Lightweight Concrete Aggregate From Sintered Fly Ash

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Lightweight concrete aggregate is being produced commercially from pulverized coal fly ash by several plants. The products are of good quality, although they vary somewhat with respect to shape and size. The type of fly ash used in the manufacturing process is generally that produced from bituminous coal. The characteristics of fly ash that are required in the forming and sintering process are described. A description of the physical properties of the fly ash aggregate is presented. The evaluation of these aggregates by the use of ASTM methods gives a good indication of the performance of the various materials in structural concrete. Comparisons are provided between other types of lightweight aggregate concrete and, in all cases, the fly ash concrete shows a favorable range of properties. Concrete strengths in excess of 6,000 psi (420 kg/cm^2) can be produced with fly ash aggregate. Of significance in making comparisons is the high rate of absorption of the aggregate, the residual pozzolanic activity, and the relatively low cement factors required for lean concrete. Information is presented on typical mix designs for use in structural concrete.

•THE PRODUCTION of lightweight aggregate from fly ash has received the attention of investigators throughout the world (1,2). Although a number of early attempts to produce a commercial product proved unsucessful, recent developments give every indication that the manufacture of fly ash aggregate is now possible. Furthermore, the product quality is quite acceptable for use in structural concrete, for insulation-type concrete, and as an aggregate for masonry units.

Fly ash serves as an exceptionally good raw material because it is available in large quantities in geographic areas where lightweight aggregates are in demand. The commercial methods in use today produce aggregate by first preparing an unfired pellet or granule of the fly ash followed by firing on some type of sinter strand. Because fly ash usually contains some unburned carbon, there is an opportunity to utilize the available heat generated by burning of residual combustible material during processing. Fly ash aggregates, therefore, are properly classified as "sintered" products rather than "bloated" materials, such as those produced by heating clay or shale in rotary kilns.

Historically, coal ash has often found application as an aggregate. Originally this was in the form of "cinders" from traveling grates or stoker-fed coal burners. These systems have now been largely replaced by pulverized-coal burners and the resulting fly ash is collected in a very finely divided condition in various types of dust-collecting systems, such as cyclone collectors or electrostatic precipitators.

It is the purpose of this paper to describe the requirements for fly ash as used in the sintering processes and the properties of the fly ash aggregates that are produced. Although it is not intended to present the techniques involved in the production of aggregates, some information is included relating to the effect of the manufacturing process on the characteristics of the aggregate.

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TABLE 1

TYPICAL FLY ASH ANALYSES FOR VARIOUS TYPES OF COAL

Sample Source	LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
			Bituminous				
Illinois	2	44	19	19	8	1	4
Kentucky	2	42	20	25	4	<1	2
Ohio	10	41	23	21	1	1	<1
West Virginia	6	41	24	21	4	<1	<1
Pennsylvania							
Source 1	10	47	26	11	2	1	<1
Source 2	5	38	24	26	4	1	1
Source 3	6	40	24	20	6	1	2
Source 4	20	40	23	12	2	<1	<1
England	2	48	26	10	4	2	1
Poland	4	50	26	12	5	2	1
West Germany	3	44	27	12	4	3	<1
			Lignitic				
Minnesota	1	23	12	14	32	10	3
Montana	<1	28	10	11	30	17	1
North Dakota	<1	31	13	11	24	11	4
North Dakota	4	23	16	8	36	9	4
Canada	1	39	21	7	19	5	2
Czechoslovakia	3	58	11	11	15	2	2
France	<1	58	9	22	6	2	2
Greece	2	38	18	9	28	2	3
East Germany	<1	39	7	21	21	2	10
Poland	2	34	8	6	38	4	9

RAW MATERIALS

The types of fly ash available cover a broad spectrum of chemical and physical properties. Table 1 gives some typical analyses of fly ashes from various parts of the world. There are several factors that affect the quality of ash as used in the manufacture of aggregate. Of prime importance is the type of coal used; thus, ash produced from bituminous coal is usually quite low in calcium and magnesium oxides, whereas ash produced from lignite coal is usually high in these two constituents. The presence of excessive amounts of free calcium oxide in a fired aggregate can have deleterious effects; among these is hydration of the oxide, resulting in the formation of "pits" or "pops" in the hardened concrete.

A second factor affecting the quality of the fly ash is the ash content of the coal. The majority of coals used in the United States is relatively low in ash, usually approximately 10 percent. The coals in Europe are frequently quite high in ash content (up to about 45 percent). European practice, therefore, requires that the coal be burned more thoroughly to recover as much fuel as possible. The resulting fly ash is low in residual carbon—in many instances less than 1 percent. Carbon contents in the United States are rarely this low and it is not uncommon for the carbon content of the ash to be in excess of 10 percent. It is essential that fly ash contain not less than about 4 percent and preferably not more than 8 percent carbon to be an acceptable material for aggregate production.

