It was found that the chemical tests cannot be used with reliance to evaluate effectiveness, and that the mortar-bar test procedure needs improvement to increase its precision. Each of the replacement materials evaluated will prevent excessive expansion if a sufficient quantity is used. Correlations were found between effectiveness and: fineness, dissolved silica, and percentage of alkali retained by reaction product.

Five of the materials tested (a fly ash, a tuff, a calcined shale, a calcined diatomite, and an uncalcined diatomite) showed a reduction in alkalinity of 40 percent or more when tested by the quick chemical test and thus complied with the specification used by the U.S. Bureau of Reclamation for Davis Dam. All of these except the fly ash met the requirement later proposed for the relationship between reduction in alkalinity and silica solubility as determined by this method.

Six of the materials tested, two slags, a fly ash, a pumicite, and two calcined shales, reduced mortar-bar expansion at least 75 percent with high-alkali cement and Pyrex glass aggregates when used as 50, 45, 35, and 30 percent replacements of the cement.

Calculations were made that suggest that the minimum quantity of each material required for effective prevention of excessive expansion ranged from 10 percent for the synthetic silica glass to 45 percent for one of the slags. By groups, these calculated minimum percentages were: calcined shale, 19 to 29; uncalcined diatomite, 22; volcanic glasses, 32 to 36; slags, 39 to 45; fly ashes, 40 to 44.

234. CHICAGO FLY ASH COMPANY, WALTER N. HANDY COMPANY, and MCNEIL BROTHERS, INCORPORATED. "Proportioning Guide for Concrete Mixes Containing Fly Ash." Leaflet, March 1958. See Bibliography No. 50, 64, 168, 183.

Leaflet on adjusting plain mixes for fly ash.

235. CHILCOTE, WILLIAM L. "Fly Ash Concrete After 7.5 Years." The Baltimore Engineer, Vol. 33, Number 8, pp. 4-6, November 1958. See Bibliography No. 94, 95, 96, 98.

History and summary of experimental pavement placed in October 1950 in Cooks Lane, near Alson Drive in Baltimore. Used 6 bags air-entraining cement in both regular and fly ash concrete, but added aggregate in latter to obtain effect of cement replacement. In each 6-bag cement batch, 114 pounds of fly ash were used. Strengths up to 1 year were obtained from job-made cylinders, and show lower strength for fly ash concrete until age of 90 days, at which time both concretes gave essentially the same strength of about 4,100 psi. After that, the fly ash concrete exceeded in strength the plain concrete. Cores taken in both concretes at about 3½, 6, and 7½ years, show the fly ash concrete to be still ahead of the plain concrete, although both are still gaining, with the fly ash at a very slightly faster rate. The strengths in April 1958 were 6,355 and 5,605 psi, respectively. There is very little difference in wearing qualities as determined from field inspection. Both pavements have been subjected to severe winters, and rock salt has been used extensively.

Concludes that use of fly ash in concrete has some merit, but that this merit must be judged for each particular case.

236. DAVIDSON, D.T., SHEELER, J.B., and DELBRIDGE, N.G., JR. "Reactivity of Four Types of Fly Ash with Lime." Highway Research Board Bulletin No. 193, pp. 24-31, 1958.

Using 4 fly ashes having ignition losses of 3.20 to 27.67, and mixing with 2, 4, 6, and 8 percent lime, cured at 20° and 60° C, and tested in unconfined compression at 0, 7, 14, 28, and 45 days, find: (1) Carbon content determined by ignition loss seems reliable indicator of pozzolanic activity with lime—10 percent maximum ignition seems to be upper limit. (2) Amount of fly ash passing No. 325 sieve decreases with increasing carbon, but does not seem to be as reliable an indicator of carbon as ignition loss. (3) Use of lime-fly ash mortar strength test for evaluating fly ash activity seems to give valid results. Curing at 60° C has advantage of shortening time for evaluation, but 20° C curing is better where time permits.

237. DEXHEIMER, W.A. "Pozzolans in Concrete Dams." (U.S.A.) Paper R. 97, Sixth International Congress on Large Dams, New York, September 1958.

Defines pozzolans and stresses fact that for most activity, silicious ingredients should be in amorphous state (glass or opal), as contrasted with crystalline state (quartz). Natural and artificial pozzolans differentiated. Short history of use of pozzolans in U.S. starting with Los Angeles Aqueduct in 1910-1912, up to present Glen Canyon Dam, and Flaming Gorge Dam currently under construction, and Yellowtail Dam to be constructed by Bureau of Reclamation. Fly ash used by USBR first in 1942 in repair of Arizona Spillway Tunnel of Hoover Dam, and since in Hungry Horse and other dams.

Effects of pozzolans on concrete: (1) When combined with lime liberated by hydration of portland cement, pozzolans produce more stable compounds, less susceptible to leaching, and are resistant to attack by mineral-free waters in contrast with compounds produced by portland cement alone. (2) Pozzolans contribute to strength of concrete at later ages (90-180 days), reduce temperature in mass concrete, increase impermability, reduce alkali-aggregate reaction, and improve workability. Improved workability is particularly true of fly ash which contains glassy, spherically shaped particles. (3) Under field conditions, pozzolans reduce resistance to freezing and thawing, but under prolonged moist curing they have a beneficial effect on durability.

Pozzolans have been used in 13 USBR dams since 1911—gives table showing details of these dams and results obtained. Fly ash was used in Hungry Horse, Canyon Ferry, Palisades, and is proposed for Yellowtail, or nearly 25 percent of the structures—calcined shale was only other material used in 4 USBR dams, while pumicite and calcined clay were used in 2; other pozzolans were used in individual cases. Gives USBR specifications for pozzolans in general, and for fly ash in particular.

Summarizes application of pozzolans by USBR to 4 dams: (1) Arrowrock Dam (1911-1915) used a "sand-cement" by intergrinding 45 percent by weight of granite and 55 percent of portland cement clinker. (2) Friant Dam (1940-

1942) used a fine-grained local pumicite found naturally in fine powder form (98 percent passing No. 325 sieve)—20 to 25 percent replacement. This reduced cost of cementing material, increased workability, increased impermeability, reduced alkali-aggregate reaction. (3) Davis Dam (1947-1950) used a 20 percent calcined shale replacement which improved workability, reduced permeability, reduced cost of cementing materials, and reduced alkali reaction. (4) Hungry Horse (1948-1953) used fly ash as 30 percent replacement. Credits fly ash and air entrainment with a large share in the completion of this dam more than a year ahead of schedule—attributed this to improved workability and placeability. Improved workability and reduced water requirements result in reduced drying shrinkage and autogenous volume change. Concrete resulted in 5-10 percent higher strength at 2 years' age. Total savings for cementitious materials for this dam about $1,675,000.

Concludes that in USBR structures, concretes containing pozzolan have compared favorably with those containing only portland cement. Favorable service records of structures containing pozzolans, since 1910, have led USBR to consider pozzolans for structures wherever economic considerations and required properties justify their use.

238. DURIE, N.D. "Uses for Fly Ash." Ontario Hydro Research News, Vol. 10, No. 3, pp. 1-6, 16 and 20, July-September 1958. See Bibliography No. 59, 97.

Discusses production of fly ash in Canada, and forecasts an increase to about 1,000,000 tons by 1975 from present 32,000 tons. Shows composition and properties of typical Canadian fly ash, as compared to standard ASTM specifications.

Gives data to show increase in 28-day strength and in ultimate strength, for fly ash concrete, with increase in fineness of fly ash used. Lists confirmed advantages: higher ultimate strength, reduced permeability, reduced heat of hydration, reduced mixer and mould wear, enhanced sulfate resistance, increased green strength (masonry units), and reduced cost. Setting time of concrete at 50° and 70° F is increased.

Summarizes British experiments and practice for making lightweight aggregate from fly ash, known as "Terlite." This requires, in general, about 1½ bags of cement less than for other lightweight aggregates, for equal strength. Terlite provides higher strength, and is a higher weight material than other lightweight aggregates that were tested. Discusses advantages and limitations of various methods of producing lightweight aggregates from fly ash.

