Commonwealth of Kentucky
Department of Highways

A STUDY OF THE USE OF A LOCAL FLY ASH IN CONCRETE MIXES

by

Frank D. Whitney
Research Engineer

Highway Materials Research Laboratory
Lexington, Kentucky

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INTRODUCTION

The widespread use of powdered coal in industrial furnaces has, since its introduction in the 1930's, produced considerable increases in efficiency for many industrial processes. In its wake, however, it has brought its own unique problems, and chief among these has been the problem of collecting and disposing of the residue which results from the combustion of the powdered or ground coal. This residue, known commonly as fly ash, is a nuisance if it is allowed to be dispersed into the atmosphere; and if collected it presents a difficult disposal problem. In present industrial practice it is almost always collected, either with electrostatic precipitators or cyclone separators, and deposited in ever-growing disposal dumps. A recent estimate (20)* gives the imposing figure of six million tons as the annual U. S. production of this waste product.

Since the first appearances of large fly ash dumps, investigators have searched for possible commercial uses of the material, some of which have proved successful. However, these consume but a small fraction of the fly ash produced -- and the rate of production is continually increasing.

The use of fly ash in concrete has probably been investigated more widely than any other possibility, and sometimes with dramatic success. Many proponents of its use claim a variety of desirable effects, such as greater mix workability, greater ultimate strengths and the like, resulting from its presence in concrete mixes. Such claims must

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* Numbers in parentheses refer to the list of references at the end of this report.

be viewed with some qualification, however, if for no other reason than the considerable variation, both chemical and physical, among fly ashes from different sources. Nor is it yet thoroughly understood to what extent the effects of a particular fly ash on a particular concrete are due to the fine size of the particles and to what extent they are the consequence of chemical reactions within the mix. In work carried on concurrently with the present study, Hardymon (22) has pointed out quite radical differences between the strengths of soil-lime-fly ash specimens made with fly ashes from two different sources, attributing these differences primarily to variations in particle size.

All fly ashes, however, do have two potential advantages in common: they are inexpensive -- often available merely for the cost of hauling -- and they are pozzolans, which means that, having negligible cementitous properties themselves, they are capable of reacting with calcium hydroxide, at normal temperatures and in the presence of water, to form cementitous compounds. This pozzolanic nature immediately suggests the possibility of providing not merely a cheap substitute for more expensive concrete mix ingredients but a possible augmentation of the desirable properties of concrete as well. Since calcium hydroxide is formed in the normal hydration of cement, and since in itself it adds nothing to the strength and water-tightness of the mix and is in fact often leached out, the use of a material which can combine with this free lime to form a cementitous product is obviously suggestive of worthwhile possibilities.

It was with some of these possibilities in mind that the present project was undertaken. Quantities of fly ash were obtained from the

Louisville Gas and Electric Company and used in various proportions to prepare concrete and mortar specimens, with and without air entrainment, in two broad categories: specimens with portions of the cement replaced, and specimens with portions of the sand replaced with fly ash. Tests were made after 14, 28, 60 and 90 days, and it was found that, in general, the use of this fly ash actually increased compressive and flexural strengths over the limited range of time intervals and that it did not show any greatly detrimental effect upon durability.

Some question can be raised as to whether the gains in strength were a consequence of the pozzolanic cementation or merely of the mechanical advantages of the presence of the extremely fine fly ash spheres in the mix. Certainly further investigation is required for ascertaining more about the exact nature of pozzolans themselves and more especially about their potential advantages in imparting such qualities as greater strength and water-tightness to concrete.

Criteria for judging the value of pozzolans in concrete have actually been fairly well established: these are reflected in some of the current specifications, such as ASTM C 205 for Type IS cement*, C 340 for Type IP cement**, and C 350 for fly ash admixtures***, none of which allows any reduction in strength of mortar cubes when compared to normal portland cements. Thus, pozzolanic additives and admixtures are expected to yield concretes having strength, durability and other properties equal to or more desireable than those achieved from standard portland cement.

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* Portland blast furnace slag cement
** Portland pozzolan cement
*** Fly ash for use as a concrete admixture

MATERIALS

All fly ash for the investigation was obtained from the West End Power Plant of the Louisville Gas and Electric Company, and upon arrival was tested for chemical and physical properties in accordance with ASTM Designation C 350. The results of these tests are given in Tables 1 and 2, below. Photomicrographs, contrasting the fly ash particles with particles of the cement used, are given in Figure 1.

TABLE 1: CHEMICAL PROPERTIES OF LOUISVILLE FLY ASH

Test	ASTM Specification C 350	Test Result
Silicon dioxide (SiO_2), percent	Min. 40.0	40.0
Magnesium oxide (MgO), percent	Max. 3.0	1.1
Sulfur trioxide (SO_3), percent	Max. 3.0	3.0
Moisture content, percent	Max. 3.0	0.3
Loss on ignition, percent	Max. 12.0	3.8

TABLE 2: PHYSICAL PROPERTIES OF LOUISVILLE FLY ASH

Test	ASTM Specification C 350	Test Result
Fineness by air permeability test, sq. cm./gm.	Min. 2800	3700
Compressive strength of mortar cubes		
7 days, percentage of control	Min. 100	121
28 days, percentage of control	Min. 100	137
Soundness by autoclave apparatus, percent	Max. 0.50	0.01
Specific gravity	--	2.60
Normal consistency, percent	--	28.0