A third factor affecting the fly ash quality is the type of ash collection systems in use. This can directly influence the fineness of the ash. Fineness varies not only between different coal-burning operations but also within a given operation. For example, in a typical collection system used in this country there may be as many as 20 hoppers removing ash from the furnace. The location of these hoppers in relation to the gas flow results in substantial differences in the particle size of the ash.

The variation of properties of the ash influences to a considerable degree the quality control of the sinter strand operations. Thus, if a fly ash changes in its fuel content (residual carbon) from a low to a high value as it is being fed into the firing process, serious difficulties can be experienced in controlling the operation. Variation in iron oxide content is of considerable importance because this ingredient serves as a primary

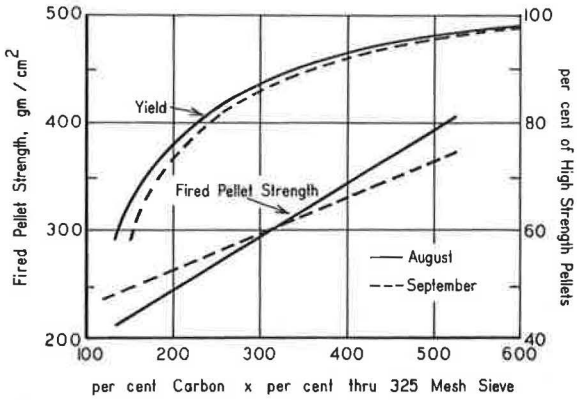

Figure 1. Effect of carbon content and sieve fineness on pellet strength and percentage of high-strength pellets.

flux and substantially influences the operation of the plant process as well as the product quality.

As a result of an intensive study made in the author's laboratory, it has been found that the most important requirements for suitable fly ash are the carbon content (or loss on ignition), the fineness (as measured with a No. 325 mesh sieve), and the iron oxide content. It has also been found from statistical studies that these individual characteristics do not reliably predict the resultant aggregate properties, but that when these characteristics are used as multiple factors they give significant relationships between the fly ash and the properties of the final product.

Figure 1 shows the effect of carbon and No. 325 mesh sieve fineness on both the percentage of high-strength pellets and the fired pellet strength on a large number of samples (at a relatively constant Fe_2O_3 content) taken at different periods of time from one power plant. Although carbon content and sieve fineness do not give a high degree of correlation individually, the product of the percent of carbon times the percent through the No. 325 mesh sieve does, as shown in Figure 1. Based on studies such as these, limits can be established to provide adequate quality control of the raw fly ash for use in the sintering processes.

The interrelationship between fineness and carbon (also Fe_2O_3 content) can be useful in arriving at the selection of fly ash material at the power station. Although fly ash from both mechanical and electrostatic collectors can be used, there are situations that require the rejection of a portion of the fly ash that does not conform to the general requirements of the lightweight aggregate process.

In addition to the control of properties of the raw material, an important factor in the preparation of the aggregate is the water content used in the formation of the green pellets prior to firing. The water is necessary not only to develop adequate physical strength of the pellet but also to control the porosity or absorption of the fired aggregate.

SHAPE AND SIZE OF FLY ASH AGGREGATE

Although there are a few exceptions, most fly ash aggregates develop the ultimate shape and volume of the individual particles at the time the material is formed in the unfired (green) state. Several devices are currently used to form the unfired pellets or granules. Pelletizing drums or pans are used in a few plants. These particular devices form spherically shaped particles usually of a very uniform diameter. In the process developed by the Corson Company, an extrusion principle is used that results in particles of varying shapes and sizes, depending on the selection of the forming equipment. Figures 2, 3, and 4 show typical shapes produced by the different forming processes.

One significant factor resulting from the choice of the forming method is the final density that is achieved in the aggregate. Furthermore, this density also contributes, to a substantial degree, to the absorption of the aggregate. The commercial operations are all engineered to produce a product that retains the discrete shape of the unfired pellet without formation of large clinkers, which are often produced from other types of raw materials.

From the standpoint of producing aggregate for structural concrete, the range of sizes of the pellets are set to meet the basic requirements of the ASTM specification for concrete aggregates. In order to get the proper gradation, usually several methods