Beneficiated fly ash has some carbon and some iron removed. This is advantageous, or disadvantageous, depending on the use to be made of it.

Fly ash can be used as a raw material in the manufacture of portland cement, and is particularly advantageous because of its high iron content.

Reviews in detail the use of fly ash in brick manufacture, giving British data and Batelle Institute research results.

Concludes that there are various fly ash consuming processes, particularly in the concrete industry. However, for the consumption of large tonnages, lightweight aggregate holds the most promise.

239. DUSERRE, HENRY. "Admixture of Fly Ash in Concrete for Saint-Hilaire-Saint-Nazaire Dam on the Isère River." (Addition de Cendres Volantes aux Bétons du Barrage de Saint-Hilaire-Saint-Nazaire sur l'Isère). (France) Paper R. 87, Sixth International Congress on Large Dams, New York, September 1958.

Using a fly ash of 9 percent loss on ignition, and 2,025 Blaine fineness, gives test results which show later age gain above control with 20 percent replacement and one cement, while strength remained below control for a high silica cement. Use 15 percent in dam, with batching and handling all by hand. Resulted in improved workability, reduced water requirement, and reduced drying shrinkage and heat of hydration. In France, intergrinding with cement (pozzolanic cement) is preferred, but perhaps addition on the job will now increase in use.

240. FOUILLOUX, PIERRE. "Pozzolanic-Metallurgical Cements and Portland Cements with Re-Crushed Fly-Ash: First Class Binders Particularly Suitable for the Construction of Large Dams." (Les Ciments Pouzzolano-Metallurgiques et les Ciments Portland aux Cendres Volantes Rebroyées—Liants de Grande Classe Particulièrement Adaptés pour la Construction des Grands Barrages). (France) Paper R. 104, Sixth International Congress on Large Dams, New York, September 1958. See Bibliography No. 121, 211.

Describes two cements: (a) pozzolanic-metallurgical cement, designated CP-M.F. No. 2, which is strictly a slag cement containing both slag and fly ash, (b) portland cement with 20 percent fly ash designated CPA-C, which falls strictly in the portland cement class. Both depend on interground fly ash, which breaks up fly ash particles and thus increases fly ash activity, providing a more uniform cementing mixture than when fly ash is mixed on the job. This utilizes more of the potential activity and advantages inherent in the raw fly ash. The slag-fly ash cement has high strength, low heat of hydration, and high resistance to chemicals. The portland-fly ash cement has strength essentially equal to ordinary portland at early ages, more workability in concrete mixes, lower drying shrinkage and lower heat of hydration, more adaptable hardened concrete (thus resists cracking more), and same rate of strength gain as standard portland—all properties making both cements particularly adaptable to large dam construction.

241. FRIIS, KRISTEN. "Use of Admixtures and Pozzolanic Materials in Concrete for Dams and the Influence of the Finer Sand Particles." Question 23, General Report D (in French), and H (in English), Sixth International Congress on Large Dams, New York, September 1958.

Summarizes 29 reports from 11 countries. Concludes, regarding fly ash and pozzolans: (1) Most of the experiments made with fly ash and pozzolans establish the following facts: (a) better workability, (b) better frost resistance, (c) lower heat evolution, (d) lower compressive strength at 28 days, but generally the same as ordinary concrete after 90 days, (e) decrease in shrinkage. (2) For use of fly ash and pozzolans, it is the prevailing opinion that chemical analyses are absolutely necessary to determine if detrimental reactions with the cement are to be feared, and suggests that an international standard for such analyses be discussed. (3) For the use of Seki's Formula, it should also be discussed how much of the water unites with the cement, and with the various pozzolans such as fly ash, trass, etc.

242. GUILLAUME, L. "Simple Control of Pozzolanic Fly Ash Added to Artificial Portland Cement." (Contrôle Simple des Cendres Volantes Pouzzolaniques Ajoutées aux Ciments Portland Artificiels). Revue des Matériaux de Construction, No. 517, pp. 272-273, October 1958.

Details of test developed by Laboratoire d'Essais des Matériaux de la Ville de Paris for determining the quantity and quality of the fly ash added to a fly ash cement: (1) Determine the residue on a 2-gram sample by standard P15-301 (dissolve in HCl for 5 minutes). The result multiplied by 100/85 gives the content of fly ash in the mixture to a reasonable approximation.

(2) The same treatment on a 2-gram sample after it has been calcined in a platinum dish in an electric furnace at 1,000° C for 60 minutes and cooled in a dessicator, provides a residue determination, which subtracted from the first determination, gives an indication of the pozzolanic activity of the fly ash. Good pozzolanic action reduces the residue under such treatment by about ⅔. These tests fill a need for checking specification compliance, even though they may be imperfect, as they nevertheless give very satisfactory results.

Gives data obtained by these methods on fly ash cements and compares them with known values from manufacturing plant data, and finds them to differ from ⅒ to 2 percentage points at most, and in full agreement at times. Sand ground to fly ash fineness, and mixed with cement shows no change on calcination. On the other hand, the same tests used on raw fly ash show an increase in the residue from about 85 percent at normal temperature to 90 or 92 percent after calcination.

243. JARRIGE, A. "Fly Ash Utilization." (Les Cendres Volantes et Leur Utilization). Revue des Matériaux de Construction, No. 513, pp. 173-179, June 1958. (This is a condensation of a larger paper which appeared in the Annales des Mines, October and November 1957 by same author.) See Bibliography No. 149, 216, 244.

Divides the article into (1) An introduction in which he examines the general problem of industrial wastes. (2) Present and foreseeable uses. (3) Characteristics of fly ash. (4) The problems to be solved for the commercialization of fly ash.

Present and Foreseeable Uses:

1. Substitution for sand in mortar (⅓ coarse sand, ⅓ fine sand, and ⅓ fly ash) improves the cohesion and quality of molded concrete products.
2. Addition to raw materials in the cement manufacturing process (15 to 20 percent).
3. Mix with very plastic clays for brick making (15 to 30 percent fly ash containing 5 to 15 percent of water and 10 percent ignition loss).
4. Raw material for manufacture of glass after preliminary addition of 10 to 20 percent of lime.
5. Principal constituent of semi-vitrified products—paving tiles of good quality—gives details.
6. Filler in asphaltic products.
7. In plaster and plaster board.
8. Pozzolanic effect.
   a. Lime and silica, in the form of sand, combine in a wet environment at 180° C and under a pressure of about 10 kilograms per square centimeter to give a silico-calcareous compound.
   b. Ordinary sand does not react with lime at normal temperatures but does with certain sands of volcanic origin known as pozzolans.
   c. The hydration of portland cement is accompanied by the liberation of lime, which carbonates progressively but which can be leached out leaving a porous concrete, or it can combine with the sulfates in aggressive water, causing expansion.
   d. Active pozzolans incorporated in portland cement concrete, fix the lime liberated by hydration, and as a result increase its resistance and assure its compactness.
   e. In addition to natural pozzolans, there are various artificial products that possess this property—fly ash, particularly that which is rich in SiO_2, Al_2O_3 and Fe_2O_3.
   f. Whereas the hydration of a cementing material obtained by the burning in a rotary kiln, is a continuous process, the strongest gain of a

cementing material of the same chemical composition resulting from a mixture of a portland cement and a pozzolan takes place in two stages, the second of which is the reaction between the liberated lime and the pozzolan (the exact process is not known).

g. The addition of fly ash to concrete improves the compressive and tensile strengths, increases the stability towards water, and reduces the heat of hydration, as well as the shrinkage. In the raw condition, such additions retard the initial strength which is largely compensated for at later ages.

h. Factors influencing pozzolanic action:
   (1) Fineness of grind.
   (2) Proportion of fly ash used.
   (3) The addition of some accelerators, such as slag or cement germ that has set.
   (4) Increase in temperature which plays a particularly favorable role.

Gives references to other articles on same subject.

Methods of incorporating fly ash in concrete:

1. On the job at the mixing plant—large projects such as dams, etc.
2. By a pre-prepared accurately proportioned pozzolanic cement at the cement mill.