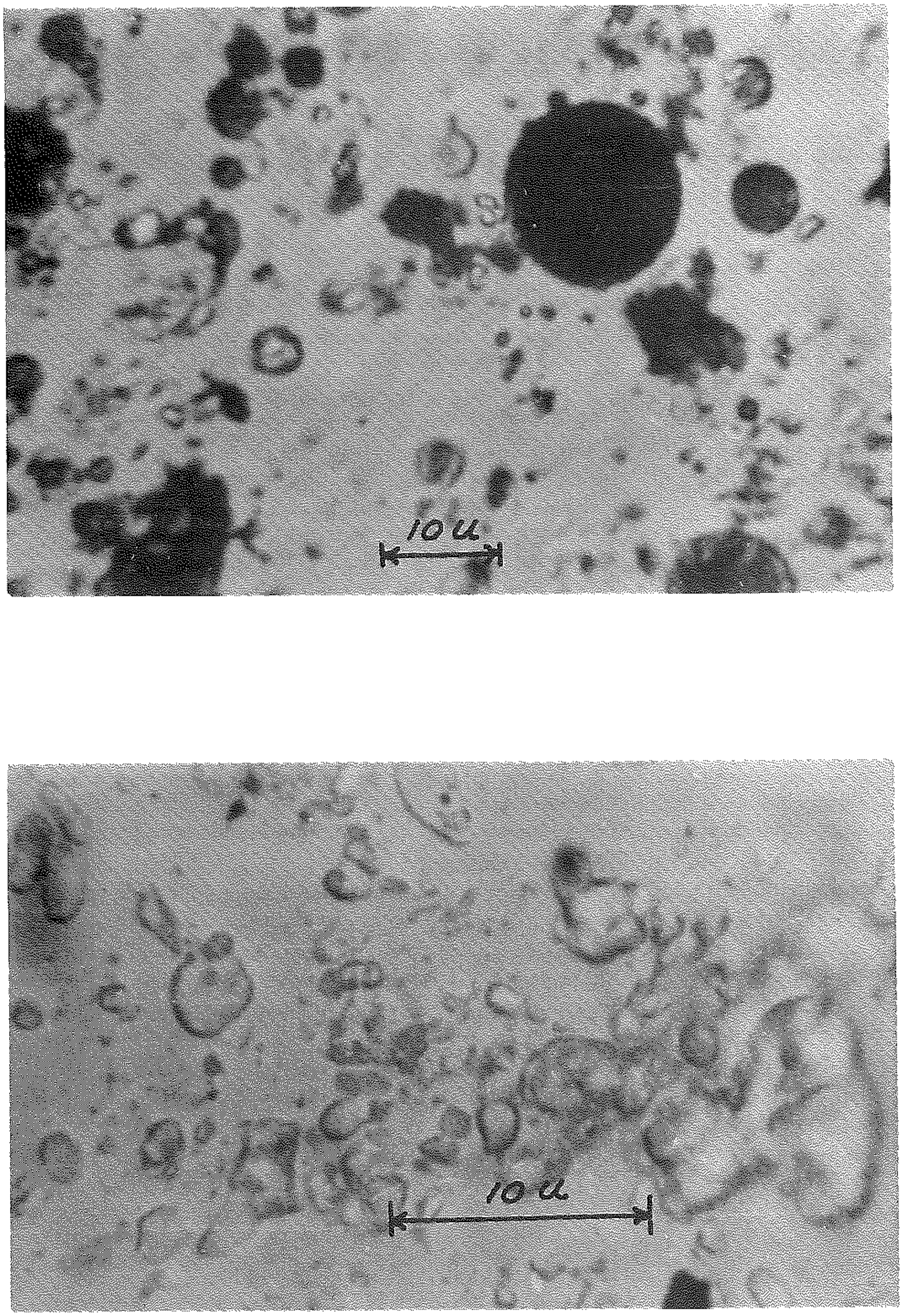

Fig. 1: Photomicrographs Illustrating the Spherical Nature of Fly Ash Particles (Above) in Contrast to the Angular Cement Particles (Below).

A Type I cement obtained in bags from a local source was used throughout. It was tested in accordance with standard ASTM procedures and found to conform to ASTM Specifications for Type I. Results of these tests are given in Table 3 below.

TABLE 3: PHYSICAL PROPERTIES OF CEMENT USED

Test	ASTM Specification	Test Result
Air content, percent	Max. 12	5.1
Autoclave expansion, percent	Max. 0.50	0.04
Compressive strength of mortar, psi		
7 day	Min. 2100	3110
28 day	Min. 3500	4765
60 day	--	5450
Tensile strength of mortar, psi		
7 day	Min. 275	310
28 day	Min. 350	420
60 day	--	450
Normal consistency, percent	--	25.8
Time of set by Gilmore needles Initial set, min.	Min. 60	125
Final set, hr.	Max. 10	5.1
Fineness by air permeability apparatus, Average, sq.cm./gm.	Min. 2800	3420

The fine aggregate, an Ohio River Sand with a fineness modulus ranging from 2.40 to 2.78, met all Kentucky Department of Highways Standard Specifications for Class I sand. The coarse aggregate, a locally obtained crushed limestone, met the Kentucky Department of Highways Specification for No. 6 stone. Table 4 gives the results of tests performed on the aggregate.

Air entrainment in all specimens so designated was obtained by the addition of commercial NVX. This admixture meets ASTM Specifications, Designation C 260.