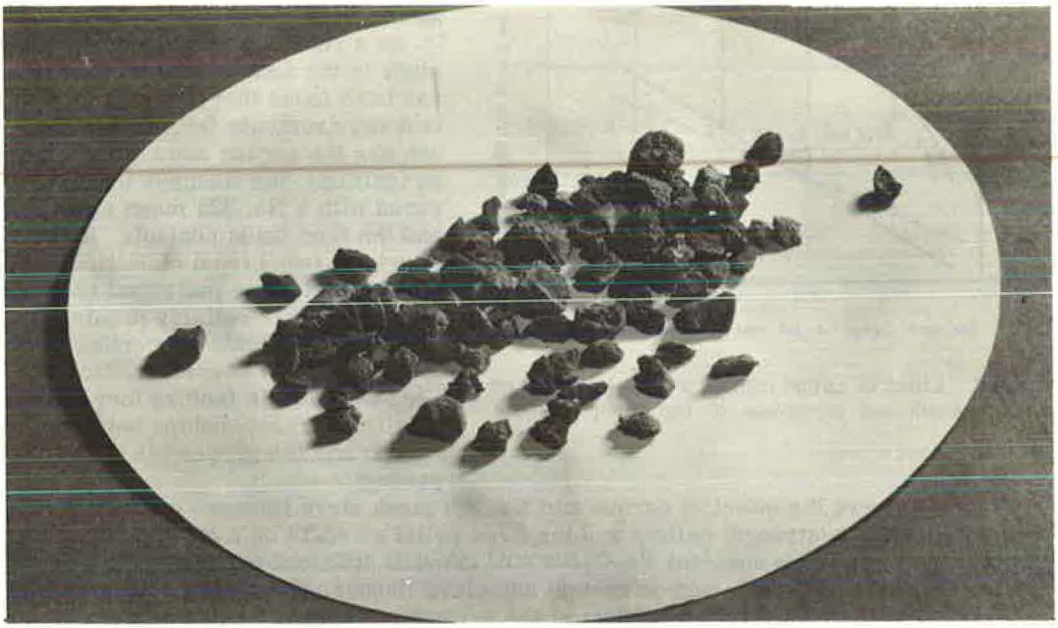

Figure 2. Extruded fly ash aggregate (crushed and graded).

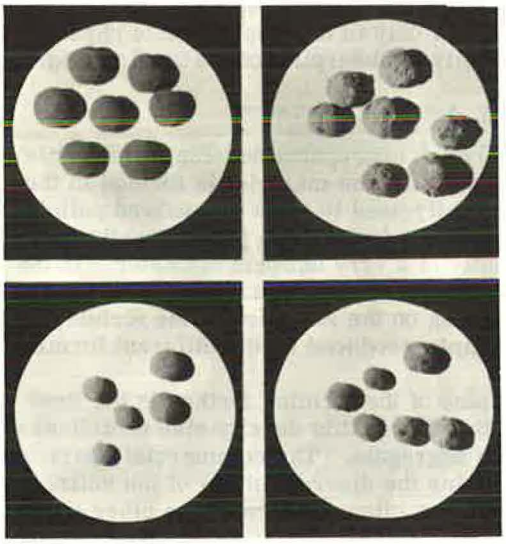

Figure 3. Unfired and fired fly ash aggregate made by pelletizing process.

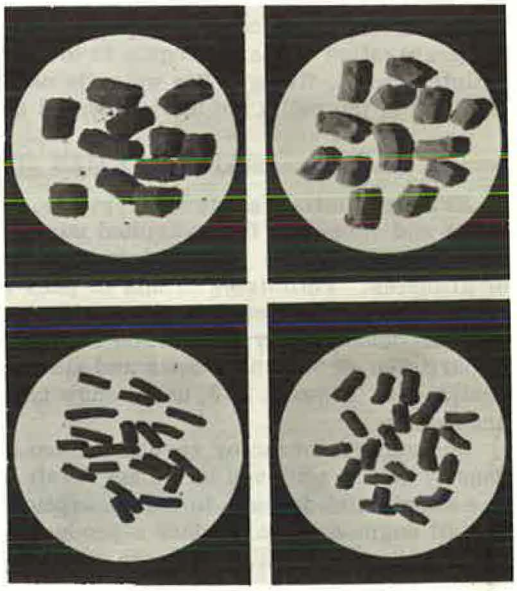

Figure 4. Unfired and fired fly ash aggregate made by extrusion process.

are used; either the material is made in different sizes and then blended, or, as in the case of extruded products, the distribution of the size may be established in the green bodies prior to the firing cycle. To produce finer aggregate, it is customary to crush the material, screen it, and proportion it so that it meets the requirements of the applicable specification for size gradation. For this reason, the fly ash aggregate plants usually incorporate crushing, screening, and blending operations in the manufacturing process.

PROPERTIES OF FLY ASH AGGREGATE

There is as yet no standard method to measure the strength of the individual granules, although several methods are used in individual laboratories. A study reported by the Central Electricity Generating Board (3) provides some results of tests of pellet strength made on aggregate utilizing different burning techniques. This report shows that the strengths are quite good for those pellets produced by the sintering grate, as well as those produced experimentally in rotary or shaft kiln equipment. In general, the aggregate produced from fly ash is evaluated on the basis of ASTM Specification C 330 and the reference test methods as called for in this specification. The tests include measurements of concrete-making properties, that is, strength and unit weights, drying shrinkage, popouts, and durability. Also of importance is the test for staining.