The development of the latter started with Fouilloux' fly ash-slag-cements in use since 1951, followed by portland cement with 15 to 20 percent fly ash in 1956. About 500,000 tons of these cements were produced in 1957 by La Loisne mill.

It is necessary to insist on the use of fly ash in highway construction, because of its local availability, and because such construction requires close limitations on grading, plasticity, impermeability, capillarity, and frost resistance. With these limitations, one can foresee the immediate use of fly ash in this work in the following:

a. As a layer below the pavement 15 to 20 inches thick to act as a filter against the movement of clay underneath.
b. For foundations as foundation sand or fillers in soil-cement or addition to cemented layers.
c. In concrete (as economical additions), or as fillers in flexible pavement.

Lightweight construction

Lightweight construction is on the increase in all countries and demand for artificial fabrication of lightweight aggregates is very great. Sintering opens this field to fly ash (gives a very detailed treatment on sintering).

Characteristics of fly ash

Even though fly ashes as a whole present large variations in properties and composition, the product of one plant using the same source of coal, is fairly regular and thus can be typed and classified. Describes the rounded ball bearing appearance of the particles, the fineness of 2,200 to 3,700 square centimeters per gram, the density of 0.54 to 0.76, the specific gravity of 1.84 to 2.03. Says that grinding increases the specific gravity to 2.7 and the fineness to 12,000 square centimeters per gram. Fly ash softens at 1,000° to 1,100° C and fuses at 1,400° to 1,500° C. Calcined fly ash changes from a grey to salmon color, and increases in density while the specific surface is reduced. Water retention is 40 to 50 percent for the raw material, and 42 to 45 percent for the finer ground material. Compaction can be obtained with optimum water content of 25 to 30 percent. Gives chemical composition.

Commercialization of fly ash

Interest is already demonstrated. Therefore, a program for a promotion campaign on the use of fly ash, involving documentary information and organization of such information, is in order. The first step is to consolidate the technical studies and information and organize these. The power plants need to develop proper installations to handle fly ash. Every effort should be made to contact cement mills, contractors, ready mixed concrete plants, lightweight aggregate manufacturers, highway projects, and block and brick manufacturers. France produces 3,000,000 tons of fly ash, and the cost of disposing of it is 1 billion francs. One can estimate that by using fly ash, a revenue of one billion can be obtained, thus a saving of 2 billion francs. Those using it will profit another 2 billion, or 4 billion total savings.

Concludes that it is impossible to neglect the source of riches that fly ash can constitute and stresses the necessity of a collaboration of everyone concerned to put fly ash to use.

244. JARRIGE, A. and DUCREUX, R. "Some Results of Laboratory Experiments on Fly Ash and Fly Ash Cements." (Quelques Résultats d' Expériences de Laboratoire sur les Cendres Volantes et les Ciments aux Cendres). Revue des Matériaux de Construction, No. 518, pp. 300-305, November 1958. See Bibliography No. 149, 216, 243.

In trying to find tests to check on commercial fly ash cements, suggests following: (1) The proportion of the residue left after treatment of sample with hydrochloric acid and sodium carbonate in accordance with French Standard P15-301, permits close determination of proportion of fly ash in the cement mixture. If treatment is continued from the 5 minutes Standard to 30 minutes, a measure of the activity of the fly ash can be obtained. (2) A comparison of the residues from a fly ash cement tested at normal temperature and after exposure to 1,000° C for 60 minutes, permits a measure of the pozzolanic activity. Thus, the pozzolanic properties that can be proven by mechanical tests in 28 to 90 days can be verified quickly by these solubility tests.

245. KARPINSKI, J.Y. "The Determination of Pozzolanic Activity of Fly Ash by the Accelerated Soundness Test." (La Détermination de l'Activité Pouzzolanique de Cendres Volantes par l'Essai à la Corrosion Accélérée). (Yugoslavia) Revue des Matériaux de Construction, No. 510, March 1958, pp. 63-74. Abstract Proceedings, American Concrete Institute, Vol. 55, No. 8, p. 916.

Claims that water-cement ratio has effect on pozzolanic activity. To differentiate between various fly ashes, the pozzolanic activity is measured by sodium sulfate soundness test. Makes tests in two stages. In the first stage mortar (1 to 3) specimens using constant water-cement ratio and variable fly ash contents are made to determine optimum fly ash proportions. Then using this optimum fly ash content, the second stage tests are made with variable water-cement ratios to determine optimum water-cement ratio. This gives values that permit comparisons between fly ashes.

The test consists in submerging specimens for 18 hours in a saturated sodium sulfate solution, followed by air drying for 3 days—or 2 cycles per week. Loss or gain in weight is plotted against the number of cycles.

The first stage tests permit the classification of fly ashes in accordance with their potential activity and the second stage tests permit adjustment of this classification. The basis is to use the force of crystallization to disrupt the mortar assuming that the more active pozzolans develop mortars that can resist this disruptive force better, and also permit less absorption of the solution due to the improved impermeability due to pozzolanic action.

246. KENNEDY, THOMAS B. "Pressure Grouting of Fine Fissures." Proceedings, American Society of Civil Engineers, Separate No. 1731, August 1958. See Bibliography No. 218, 247.

Using artificial laboratory fissures of 0.01-, 0.02-, and 0.03-inch width, studies penetration of neat cement grout, cement plus fly ash, cement plus fly ash plus intrusion aid, cement plus intrusion aid, and cement plus calcium lignosulfonate, all with minimum water-cement ratio that could be used, under pressures varying from 25 to 100 psi.

Penetration characteristics and quality of hardened grout film were determined for neat cement grout, cement plus fly ash, cement plus fly ash plus calcium lignosulfonate, cement plus calcium lignosulfonate, cement plus finely ground water-quenched slag, cement plus pumicite, and cement plus finely ground calcined shale.

A low water-cement ratio is desirable for tightness and resistance to leaching. Type II low alkali cement was used. The Chicago Fly Ash used had 0.8 percent ignition loss, and total carbon of 0.43 percent.

Intrusion aid causes slight expansion of grout, and is supposed to prevent agglomeration of solids, and to aid penetration into fissures. It was used in all tests at rate of 1 percent of cement, or of cement plus fly ash. Calcium lignosulfonate was used for same purpose, but did not cause expansion. It was used at rate of 0.23 percent of the weight of the cement.

Finds: (1) Smooth fissure surface, and grout solids sieved through a No. 50 sieve permit use of lower water-cement ratio than rubbed fissure and sieving through No. 30 sieve. (2) Grout with fly ash could not be pumped through 0.01-inch opening regardless of how high a water-cement ratio (maximum 4.30) was used. Fly ash which was used was coarser than the cement, and some particles were larger than the finer fissures. (3) Intrusion aid permitted reduction of water-cement ratio in 0.03-inch fissures when used in cement-fly ash mixes, but did not help in other cases. (4) Intrusion aid permits reduction of water-cement ratio in cement grouts in 0.02- and 0.03-inch fissures, but did not in the 0.01-inch fissures. (5) In general, fly ash helped reduce water-cement ratio, only in fissures of 0.03-inch under 25 and 50 psi pressures, but not under other conditions. (6) At given pressure and fissure opening, the flow of cement plus fly ash grout was greater than for neat cement grout. (7) Intrusion aid did the same but to a larger extent. (8) Crack thickness had great effect on lowest water-cement ratio that could be used, but pressure had little practical effect. (9) The crack opening to grain size ratio should probably exceed 3.0. (10) All grouts with water-cement ratio of 0.6 or less appeared "good" to "fair," and anything with water-cement ratio of over 3.0 appeared "poor." (11) Use of fly ash may have had adverse effect on bond between the two slabs constituting the sides of the fissure—calcium lignosulfonate appeared to improve this. (12) Bleeding was reduced slightly by intrusion aid. (13) Fly ash did not materially affect solubility of grouts at 0.4 water-cement ratio, and appeared to increase that at 0.8 water-cement ratio. (14) Fly ash appeared to increase the fluidity of grouts.