TABLE 4: PHYSICAL PROPERTIES OF AGGREGATES

Test	Fine Aggregate	Coarse Aggregate
Abrasion by the use of the Los Angeles machine, percent of wear	--	24.6(40.0)
Lightweight pieces in aggregate, percent	0.1(1.0)	--
Soundness, percent	1.7(10.0)	9.7(15.0)
Specific gravity		
Apparent	2.70	2.74
Bulk sat. surf. dry	2.66	2.71
Bulk oven dry	2.64	2.70
Absorption, percent	0.72	0.48
Unit weight, lb./cu.ft.		
Loose	101.1	87.8
Dry rodded	107.2	95.0
Fineness modulus	2.60	--

Note: The figures in parentheses are maximum values of Kentucky Department of Highways Standard Specifications.

TESTING PROCEDURES

Equipment

After mixing with the 2 cu. ft. counter-current mixer shown in Fig. 2, each batch was tested for air content with a pressure meter. All specimens were cured in the laboratory constant humidity room at 100 percent relative humidity and 70° ± 3°F, and durability specimens were submitted to freezing in air and thawing in water with equipment designed in accordance with ASTM Designation C 291-52T. The dynamic modulus of elasticity of durability specimens was determined by the use of a sonic apparatus similar to that described in ASTM Designation C 215, using an audio frequency oscillator with a range of 20 to 20,000 cps.

Preparation of Specimens

Concrete specimens were made in two parallel groups: one air entrained, the other plain. Each category consisted of eight different mixes: one control mix with no fly ash, three mixes in which varying amounts of the cement -- 15, 25 and 35 percent by weight -- were replaced with fly ash, and four mixes in which amounts of the sand -- 10, 15, 20 and 25 percent by weight -- were replaced. Slump, air content, actual and calculated unit weight, fly ash-cement ratio, and water requirement were recorded for each mix. Specimens were then cast in 3- by 5- by 20-inch beam, and 6- by 12-inch cylindrical molds and allowed to cure for 7, 14, 28 and 60 days before testing.

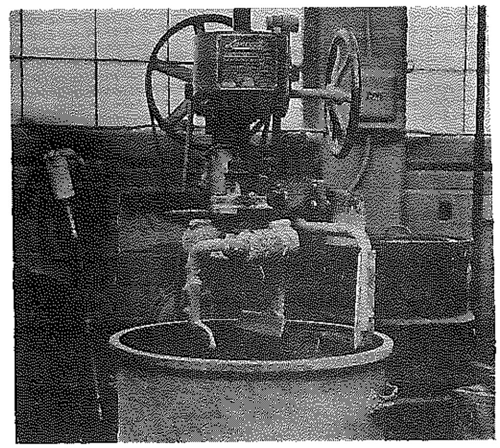

Fig. 2: Counter-Current Concrete Mixer

Mortar cubes and briquettes were made with the same percentages of cement and sand replacements as the concrete specimens, except that a 30 percent cement replacement was used for the briquettes instead of the 35 percent figure used in the other specimens. Curing periods were the same as for the concrete specimens.

The basic mix used throughout, and from which the varying percentages of sand and cement were "subtracted", was designed by the b/b_o method. The amount of sand in the total aggregate by absolute volume for this basic mix ranged from 38.7 to 39.7 percent for air entrained concrete, and from 43.7 to 44.3 percent for plain concrete. The amount of mixing water and the b/b_o were varied slightly in order to stay within these ranges. A cement factor of 1.50 before replacement was used, slump was kept within 2 to 3 inches, and air entrainment, when used, ranged from 3 to 6 percent.

RESULTS

The results of compressive and flexural strength tests on all concrete specimens are presented, together with mix design data, in Table 5. Table 6 presents similar data for the mortar cube and briquette specimens. Data from these tables were used to plot the general relationships shown in the trend lines in Figures 3 through 12.

The results of durability tests on concrete beams are given in Figures 13 and 14, where the reduction in dynamic modulus of elasticity as determined with the sonic apparatus is plotted against the number of freeze-thaw cycles. All specimens were cured for 14 days prior to testing.

Table 6 and Figures 15 and 16 present the results of compressive strength tests on the mortar cubes and tensile strength tests on the briquettes, after various curing periods.

Compressive Strength - Concrete

As can be seen in Figures 3 through 6, the tendency is for the addition of fly ash to produce slight gains in compressive strength, except for the rather "extreme" 35 percent cement replacement. Yet even the largest additions of fly ash used did not effect any considerable loss in strength once the concrete had attained an age of 28 days; and the early strength losses in these specimens are merely indicative of the generally known slowness of the pozzolanic reactions.

It is also evident that the specimens with sand replacement made a better showing than those with the cement replaced. This is, of course, largely the result of the higher cement factor in the sand