The firing process results in some sintering of individual particles of fly ash on the outer surface of the aggregate coupled with a more general fusion action in the interior. The sintered exterior normally represents less than 10 percent of the total volume. Figure 5 shows a close-up view of the typical structure of a cross section of fly ash aggregate. The structure of the exterior sintered portion of the aggregate results from the individual particles of the fly ash adhering to adjacent particles by partial melting or softening. The structure of the interior of the aggregate represents a

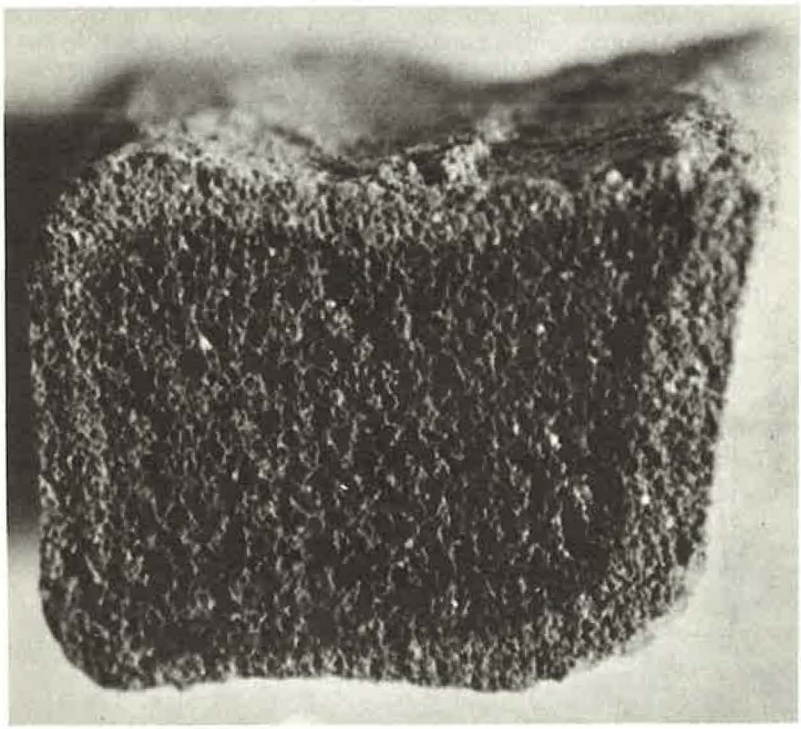

Figure 5. Close-up of a sawed particle of fly ash aggregate enlarged 10 times.

TABLE 2

FLY ASH LIGHTWEIGHT AGGREGATE PROPERTIES

Test	Normal Range for Fly Ash Aggregate	ASTM Specification C 330
Unit weight, lb/ft^3 (kg/m^3)		
At F. M. = 6.5 (nominal $^3/_4$ in. to No. 4)	37 to 48 (593 to 769)	55 maximum
At F. M. = 5.8 (nominal $^3/_8$ in. to No. 8)	41 to 51 (657 to 817)	55 maximum
At F. M. = 3.5 (nominal $^3/_8$ in. to 0)	53 to 61 (849 to 977)	65 maximum
At F. M. = 3.0 (nominal No. 4 to 0)	56 to 63 (897 to 1,009)	70 maximum
24-hour absorption, percent	14 to 24	—
Staining	None to very light	—
Loss on ignition, percent	0 to 3.4	5.0 maximum

NOTE: F.M. means fineness modulus.

multicellular structure of a more completely melted product. In both cases the voids in the aggregate are caused by evaporation of the mixing water and elimination of carbon during the sintering process.

Table 2 gives the normal ranges of properties on a number of fly ash aggregates. It is to be noted that the values for absorption are quite high. The rate of absorption is also high and the effect that this has on compositions such as concrete is believed to be more beneficial than deleterious. It has been reported (4) that the water absorbed by this aggregate when preparing a batch of concrete is continuously available during the curing process. The aggregate can thereby provide curing water rather than absorbing water out of the cement matrix of the concrete mix. This may explain in part why these materials often provide somewhat superior performance when used in concrete. Field experience has indicated that plastic shrinkage of the concrete is also substantially reduced (presumably as a result of the highly saturated condition of the aggregate). The relative absorption of the different portions of the fly ash aggregate, as well as the uncrushed and crushed aggregate materials, is shown in Figure 6. This graph is representative of materials produced commercially at the Corson Plant at Plymouth Meeting, Pennsylvania.