247. KENNEDY, THOMAS B. "Investigation of Pozzolanic and Other Materials to Replace Part of the Portland Cement in Mass Concrete Dams." (U.S.A.) Paper R. 120, Sixth International Congress on Large Dams, New York, September 1958. See Bibliography No. 170, 192, 218, 233, 265.

U.S. Corps of Engineers investigation using water-quenched blast furnace slag, natural cement, fly ash, pumicite, tuff, obsidian, calcined shale, and uncalcined diatomite. Finds: (1) Workability as judged visually, was generally improved by replacements. (2) Slag, fly ash, obsidian, and natural cement appeared to increase bleeding in ¾-inch concrete, but these would not have caused any difficulty in placement, except two blocks made with Fly Ash II. (3) Permeability, although excessive in some specimens at early ages, decreased appreciably at one year. (4) Some early age strengths were very low, particularly with slag and fly ash, but all became satisfactory at later ages. (5) All replacements reduced heat of hydration, both at 3 and 28 days. (6) Durability of all mixes containing air, in laboratory freezing and thawing was satisfactory. In field (Treat Island) exposure, after 566 cycles—blocks in sound condition except for scaling of fly ash specimens—include plain portland cement, natural cément, and fly ash replacement. (7) As result of investigation, it is concluded that properties of within-mass concrete need not be affected adversely by judicious use of replacements. Gives specifications.

248. LAFUMA, H. "The Influence of Grinding Upon the Pozzolanic Properties of Fly Ash." (Influence du Broyage des Cendres Volantes sur Leurs Propriétés Pouzzolaniques). (France) Paper R. 107, Sixth International Congress on Large Dams, New York, September 1958.

Gives results of mortar strength—both compressive and flexural—in mixes with 3 fly ashes, raw and interground. Finds that although all raw fly ashes exceed strengths of controls at 1 year age, they all fall short at early ages. But grinding makes early strengths equal to control or exceed it at 28 days. Grinding also increases Feret's coefficient of pozzolanic activity and exceeds control at 7 days. The ash-cement mixtures give in addition to reduced price, higher strengths at 1 year, and reduced shrinkage and heat of hydration at early ages. Grinding improves the early age strength. Therefore, such mixtures are advantageous for use in large concrete masses such as large dams.

249. LEONARD, GEORGE K. and SCHWAB, PHILIP A. "TVA Uses Non-Specification Fly Ash." Civil Engineer, Vol. 28, pp. 188-192, March 1958. See Bibliography No. 250, 251.

Using mechanically collected ash of specific surface below 2,000, find improved concrete for power plant and lock. Fly ash increases ultimate strength, reduces lime leaching, provides greater watertightness, reduces drying shrinkage, and improves workability.

Conclude: (1) Lower specific surface fly ash similar to that produced through mechanical collection at TVA plants can be used successfully to improve concrete properties. (2) Fly ash benefits lean mixes more than rich mixes. (3) Minimum of 2.3 percent air required for durability. (4) Air-entraining agent requirement is increased 3 to 4 times to obtain same air as control mix. (5) TVA fly ash has large potential use as filler in bituminous concrete and in block manufacture. Use 30 percent replacement by weight of cement and 8.5 percent replacement of sand.

250. LEONARD, GEORGE K., MC MAHAN, WARREN, and RAGSDALE, LEE M. "Canal Juggling Keeps Lock Traffic Moving." Engineering News-Record, Vol. 160, pp. 40-44, April 10, 1958. See Bibliography No. 249, 251.

Describe construction operations on new lock at TVA's Wilson Dam, with special emphasis on canal construction.

Fly ash concrete mixes for both mass and face concrete are given. Project uses crushed limestone aggregate and manufactured sand. For mass concrete, using 6-inch maximum aggregate size, the mix contains 0.51 barrels of cement with 170 pounds of fly ash, and gives at 28 days a compressive strength of 2,500 psi, and of 3,800 psi at 90 days. For face concrete, the cement content is 0.88 barrels with 182 pounds of fly ash, resulting in a compressive strength at 28 days of 3,500 psi, and of 4,800 psi at 90 days.

Fly ash comes from TVA Colbert steam plant and is mechanically collected, resulting in a relatively coarse product with only 80 percent passing the No. 325 mesh screen. It is used not only as cement replacement, but also as a replacement of sand fines, 32 percent and 20 percent as cement replacement in the two mixes, respectively, and 8.6 percent and 10 percent as sand replacement in the same manner. Freezing and thawing tests indicate that with a minimum of 2.3 percent of air entrainment, the durability exceeds that of regular concrete, even with only 28-day curing prior to start of freezing and thawing test. But without air entrainment, and curing short of 90 days, the durability is less than that of regular concrete.

251. LOFFT, HENRY T. and BELL, CORYDON W., JR. "Lock of 100-ft Lift Built into Wilson Dam." Civil Engineering, Vol. 28, pp. 496-501, July 1958. See Bibliography No. 249, 250.

General description of construction procedures and problems. Make use of fly ash in concrete to reduce cost and improve workability of mix containing crushed limestone aggregate. With savings, however, come difficulties. The fly ash has the consistency of "dense smoke," thus creating a serious dust problem requiring proper handling. Some of the provisions for reducing the dust problem are vents in the silos, and introducing the fly ash with the mixing water. Give mix proportions for both mass and face concrete.

252. LOVEWELL, C.E. and WASHA, GEORGE W. "Proportioning Concrete Mixtures Using Fly Ash." Proceedings, American Concrete Institute, Vol. 54, pp. 1093-1101, June 1958.

For comparable early strengths, the fly ash mixes require fly ash replacement in excess of the replaced cement. The fly ash required to replace a given amount of cement increases as the richness of the concrete mix decreases. In no case should more than one bag of cement be replaced by fly ash in 4 to 6 sack mixes. These conclusions were reached from compressive strength tests of three series of mixes using Type I and Type IS portland cements, with Chicago Fly Ash.

253. MAC DONALD, R.H. and ALLEN, A.C. "Use of Fly Ash at Lednock Dam." (Britain) Paper R. 11, Sixth International Congress on Large Dams, New York, September 1958.

Used 20 percent by weight replacement in inside concrete and 15 percent in outside layer. Obtained 71 percent of 28-day strength of plain concrete. No apparent relationship between fineness and strength, but definite correlation between carbon content and strength. Permitted reduction of water-cement ratio by 0.04, and produced more workable concrete, and slower hardening. Latter helped in removal of laitance and permitted placing over larger areas without loss of bond. Fly ash lowered heat of hydration. Specific surface measurements unsatisfactory, and suggest some other criterion be used. Experimented with accelerated specimen curing in hot water, but did not develop it sufficiently to be reliable.

254. MARSHALL, W.T. "The Influence of Fine Aggregate on Concrete Containing Fly Ash." (Britain), Paper R. 1, Sixth International Congress on Large Dams, New York, September 1958. See Bibliography No. 186, 187.

In two experiments in which 20 percent by weight replacement was used, finds differing results. In the Glasgow University experiment, finds workability not greatly affected by fineness of fine aggregates, but compressive strength decreased with increased fineness. In the Lednock Dam tests, finds loss of workability with increased fineness, and no change in compressive strength.

255. MIZUKOSHI, TATSUO. "Study of the Fly Ash Concrete in Sudagai Dam." Paper R. 29, Sixth International Congress on Large Dams, New York, September 1958.

Study shows, using fly ash with less than 1 percent (0.84) ignition loss and fineness of 3,190, that: (1) Higher strength is obtained at later ages with 20-30 percent replacement (solid volume). (2) Lower heat of hydration and shrinkage, improved workability and impermeability, unimpaired freezing and thawing durability result. (3) Thus, improved quality of concrete, and economy in construction resulted from use of fly ash. (4) Obtained good quality control on job. (5) Field curing gave lower strength than standard curing, and so did sealed curing, but in every curing condition the fly ash concrete gave higher strengths after 4 to 6 months than plain concrete.

256. MORGAN, H.D. "Some Advantages and Economies Obtained by the Inclusion in Concrete of Admixtures and Fly Ash." (Britain) Paper R. 12, Sixth International Congress on Large Dams, New York, September 1958.