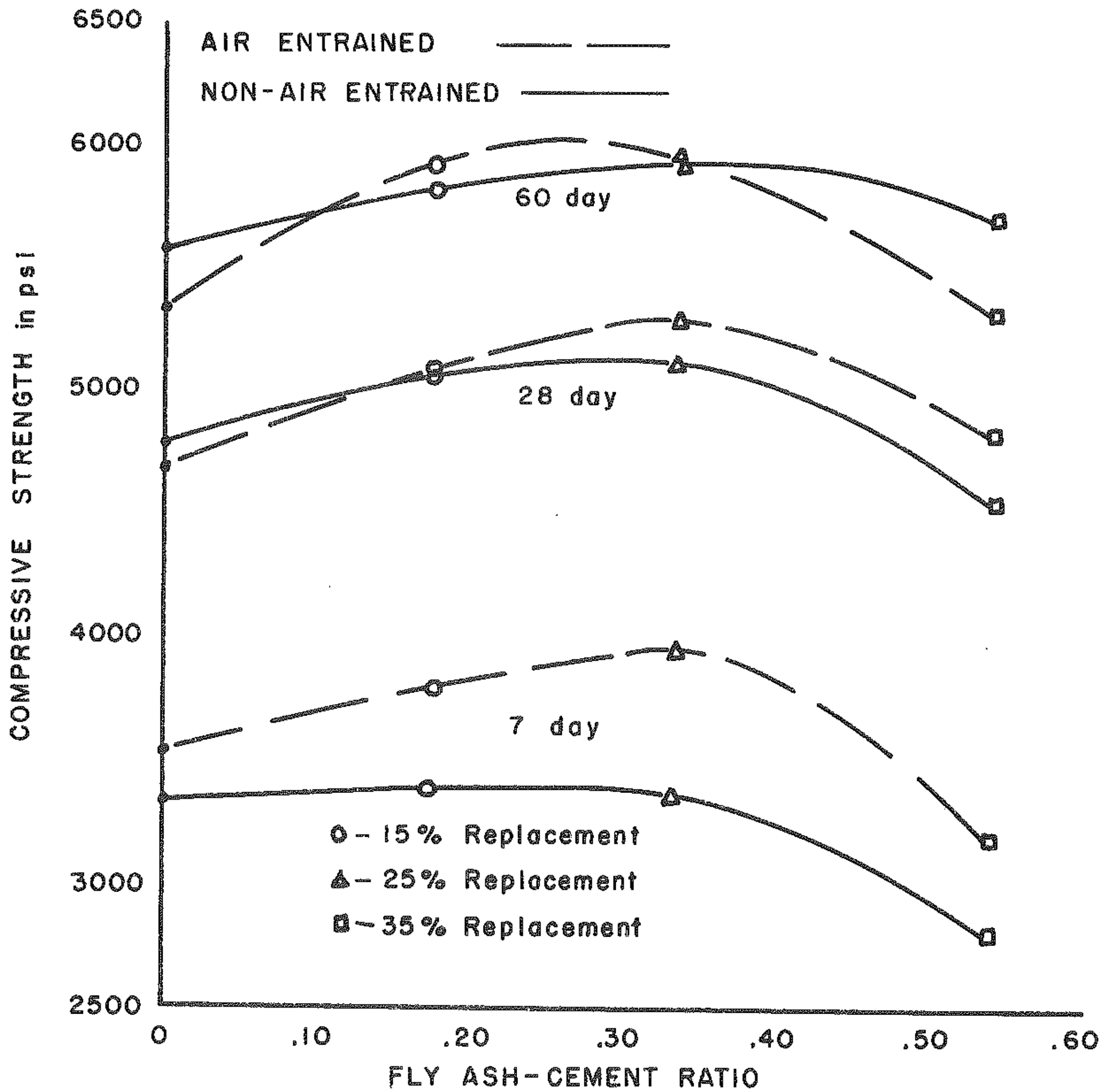

Fig. 3: Trend Lines Showing the Relationship of Compressive Strength of Concrete to the Percentage of Cement Replaced with Fly Ash.