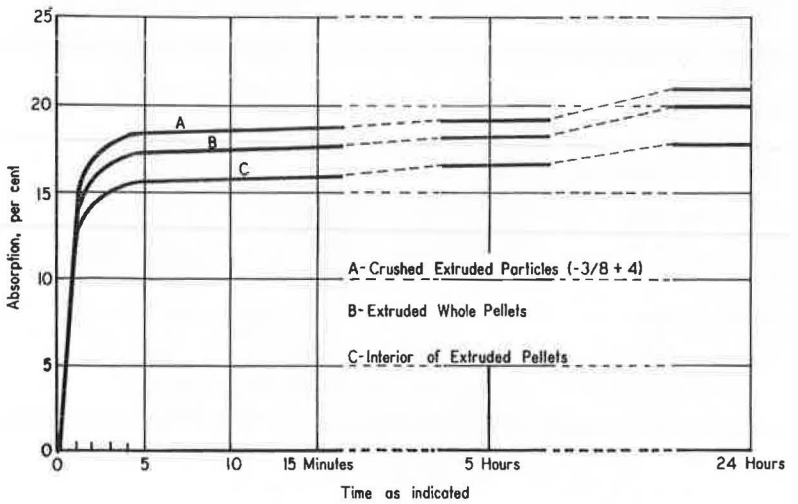

Figure 6. Moisture absorption of different fly ash aggregate products made from a single source of fly ash.

TABLE 3

POZZOLANIC STRENGTH OF FINELY GROUND FLY ASH AGGREGATE[a]

Material Under Test	Blaine Fineness, cm^2/gm	Pozzolanic Index, Percent of Control
Fly ash from source A	2,450	121
Ground lightweight aggregate made from source A fly ash	2,250	197
Fly ash from source B	5,420	130
Ground lightweight aggregate made from source B fly ash	5,330	151

[a]Modified test according to ASTM Method C 311-63 T.

With respect to the bulk density of aggregate produced from fly ash, some of the variation depends on the raw material from which the aggregate was produced. For instance, fly ash with very high fineness and low carbon content will usually result in a product having the higher densities. The data given in Table 2 illustrate the effect of aggregate size on bulk density.

Any residual fine fly ash particles that are either carried through the burning process or are formed by abrasive action of the aggregate during handling are still highly pozzolanic and will react in much the same manner when mixed with portland cement as the unfired fly ash. This results in the usual long-term improvements in strength and dimensional stability of the concrete. When the lightweight aggregate produced from fly ash is pulverized to pass a No. 200 mesh sieve, virtually all of the original pozzolanic activity is recovered. Table 3 gives data on this effect as measured with two lightweight aggregate materials from different sources of fly ash. Figure 7 is a close-up of a fractured specimen of concrete containing fly ash aggregate. The excellent bond established at the interface between the aggregate and the mortar matrix is typical of results with fly ash material.

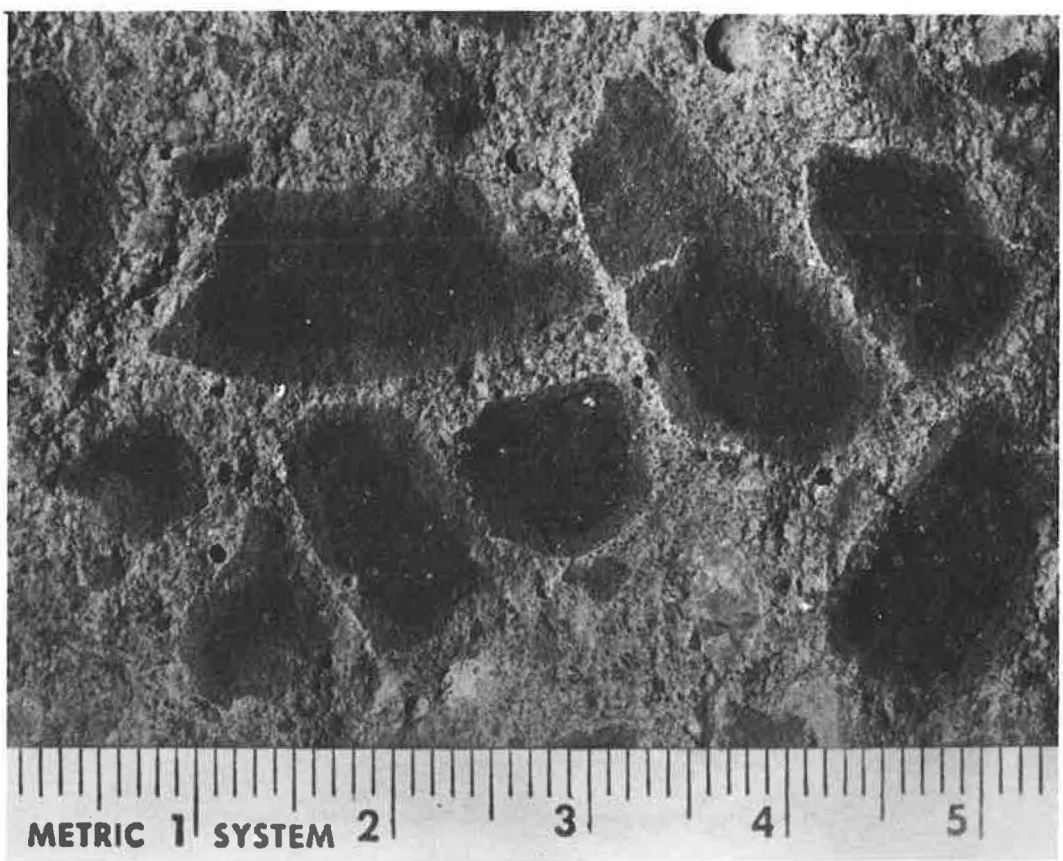

Figure 7. Fractured specimen of lightweight concrete containing fly ash aggregate.