Reviewing various data from different projects and tests finds: (1) Advantages of plasticizers are increased workability, reduced water-cement ratio, and increased strength. In mass concrete by reducing cement, reduces heat of hydration. No adverse results observed so far. (2) Waterproofers help maintain dry basements and watertight chambers (such as Sika No. 1). (3) Densifiers (such as Plastiment) improve mass concrete by reducing cement, thus reducing heat of hydration, and by retarding set (which also reduces heat of hydration peak), and provide more impervious concrete with the leaner mixes. (4) Fly ash, no doubt, is useful as replacement of cement and is a potentially important material. At present, it is highly variable, but it is hoped this will be improved with increased demand. Unpopular because hard to handle and one more material to batch. Last disadvantage applies to all additives. With proper equipment, problem of handling is reduced considerably for all practical purposes. Advantages are saving in cost, increased workability, increased ultimate strength, decrease in generated heat by virtue of slower setting, and greater ultimate impermeability. Disadvantages are not as certain, but variations in consistency, possible high carbon, and thus reduced silica-alumina balance, may have a bearing. Fineness is more important than carbon. Two courses are open to correct effect of carbon in fly ash. The first is to insure that all compounds contained in the ash are finely divided, and the second consists in the cement replacement on the basis of exclusion of the carbon content, or the anticipated average carbon content for the cementitious material. (5) All additives should be used only after thorough testing or when their effect on mix is known from previous experience.

257. POLIVKA, MILOS and BROWN, ELWOOD H. "Influence of Various Factors on Sulfate Resistance of Concretes Containing Pozzolan." Proceedings, American Society for Testing Materials, Vol. 58, pp. 1077-1100, 1958.

Use Type I and Type V cements, and pozzolan replacements of 25 percent by weight of calcined shale, raw pumicite, and fly ash, in concrete mixes. Specimens immersed in 10 percent NaOH (other cycles and weaker solution also used). Find: (1) Loss of weight and photographs of appearance are best criteria to evaluate resistance. (2) Little benefit from long initial curing time. (3) Probably most promise is method using complete immersion in 10 percent solution (50 percent Na_2SO_4+50 percent $MgSO_4$) at 70° F. (4) Of all pozzolans and all conditions of treatment used, fly ash mixtures show best resistance. (5) Type V cement stands up as well as Type V blended with pozzolan.

258. STEOPOE, A. "The Action of Pozzolans and Its Influence on the Structure of Hardened Binders and on the Properties of Concrete." (Le Comportement des Pouzzolanes et son Influence sur la Structure des Liants Durcis et sur les Propriétés Techniques des Bétons). Paper R. 35, (Roumania), Sixth International Congress on Large Dams, New York, September 1958.

Detailed discussion of pozzolans and mechanics of some of the phenomena that are observed. The most important points may be summarized: (1) Pozzolans are finely divided natural materials which, mixed with lime and water, harden in a moist atmosphere, and after hardening are water resistant. Without lime, pozzolans do not harden. There are artificial materials that react in the same manner—known as artificial pozzolans. (2) Silica reacts slowly with the lime, but alumina reacts relatively fast. Inasmuch as most Roumanian pozzolans are high in silica (tuffs), the paper is limited to these. Gives table showing silica content of various natural pozzolans. (3) Gives chemistry and physico-chemical reactions of silica and alumina with lime—action is a surface phenomenon. (4) Pozzolans in presence of NaOH and Na_2CO_3 give soluble products and should only be evaluated in presence of $Ca(OH)_2$. (5) To qualitatively evaluate pozzolanic activity, proposes following test: Mix proposed pozzolan and $Ca(OH)_2$ in equal quantities with enough water to obtain a plastic paste, and spread on a sheet of glass in a layer 30 x 30 x 5 mm (1¼" x 1¼" x ¼" approx.), then place in a water-saturated atmosphere devoid of CO_2. If the pozzolan is active, the layer hardens in 3 days and remains intact after boiling for 2 hours. For a quantitative evaluation, refers to a method he proposed previously which is based on determining the composition by solution in HCl, after having reacted with lime in a plastic paste after various curing periods (gives references in German and French for more details). (6) In a pozzolan cement mixture the volume increases in excess of the change of volume of replacement pozzolan due to change in the electric charges on the ions, and that is the reason for increased water demand. Set is also delayed because of increase in water-cement ratio. This is true for cements high in CaO and pozzolans of low activity. The reverse is true in other cases, and the interval between beginning of set and final set is reduced to a minimum. For larger quantities of pozzolans, the beginning of set is still accelerated further but final set is delayed appreciably. (7) Concrete with pozzolan has lower unit weight than normal concrete but has good impermeability when saturated, but when air dried the less dense gel contracts more than in normal concrete paste and because of the interfering of the hardened embedded particles, there develop microfissures—this influences physical properties of mortars rich in pozzolans. To observe this, it is best to use normal mortars and not mortars with standard uniform grained sand. (8) To determine effect of these basic properties on the practical properties of concrete, author uses two Roumanian pozzolans with 8 cements in plastic concrete containing 300 kg of cementitious material per cubic meter, and replacements of 25 and 50 percent with water-cement ratios of 0.70 for control, 0.75 for 25 percent replacement, and 0.80 for 50 percent replacement. Average reduction of unit weight was 3 percent. Tests were made on prisms 10 x 10 x 55 cm, at 28 and 56 days in water, and after 7 days in water followed by 21 and 49 days in air. In air the unit weight decreased on the average 3.7 percent for the control, 4.5 percent for 25 percent replacement, and 5.6 percent for 50 percent replacement. Compressive strength is lowered for both methods of curing. For water curing the reduction is less than for air curing and improves after 56 days, while in air, reduction continues after 56 days. For flexure the same general trends are noted but are accentuated for air drying. This is because the microfissures affect tensile strength more than the compressive strength. The slow gain, under water curing conditions, is due to the larger volume and therefore the slower hydration due to the slower suction. Impermeability is also decreased after air curing, but returns after re-immersion, because the gel swells and seals off the microfissures. (9) In concretes, with 10 percent replacement, no change takes place in resistance to freezing and thawing because the quantity of pozzolans is too small to affect the structure of the hardened paste, but if replacement exceeds 10 percent of the weight of the cement, the durability to freezing and thawing decreases, as the pozzolan increases, particularly if air curing which amplifies the micro- and macrofissures has taken place. For this reason, cement containing pozzolans is prohibited for concrete exposed to water and alternate freezing and thawing. (10) Resistance to corrosive action is not due to fixation of lime by pozzolan, but rather by formation of insoluble silica and alumina which results from the decalcification action of the aggressive waters, which seal the pores and improve the impermeability. (11) Pozzolans rich in reactive silica should not be used in hydraulic structures.

259. WELCH, G.B. and BURTON, J.R. "Sydney Fly Ash in Concrete." Commonwealth Engineer, Vol. 45, pp. 48-53, December 1957, and Vol. 45, pp. 62-67, January 1958. See Bibliography No. 142.