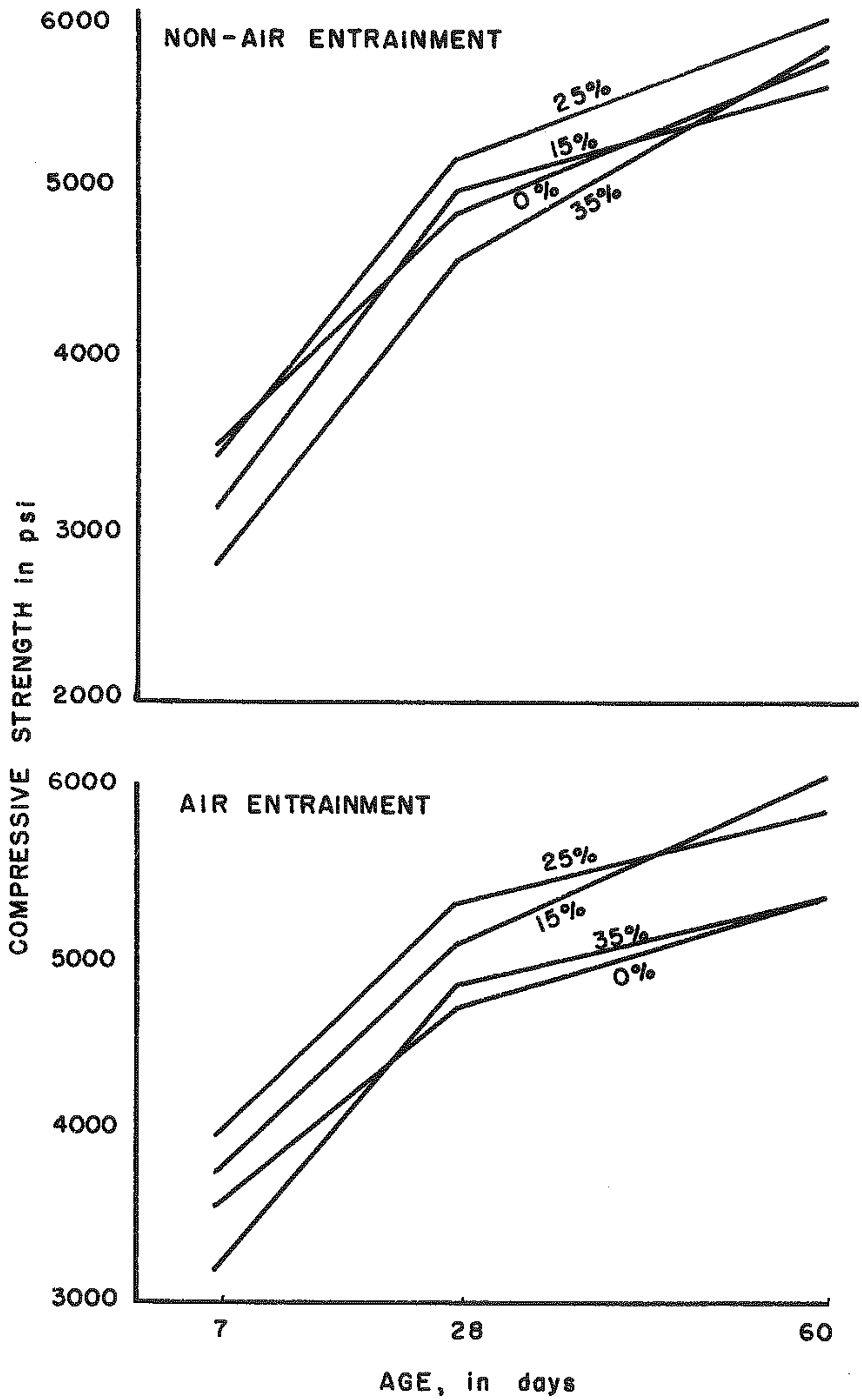

Fig. 4: Results of Compressive Strength Tests of Concrete with Various Percentages of Cement Replaced with Fly Ash.

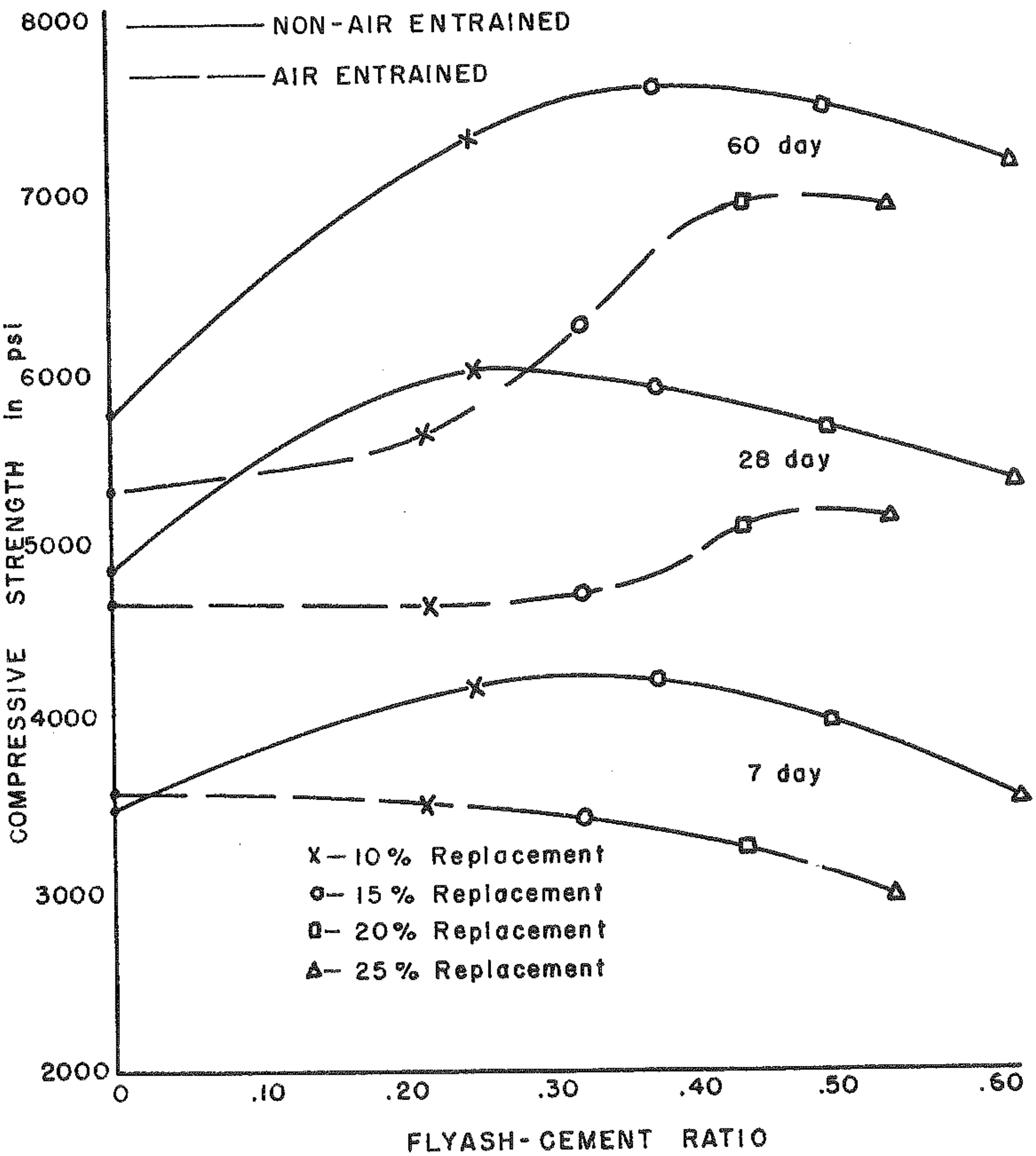

Fig. 5: Trend Lines Showing the Relationship of Compressive Strength of Concrete to the Percentage of Sand Replaced with Fly Ash.