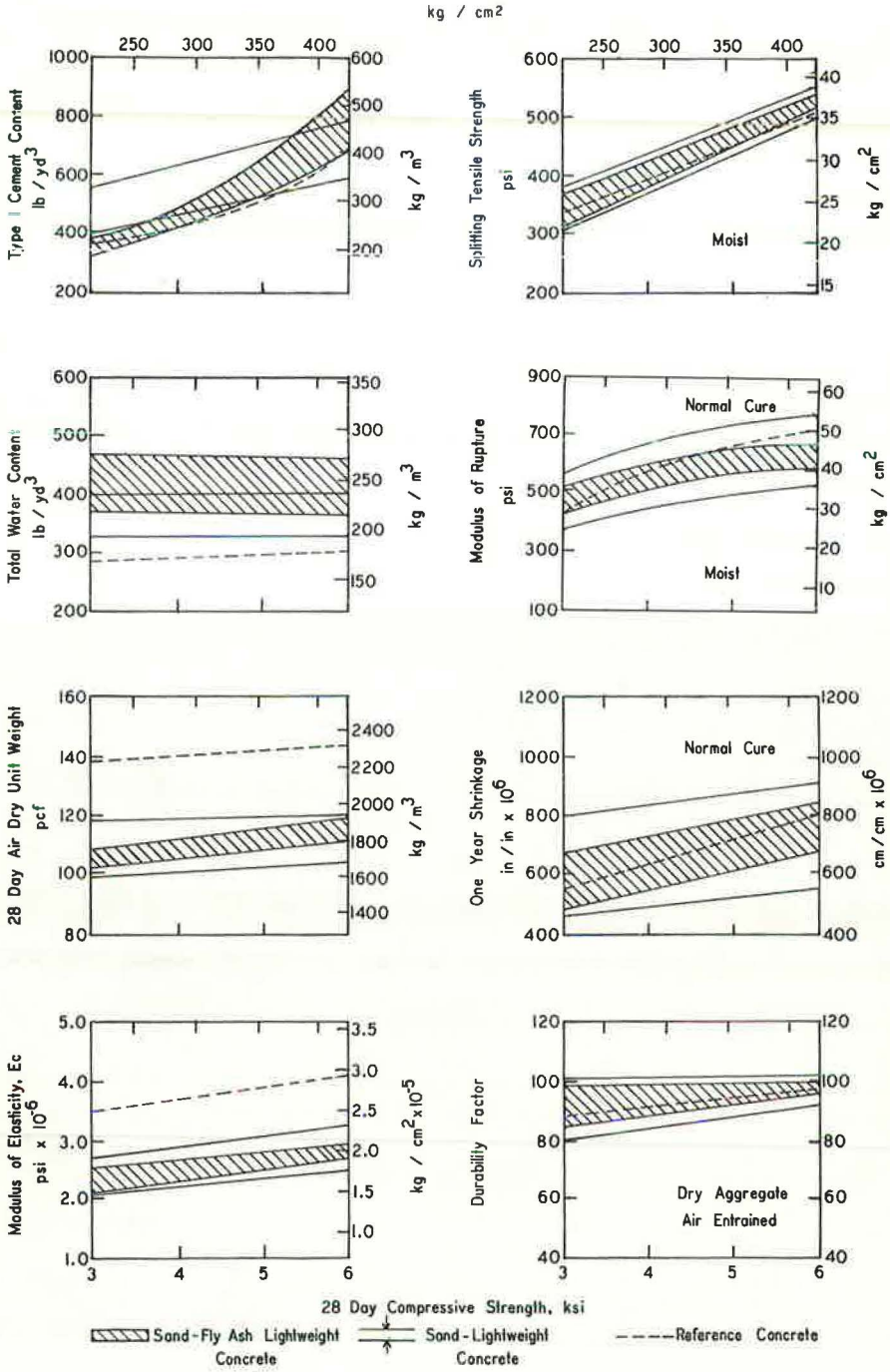

Figure 8. Comparison of lightweight concretes using sand as the fine aggregate.

Another important difference between aggregates produced from fly ash is in the shape of the individual granule. Uncrushed materials, such as those produced by the Corson process (which makes an extruded shape), have been demonstrated to have some advantage over the round pellets in improved workability and pumpability of the concrete. Crushed materials have been blended with sand and have been found to be effective in packaged concrete. The overall balance of properties, i.e., density, strength, and workability, in these latter mixtures is quite good.