Report in two parts: (1) Refers to U.S. work on fly ash and improvement obtained in concrete properties. (2) Sydney fly ashes are higher in carbon than the better U.S. product, but effects of variations in physical and chemical characteristics were found to be less in concrete than in mortar. (3) Rate of gain in compressive strength used as a measure of pozzolanic activity. (4) Four Sydney fly ashes were used in the tests: Pyrmont B sample 1, Pyrmont B sample 3, Ultimo, and Bunnerong, with low heat portland cement in 3 of the test series, and with high early in a fourth series. Nepean river gravel and sand were used in the mix. Inert pulverized weathered basalt was used in some of the tests for comparison. Tests were conducted at New South Wales University of Technology. Basic mix 0.63 water-cement ratio and $^3/_4$-inch maximum aggregate, with 5.00 bags of cement and 296 pounds of water per cubic yard. (5) First series studied effect of replacing cement with fly ash in varying proportions; 2nd series used fly ash as admixture, either added to the mix or replacing sand; 3rd series examined effect of air entrainment; 4th series examined effect of fly ash on high early strength concrete. (6) Cement replacement by fly ash was on equal weight basis resulting in about 50 percent increase in absolute volume replaced. When used as addition or sand replacement, the fly ash was also determined on a weight basis, expressed as percentage of the cement. (7) Cylinders (4" x 8") were used for compressive strength tests, and were stored in water at 70^0 F, capped with mortar except for the 7-day tests, which were capped with sulphur-fly ash. (8) Analysis showed 8 percent coefficient of variation and 8 cylinders out of 420 were discarded because results showed them to be outside the universe being tested. (9) Results are expressed as percentage of 90-day mean strength of the control, but in case of high-early strength, 28-day strength was used as basis. (10) With 15 percent replacement using low heat cement, Ultimo exceeded control at 60 days and kept gaining while Pyrmont B-1 remained lower than control but closer to control with time up to 12 months. (11) With 25 percent replacement of low heat cement, all 4 fly ashes remained below control though continuously closer to control with time. (12) With 35 percent replacement of low heat cement, all 3 remained well below control. (13) With high early strength replacement of 25 percent and 35 percent of Pyrmont B-3, strengths remained below control, but with 25 percent replacement of sand they exceeded control at all ages. (14) Suggest that carbon content has important effect on water requirement and air entrainment, while the glass phase of the fly ash is more important in pozzolanic activity. (15) In all cases of addition or sand replacement, strengths exceeded control dramatically—use 15 percent admixture or

25 percent sand replacement, also part replacement of cement and part addition, 25 percent + 25 percent. The latter did not catch up with control strengths until about 8 months. (16) Required three times amount of Darex. Reduction of strength with fly ash for equal air was less at 90 days than in control—9 percent and 17 percent, respectively. (17) Find with their fly ash, 15 percent optimum replacement against Davis' 30 percent. (18) Slump and flow are little affected with replacements up to 25 percent, but definite reduction in consistency occurs at higher fly ash contents. Water requirements of Sydney fly ash are high as compared to Chicago fly ash, and therefore resulted in stiffening of mix with increase of fly ash. In spite of this, concrete was more workable—that is, more cohesive, and less tendency to segregate due to increase of absolute volume of fines in mix. Reduced bleeding by use of fly ash.

Concluded for Sydney fly ash: (1) Sydney fly ashes are slightly inferior to better class of U.S. fly ashes when used to replace cement, using strength gain at 12 months as criterion. (2) Optimum replacement of 15 percent with prolonged moist curing, but reduction of strength with 25 percent replacement is relatively small—only about 10 percent at 6 months. (3) Use of Sydney fly ash to replace portion of sand, or as an addition results in increased compressive strengths at all ages. (4) Rate of gain increases with high early strength cement. (5) Consistency may be slightly improved with small amounts of Sydney fly ash to replace cement, sand, or as an admixture, but is considerably reduced with 25-35 percent replacement of cement depending on carbon content. On the other hand, workability such as cohesiveness, placeability, reduced segregation and bleeding, is considerably improved with small amounts of Sydney fly ash of medium carbon content, even though workability is reduced with the higher fly ash contents, the mix being markedly drier and less plastic. (6) Effect of carbon on strength at late ages is less marked in concrete than in mortar, but high carbon may considerably affect workability and air entrainment. (7) Sydney fly ashes would appear to be suitable in mass concrete with up to 25 percent replacement, and for structural work (when rapid drying out is prevented) using smaller replacements of cement, or replacing up to 15 percent sand, or as a workability admixture. It should be possible to reduce cement slightly when using fly ash as sand replacement, or as an admixture, and still maintain 28-day strengths.

260. YAMAZAKI, KANJI. "Influence of Various Mineral Fines on the Properties of Concrete." Paper R. 30, Sixth International Congress on Large Dams, New York, September 1958.

Very thorough study involving 5 fly ashes, pulverized slag, graywacke, and limestone. Fly ash properties: specific gravity of 2.08 to 2.41; specific surface 2,910 to 3,620 square centimeters per gram, and for separated samples a fineness up to 5,790; loss on ignition of 0.90 to 2.63; and spherical particles of 50-75 percent. Gives grain size distribution of fly ashes, and proportions of different types of grains.

Finds: (1) All fly ash decreased unit water requirement, heat of hydration, drying shrinkage, and increased strength at advanced ages and resistance to sulfates. (2) These advantages claimed to be due to low carbon and low percentage of coarser particles. (3) Fly ashes were collected under constant load conditions, and would not have been this good had they originated from power plants with varying load. (4) Fly ash did not reduce bleeding as much as other fines, and in one case actually increased it. (5) With 30 percent (absolute volume) cement replacement, water content ranged from 94 to 97 percent of control, bleeding from 90 to 190 percent, compressive strength at 91 days from 71 to 88 percent, and watertightness index in middle of specimens from 70 to 82 percent—the more spherical particles the more bleeding but the most reduction in water requirement. (6) Fly ash decreased shrinkage in all cases from 80 to 87 percent, with 30 percent replacement at 28 days. (7) Rock fines have no pozzolanic action, but as additions in amounts up to 10 percent, they improve strength, decrease bleeding, and improve watertightness—they will not increase water requirements if of sufficient fineness and satisfactory particle surface properties, but under unfavorable fineness and particle surface properties, they increase water requirements. (8) Rock fines lower freezing and thawing durability, if used in large quantities, and also the resistance to sulfates, and at the same time increase drying shrinkage. Limit should be about 10 percent of the weight of the fine aggregate but should be adjusted to aggregate and other ingredients in the mix. (9) Freezing and thawing durability for fly ash concrete is lower than control without air entrainment, but close to control and adequate, with air entrainment.

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261. AMERICAN SOCIETY FOR TESTING MATERIALS. "Effectiveness of Mineral Admixtures in Preventing Excessive Expansion of Concrete Due to the Alkali-Aggregate Reaction." Designation: C 441-59T, 1959 Supplement to Book of Standards, Part 4, pp. 113-116, 1959.

Test method for determining effectiveness of mineral admixtures in preventing excessive expansion due to reaction between aggregates and alkalies in portland cement. Uses expansion mortar bars with Pyrex glass aggregate, in control and in bars made with a mixture of cement and admixtures, the latter replacing a portion of the cement. Requires 75 percent reduction in expansion as compared to control without admixture.

262. ANON. "Kentucky Fly Ash Plant Serves Lock and Dam Projects." Pit and Quarry, Vol. 52, No. 5, pp. 126-127, November 1959.

Description of Walter N. Handy Company fly ash handling plant at the Cane Run Power Plant of the Louisville Gas and Electric Company. Plant takes fly ash from power plant, stores it, and then loads it into bulk trucks.

263. BAUER, WOLF G. "The Coming Role of Pozzolans." Pit and Quarry, Vol. 51, No. 12, pp. 92-97 and 101, June 1959, and Vol. 52, No. 1, pp. 89-91 and 96, July 1959.

Covers in general advantages of pozzolans in improving quality of concrete and compensating for some deficiencies in aggregates. Attempts to show cement industry that it is to their advantage to manufacture pozzolan cements. Stresses need for some type of pozzolan industry association.

264. BRZAKOVIC, P. "Study of the Utilization of Fly Ash in Building." Nase Gradevinarstvo (Belgrade), Vol. 13; Part 1, No. 2, February 1959; Part 2, No. 3, pp. 42-47, March 1959; Part 3, No. 4, pp. 86-92, April 1959. Abstracted in Proceedings, American Concrete Institute, Vol. 50, p. 801, February 1960.

Presents a thorough description of all characteristic properties of fly ash in cement and lime mixtures, especially those used for the production of lightweight concrete.

Pozzolanic effects and the influence of different factors, such as fineness, carbon content, and water-cement ratio are discussed in Part 2. Characteristics of concrete made with fly ash, such as its influence on strength, resistance to weather conditions, especially to frost and corrosion, are discussed. The study includes shrinkage, heat of hydration, alkali reaction, and waterproofing of these concretes.