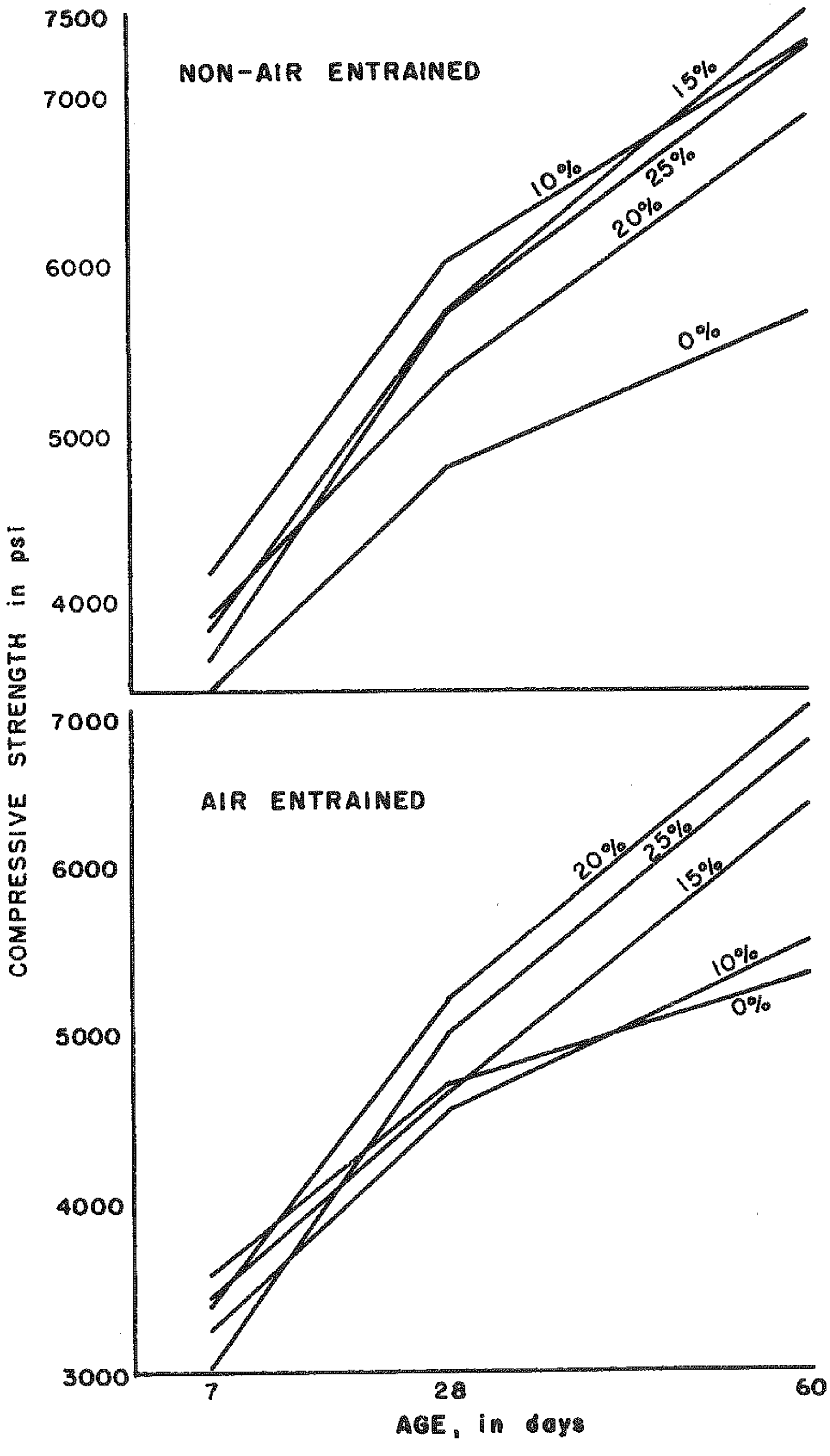

Fig. 6: Results of Compressive Strength Tests of Concrete with Various Percentages of the Sand Replaced with Fly Ash.

replacement specimens. A 35 percent cement replacement of a 6-bag mix reduces it to a 3.9-bag mix, while a sand replacement has the effect of a slightly increased cement factor.

It would seem that the most significant conclusion that can be drawn from these trend lines is that a "moderate" replacement of 25 percent of either the sand or cement in these mixes produced no detrimental effects on the 28- and 60-day compressive strengths.

Flexural Strength - Concrete

Immediately obvious from the trend lines in Figure 7 is the considerable drop in 7-day flexural strength for the air entrained specimens with cement replacement. This is again explained by the slowness of pozzolans; and the explanation is borne out by the general flatness of the 28- and 60-day curves. The same overall situation prevails in the sand replacement specimens, as can be seen in Fig. 9; but here the initial 7-day drop is far less dramatic, apparently because of the cement factor differential.

In general it must be noted that here, as with the compressive strength results, although there are some variations among the 28-day values and the 60-day values, these are relatively minor and generally fall within the error limits of the experimental methods followed. The 7-day strengths in some cases tell a quite different story.