PROPERTIES OF HARDENED CONCRETE

Considerable structural concrete has been produced with lightweight aggregate made from fly ash. In general, the concrete has demonstrated satisfactory performance and compares very favorably with other forms of lightweight aggregate concrete. A recent report of Committee 213 of the American Concrete Institute (5) provides a good description of lightweight aggregate concrete and includes fly ash aggregate in the total evaluation made.

Figure 8 shows graphs describing concrete properties using fly ash aggregates produced in various plants throughout the world. The unshaded bands shown in the graphs are taken directly from the ACI report, as are the dotted lines representing a typical normal weight concrete. The shaded bands, as superimposed on this background, represent the fly ash lightweight aggregate concrete.

The graphs in Figure 8 are based on the use of normal weight natural sand as the fine aggregate. Most of the companies producing concrete commercially use this type of composition because of difficulties in workability experienced when lightweight aggregate is used in both the coarse and fine fractions.

Figure 9 shows data on the latter type mixtures. Because the source of this information is limited to fly ash aggregate concrete produced at the Corson Company plant, the pertinent data are given in the form of a single line rather than in a band, as is the case in Figure 8. For comparative purposes, Figure 9 also includes the background information as presented by ACI; the shaded band represents all lightweight aggregates and the dotted line again represents normal concrete.

A study recently reported by the Portland Cement Association Laboratories (6) provides additional information on fly ash aggregate concrete. The Portland Cement Association program has utilized material that has been supplied from a number of processing plants in this country. An interesting report of studies carried out in Yugoslavia (7) gives information on the feasibility of using fly ash from lignite coal to produce acceptable lightweight materials. A cooperative investigation is currently under way (8) to determine the fire-resistance of concretes produced with fly ash lightweight aggregate. An early report by Pearson and Asce (9) states that fire tests on fly ash aggregate concrete conducted for New York City, using ASTM Method E 119-62, shows that a nominal-size specimen of 4 by 12 by 60 in. has a fire-resistance of 3 hours.

Figure 10 provides some data on the thermal values for fly ash lightweight aggregate concrete. Included in this figure are data supplied through the courtesy of the Centre Scientifique et Technique du Bâtiment (10). The spread in the K-values as plotted reflects the conditions present at the time the measurements are made. The higher value of K at each density results primarily from tests of concrete made in a moist condition. There is considerable interest, in France as well as in other parts of the world, in the use of this type of concrete in building prefabricated structures. The very favorable K-values that are obtained, together with the high strength and other properties of the fly ash aggregate concrete, enable the fabricator to produce exterior walls and other units of minimum thickness and weight but of adequate strength.

Table 4 gives design criteria that are currently in use for commercial mixtures in this country. Comparison of these designs with the recommended practice, as developed by ACI 613A-59, indicate that the fly ash aggregate falls well within the ranges of that study. These design criteria provide adequate factors of safety when compared with the strength results as shown in Figures 8 and 9.