Part 3 refers primarily to lightweight concrete manufactured in Yugoslavia, especially those utilizing fly ash from the power station in Kostolac, Serbia. It is emphasized that this fly ash, obtained by combustion of lignite, has similar properties to European anthracite coals. Investigation of lightweight concrete using this type of fly ash shows that good quality can be obtained from a mixture of 70 percent fly ash and 30 percent of cement lime. Such concrete weighs 71 to 80 pounds per square foot after treatment in the vacuum press. Insulation properties are about the same as lightweight concretes with light aggregates.

265. BRZAKOVIC, P. "Use of Fly Ash in Building Industry." Nase Gradevinarstvo (Belgrade), Vol. 13, No. 7, pp. 149-155, July 1959. Abstracted in Proceedings, American Concrete Institute, Vol. 56, p. 1083, April 1960.

Utilization of fly ash is discussed from three different aspects: (1) with reference to existing Yugoslav standards; (2) consideration of experiences gained in the Yugoslav building industry; (3) recommendation of certain foreign uses to be tried in Yugoslavia.

Other materials reviewed are those that may be manufactured by addition of fly ash, including: binding materials, concrete, porous brick products, asphalt, and lightweight aggregates. Binding materials include hydraulic lime, pozzolanic cements, and pozzolanic metallurgical slag cements. Use of fly ash in heavy and lightweight concrete is discussed, especially concrete produced with lime and fly ash. Experiences in brick industry confirm German investigations. Special attention is paid to the lightweight aggregates obtained by sintering of fly ash. Three types of furnaces for manufacturing this material are described. Finally, the author discusses the possibility of using fly ash in road slab construction.

266. CORDON, WILLIAM A. "Pozzolans as a Natural Resource of the State of Utah." Utah State University Research Project U-22, Logan, Utah. October 1, 1959.

Defines pozzolans and gives history back to Roman days. Gives outline of federal specifications. Tests made on Utah fly ashes and natural pozzolans. Finds good fly ash at Gadsby Plant of Utah Power Company but not so good at Carbon where the quantities are much more abundant. Former is converting to oil burning and will have less fly ash. Latter has fly ash that is coarse and high in carbon. Fly ash had the greatest strength and workability when compared to 3 natural pozzolans tested, but rather low durability, for given water requirement. Apparently no air entrainment was used.

Concludes that all four pozzolans tested are usable in concrete, providing calcination, grinding, and air entrainment are carried out properly.

267. DAVIDSON, D.T., MATEOS, MANUEL, and KATTI, R.K. "Activation of the Lime-Fly Ash Reaction by Trace Chemicals." Highway Research Board, Bulletin No. 231, pp. 67-81, 1959.

Using Ottawa sand, fly ash, lime, and each of 47 different chemicals in laboratory mixes, evaluate the strength improvement due to small proportions of the chemicals in the mixtures.

Find several chemicals increase early strength, while others benefit long-term strength more than early strength. Calcium chloride is one of the most promising in latter group.

All factors considered, sodium carbonate (soda ash) is considered the most promising trace chemical activator investigated. Best results are obtained when it is mixed in powdered form. The use of 0.5 percent powdered sodium carbonate in a mixture of 75 percent Ottawa sand, 5 percent lime, and 20 percent fly ash, increased 7-day strength about 60 times, and 28-day and 4-month strengths about two times.

268. HANSEN, W.C. "Release of Alkalies by Sands and Admixtures in Portland Cement Mortars." American Society for Testing Materials, Bulletin No. 236, pp. 35-38, February 1959.

Using various sands and pozzolans, including fly ash, in 1" x 1" x 11¾" mortar prisms, leaches them in de-ionized water, and analyzes extracts periodically for K_2O and Na_2O, at various intervals, up to approximately one year.

Finds that alkalies are released with 25 percent fly ash admixture and high alkali cement with graded Ottawa sand, in excess of control without fly ash, indicating that fly ash contributes alkalies to the solution, or liquid phase of hardened cement paste. He concludes that certain admixtures (including fly ash) and sands, might release alkalies in sufficient quantities to produce expansion in concrete if the aggregate also contains minerals which would react with the alkalies. Therefore, the alkalies in admixtures and aggregates should be considered in designing concrete if the aggregate is known to contain, or suspected to contain, components which will react with alkalies.

269. KONDO, YASUO, TAKEDA, AKIHIKO, and HIDESHIMA, SETSUJI. "Effect of Admixtures on Electrolytic Corrosion of Steel Bars in Reinforced Concrete." Proceedings, American Concrete Institute, Vol. 56, pp. 299-312, October 1959.

Laboratory studies on concrete cubes with embedded reinforcing, with calcium chloride or fly ash in mixes, and also these admixtures with calcium lignosulfonate additions.

Apply both direct and alternating current of varying voltages. Purpose is to simulate corrosion effect from current leakage in electric railway operation.

Find, in control, bond improves with addition of CaC_2 and is enhanced by use of lignosulfonate, while in fly ash concrete, bond decreases as percent substitution increases but lignosulfonate brings it back to value obtained in control. When subjected to either direct or alternating current, the bond increases in all cases.

Also find no effect from direct current up to 5 volts when using calcium chloride or fly ash as admixtures, where parts of the reinforcing bars are exposed and act as anodes. At 10 volts dc, when 1 percent and more calcium chloride or 30 percent and more fly ash are used, the entire surface of the parts of reinforcing bars embedded in concrete show light rust, but no cracking occurs and bond of steel to concrete is increased by 4 to 10 percent. With the same amount of calcium chloride or fly ash at 20 volts dc, the rusting of bars embedded in concrete differs, depending on the amounts of admixture used, in some cases being comparatively pronounced, and cracking of concrete occurs when the amount of calcium chloride used exceeds 1 percent. Over-all bond of steel to concrete is not lowered but is rather increased by 13 to 18 percent. When the reinforcing bars act as cathodes or when alternating current is applied no electrolysis occurs under 20 volts.

When the properties of concrete containing 1 percent calcium chloride or 30 percent fly ash are improved by the addition of 0.25 percent calcium lignosulfonate, the corrosion phenomena of bars acting as anodes, occurring when direct current is applied, are greatly reduced.

It appears that the damage from electrolytic corrosion in reinforced concrete containing calcium chloride or fly ash as admixtures is generally overestimated. The greatest cause of such damage is current straying from railroad tracks, the voltage reaching concrete nearby being about 14 volts when ties and ballast are approximately 10 years old and electrical resistance is weakened. However, when steel bars are not exposed from the concrete no corrosion can be seen although 1 percent calcium chloride is used and as much as 20 volts dc are applied.

Usually, the actual voltages of currents reaching concrete in the field are considerably lower than the 20 volts used in these experiments and furthermore they occur off and on over a long period. It may be assumed that reinforced concrete containing calcium chloride or fly ash in moderate quantities can be amply protected by improving properties of the concrete by addition of calcium lignosulfonate and through observation of proper concrete practices.

270. LEONARD, R.J. and DAVIDSON, D.T. "Pozzolanic Reactivity Study of Fly Ash." Highway Research Board, Bulletin No. 231, pp. 1-17, 1959.

From laboratory studies of several fly ashes mixed with lime, find that rate of compressive strength development is directly related to rate of lime absorption by fly ash. This is limited by rate of diffusion of calcium through reaction products. Rate of diffusion varies with lime concentration, temperature, and type of fly ash. At temperatures less than 20° C. (68° F.) most fly ashes are nonreactive.

The source of strength of lime-fly ash mortars is the reaction products formed as a result of pozzolanic reaction. From X-ray diffraction studies it appears that a crystalline product does not form at first, but develops from a noncrystalline reaction product. The initial product is probably a gel. The final crystalline product is believed to be calcium silicate hydrate I, a reaction product that has been found in set portland cement pastes.

Unburned material (carbon) that is found in fly ashes is nonreactive with calcium hydroxide, and its presence seems to indicate a fly ash of coarse grain size in both the organic and inorganic phases. Since the total mortar strength developed depends on the number of contacts of the cementitious reaction products, the organic material breaks the continuity of this system and thus decreases the total strength.