Water Requirement - Concrete

As can be seen in Figure 11, the substitution of fly ash for cement had little effect on the water requirement of the plain and a moderate effect on the air entrained mixes. In the sand replacement

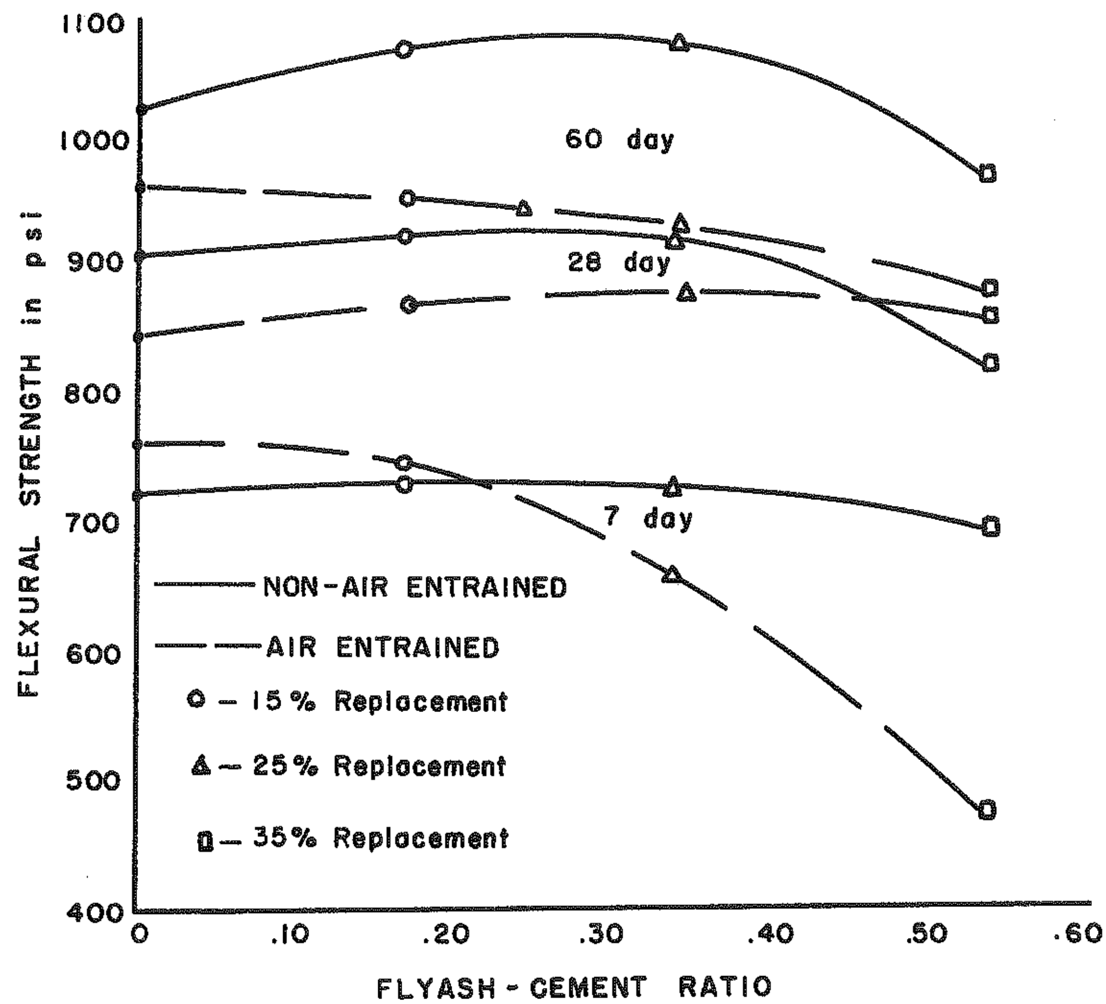

Fig. 7: Trend Lines Showing the Relationship of Flexural Strength of Concrete to the Percentage of Cement Replaced with Fly Ash.