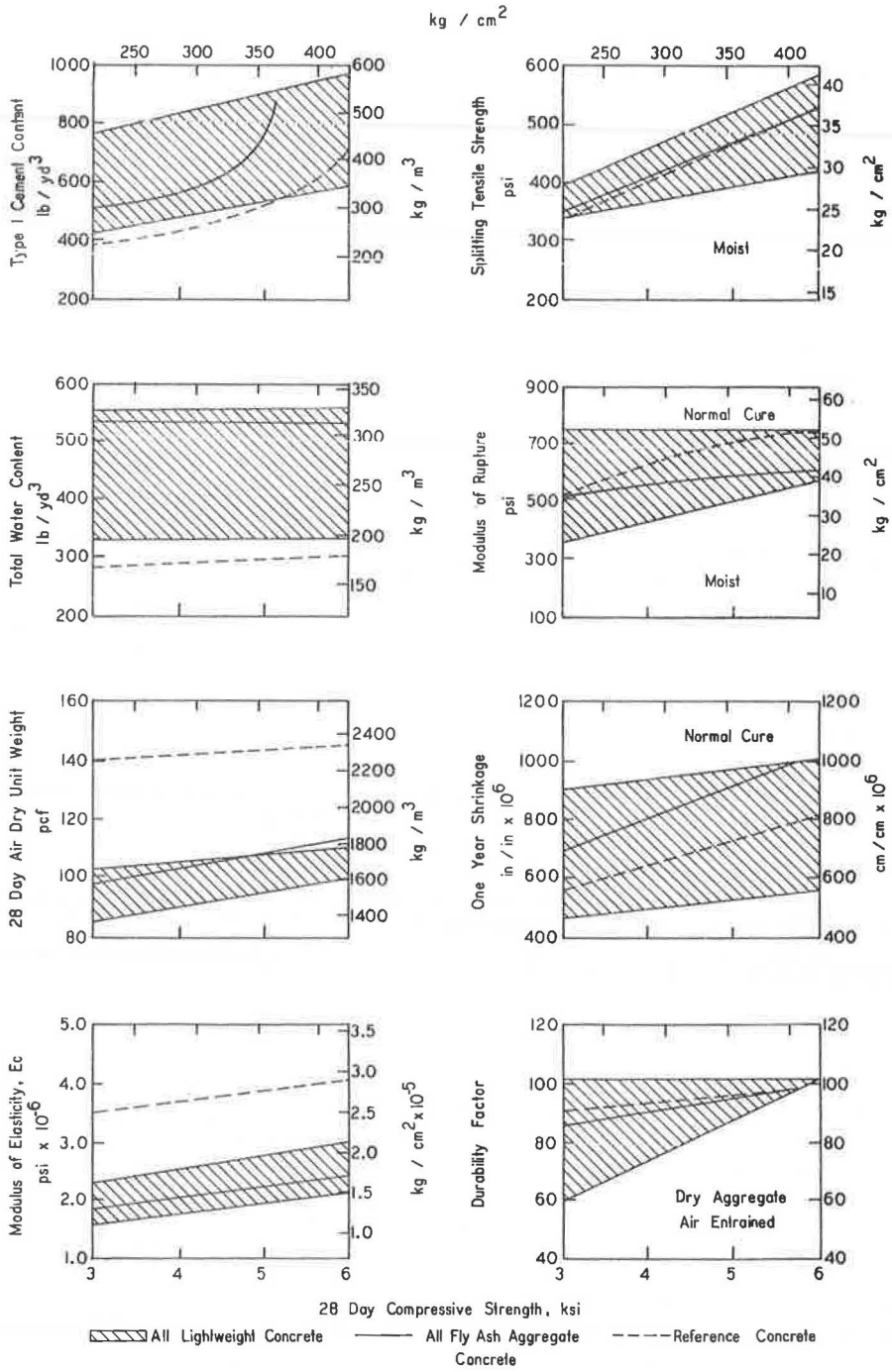

Figure 9. Comparison of concretes using all lightweight aggregate.

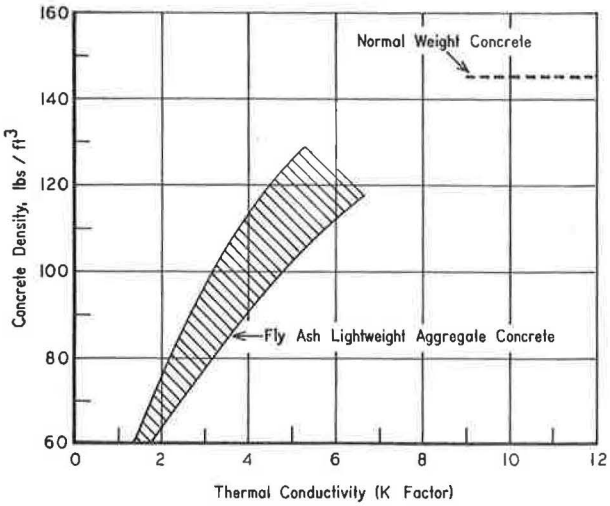

Figure 10. Range of thermal conductivities for fly ash aggregate concrete.

TABLE 4

CONCRETE MIX DATA

Design Mix	Quantities Per Cubic Yard						Slump (in.)	Air-Entraining Agent (oz/sack)	Percent Air	Weight of Plastic Concrete (lb/cu ft)	Weight of Concrete, 28 Days (lb/cu ft)
	Cement		Aggregate (lb)		Water[a]						
	Sacks	Pounds	Corson-Lite, ¾-in. Size, Bone Dry[b]	Concrete Sand, S. S. D.[c]	Pounds	Gallons					
1000	3.35	315	950	1,320	441	53	4	1.50	6	112	106
2000	5.00	470	875	1,300	433	52	4	1.75	6	114	109
3000	6.00	564	875	1,240	437	52.5	4	1.75	6	115	110
4000	7.00	658	875	1,180	441	53	4	1.75	6	116	111
5000	8.00	752	875	1,120	441	53	4	2.00	6	117	112

[a]Total water, including water of absorption. [b]Based on Corson-Lite, 44 lb/cu ft density. [c]S.S.D. = saturated surface dry.

SUMMARY

Fly ash aggregate is being successfully used in structural concrete. Because of the light weight of the aggregate, it finds application for structural concrete in the range of 95 to 116 pcf (1,520 to 1,860 kg/cm^2) and may also be used for insulating concrete at lower densities. With proper quality fly ash, commercial sintering processes produce various shapes of aggregate similar in properties to other structural lightweight aggregates. However, the high rate of absorption and residual pozzolanic properties provide some advantage over other materials. Tests of concrete using fly ash aggregate give results falling well within the range of values typical of lightweight concrete in general use.

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