271. MINNICK, L.J. "Fundamental Characteristics of Pulverized Coal Fly Ashes." American Society for Testing Materials, Annual Meeting, June 1959. Summary in American Society for Testing Materials Bulletin No. 239, p. 12, July 1959. Proceedings, American Society for Testing Materials, Vol. 59, pp. 1155-1177, 1959. See Bibliography No. 53, 70, 101, 153.

Finds from chemical, physical, X-ray, spectro-graphic, microscopic, and differential thermal analyses, that differential thermal analysis results correlated with strength or X-ray may prove a useful tool for initial evaluations.

272. PEPPER, LEONARD and MATHER, BRYANT. "Effectiveness of Mineral Admixtures in Preventing Excessive Expansion of Concrete Due to Alkali-Aggregate Reaction." American Society for Testing Materials, Annual Meeting, June 1959. Proceedings, American Society for Testing Materials, Vol. 59, pp. 1178-1203, 1959. See Bibliography No. 170, 192, 233, 247.

Twenty materials, representing eight different classes of mineral admixtures, were evaluated, using both chemical and mortar-bar test methods, for their effectiveness in preventing excessive expansion of concrete due to alkali-aggregate reaction. It was found that the chemical tests cannot be used with reliance to evaluate effectiveness. Each of the replacement materials evaluated will prevent excessive expansion if a sufficient quantity is used. Correlations were found between effectiveness and fineness, dissolved silica, and percentage of alkali retained by reaction product.

Five of the materials tested (a fly ash, a tuff, a calcined shale, a calcined diatomite, and an uncalcined diatomite) showed a reduction in alkalinity of 40 percent or more when tested by the quick chemical test. All of these except the fly ash met the requirement proposed by Moran and Gilliland for the relationship between reduction in alkalinity and silica solubility.

Six of the materials tested (two slags, a fly ash, a pumicite, and two calcined shales) reduced mortar-bar expansion at least 75 percent with high-alkali cement and Pyrex glass aggregates when used as 50, 45, 35, and 30 percent replacements of the cement.

Calculations were made that suggest that the minimum quantity of each material required for effective prevention of excessive expansion ranged from 10 percent for the synthetic silica glass to 45 percent for one of the slags. By groups, these calculated minimum percentages were: calcined shales, 19 to 29; uncalcined diatomite, 22; volcanic glasses, 32 to 36; slags, 39 to 45; and fly ashes, 40 to 44.

273. U.S. BUREAU OF RECLAMATION. "Summary of the Results of a Study of the Alkali Release from Various Combinations of Pozzolans with Hydrated Lime versus the Expansion Due to the Alkali-Aggregate Reaction in Pyrex Mortar Bars." Petrographic Laboratory Report No. PET-123, June 3, 1959.

Test several pozzolans, among them two fly ashes with high, medium, and low alkali cements for amount of leached alkalies and expansion in Pyrex expansion bars. Find no apparent relationship between amount of alkalies leached and expansion obtained from bars.

274. VOLLICK, CHARLES A. "Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on the Properties of Plastic Concrete." Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, American Society for Testing Materials, Special Technical Publication No. 266, pp. 180-200. See Bibliography No. 275.

From tests made on two fly ashes, using a water-reducing retarder, finds a reduction of water from 5 to 10 percent, but less than reduction obtained when no fly ash was used.

Refers to work by Michelis on Bureau of Reclamation project where a reduction of 7.5 percent was obtained with a pozzolan mix with admixture, and 14 percent without pozzolan. Work at Tecolote Tunnel with a pozzolan mix and water-reducing retarder in some 16,000 cubic yards of concrete showed water requirement of 9.4 percent less than without admixture.

275. WALLACE, G.B. and ORE, E.L. "Structural and Lean Mass Concrete as Affected by Water-Reducing, Set-Retarding Agents." Symposium on Effect of Water-Reducing Admixtures and Set-Retarding Admixtures on Properties of Concrete, American Society for Testing Materials, Special Technical Publication No. 266, pp. 38-93. See Bibliography No. 274.

Very thorough and detailed summary and data developed through tests on water-reducing agents by Bureau of Reclamation. General conclusions:
(1) Improvements in compressive, tensile, and shear strengths, resistivity to freeze-thaw and sulfate-induced expansive forces are obtained through the addition of optimum amounts of water-reducing retarders to structural and mass concrete mixes containing given amounts of cement. These benefits are reduced in amount when cement content is reduced to offset cost of

admixture. Adjustment of entrained air is usually required. (2) Ease of handling concrete as measured by slump loss is not usually changed. Principal contribution of these admixtures towards workability is through their ability to extend the vibration time and thus reduce possibility of cold joints. The surface retardation, under moderate temperature and humidity conditions, permits more time between floating and troweling operations. Concrete with water-reducing retarders may require less effort to pump through pipelines. (3) Volume changes due to wetting and drying and permeability of mass concrete are not affected sufficiently to warrant being taken into consideration in designs and construction procedures. Reduced temperature rise as a result of lowered cement content offers possible savings in cooling mass concrete.

Specifically: (1) Different agents affect mix water requirement and entrained air differently for various cements and given admixture dosage, and differently for the same cement with varying admixture dosage. (2) Water requirement reduction was more effective with lignin type agents than with hydroxylated carboxylic acid agents: 6 and 4 percent respectively. (3) Retardation for given agent better with pozzolan than without. With a given pozzolan and 0.37 percent lignin type agent, retardation is better with coarser grind but this may change with different dosage of retarding agent. (4) With rising temperature, larger dosages may be used without objectionable retardation. (5) Concrete with both pozzolans and water-reducing retarders, gains strength above control or control with pozzolan alone, in some cases even at early ages. The agents appear to increase pozzolanic activity. Improvement in strength is not temporary in nature but can still be detected after 5 years, in mass concrete. Flaming Gorge Dam 3-sack mix at 180 days containing 33 percent fly ash and lignin type agent had strength of 130 percent of control at 28 days, as compared to a strength of 114 percent for the same age for a mix with agent alone. Monticello Dam mixes indicate the mix with fly ash and lignin type agent exceeded in strength all other combinations, after 90 days, and essentially equal to control for earlier ages under standard curing conditions. Under sealed field cycle curing, the same mix with fly ash and agent exceeded in strength, the control at all ages, was essentially equal to the mix with agent alone at ages below 90 days, and exceeded it at higher ages, essentially equaling it again at age of 5 years. The detrimental effect of early high temperature curing (100° F) on ultimate strength is offset in mixes containing pozzolans, by larger than normal dosages of retarding agents even at reduced cement contents due to the agent. The cost of the agent is equivalent to 5 percent reduction in cement. Even with this reduced cement content, the strength obtained is higher than the control. In the field tests an average reduction of 80 percent cement was obtained with 5 percent greater strength. (6) Void parameters of entrained air were essentially the same for concrete with agents and without. Higher freezing and thawing resistance was obtained with concrete having agents, than control concrete without agents. This is valuable in pozzolan concrete. The fly ash mix with agent gave essentially the same number of cycles as the agent alone. With the combination, one can use pozzolan to reduce heat of hydration and water-reducing retarder to increase the durability. The improvement in durability may be attributed to the decreased water-cement ratio. The agents appear to improve the resistance to sulfate attack in most cases. Fly ash and agent show the highest cycles to date without reaching the expansion limit (1,752 cycles and 0.2 percent expansion). (7) Drying shrinkage does not seem to be improved by water-reducing retarders, neither do they seem to have any detrimental effect. In Monticello Dam mixes, the mix containing fly ash and lignin type agent had lower drying shrinkage than control up to age of 1 year, while all other mixes exceeded control after 7 days of age. (8) Temperature rise of mixes with pozzolan and agent exhibited decrease in temperature rise with fly ash mixes, showing the least rise after 7 days. Mixes with agents alone and no pozzolan showed slight increase in temperature rise. Reduction of early temperature rise due to retardation may be beneficial in permitting increased creep to take place while concrete is still capable of accommodating to volume changes without undue cracking. (9) Lignin type agents appear to reduce permeability, but this is not very important as permeability without agents is satisfactory, anyway.

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