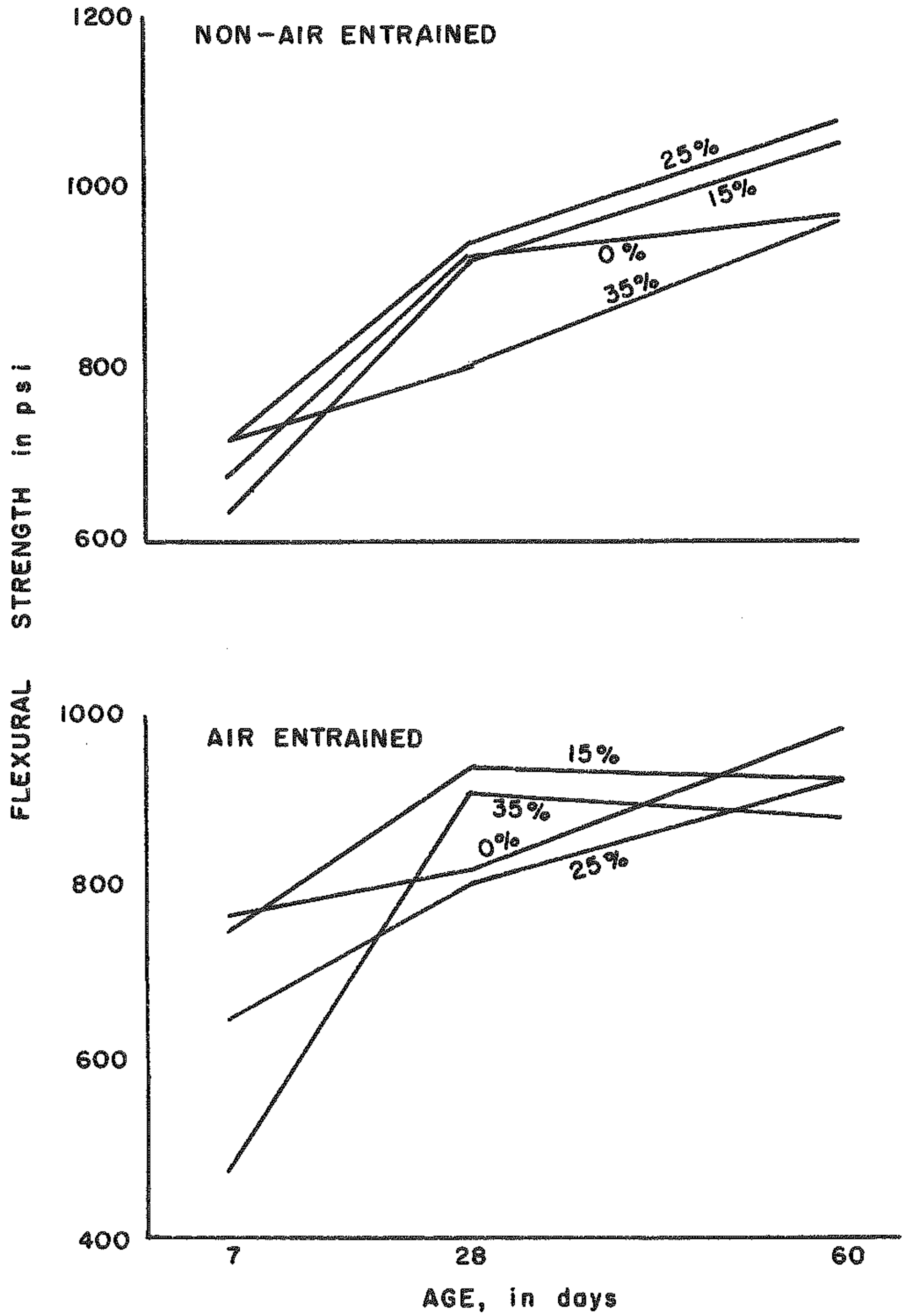

Fig. 8: Results of Flexural Strength Tests of Concrete with Various Percentages of the Cement Replaced with Fly Ash.

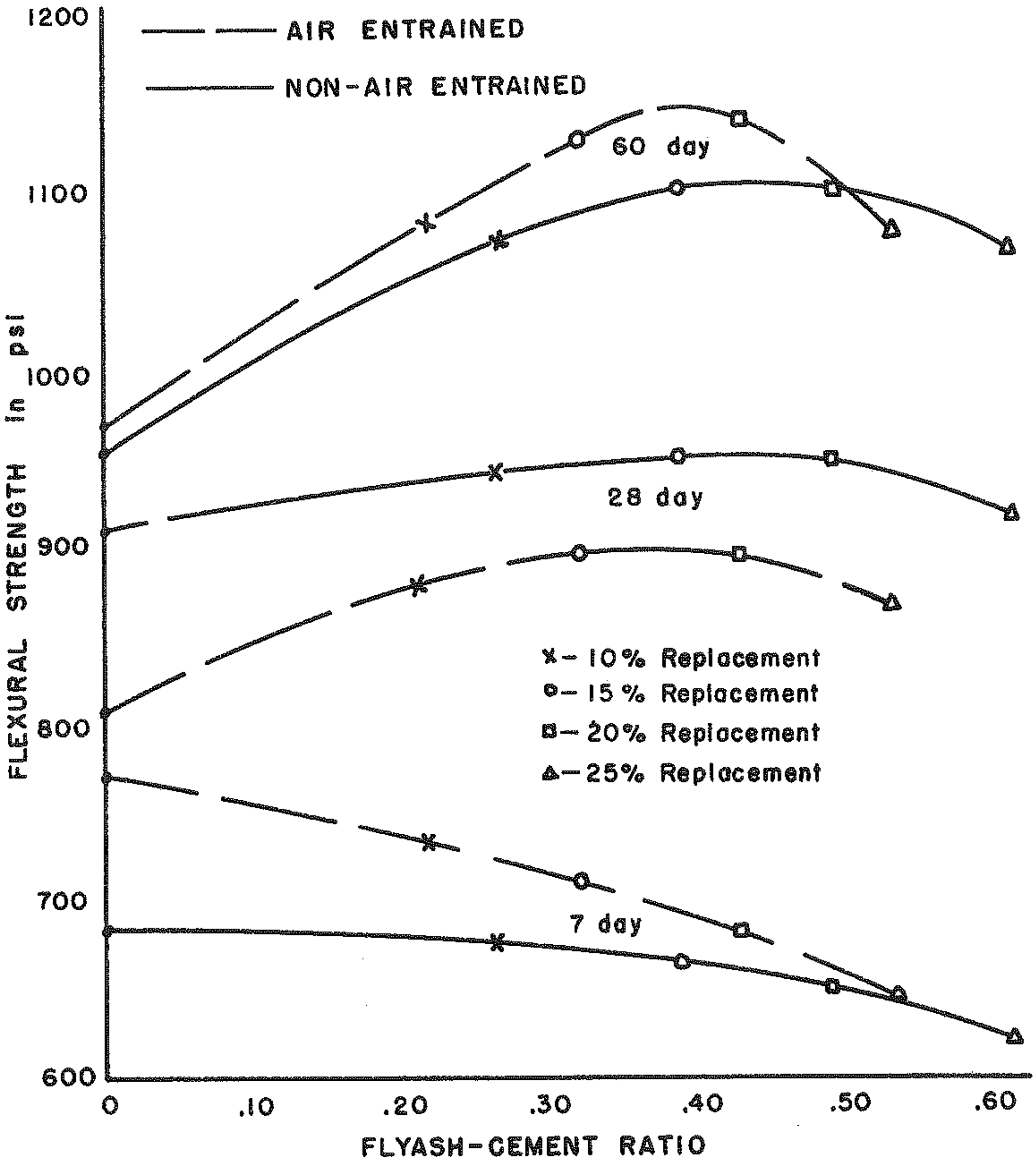

Fig. 9: Trend Lines Showing Relationship of Flexural Strength of Concrete to the Percentage of Sand Replaced with Fly Ash.

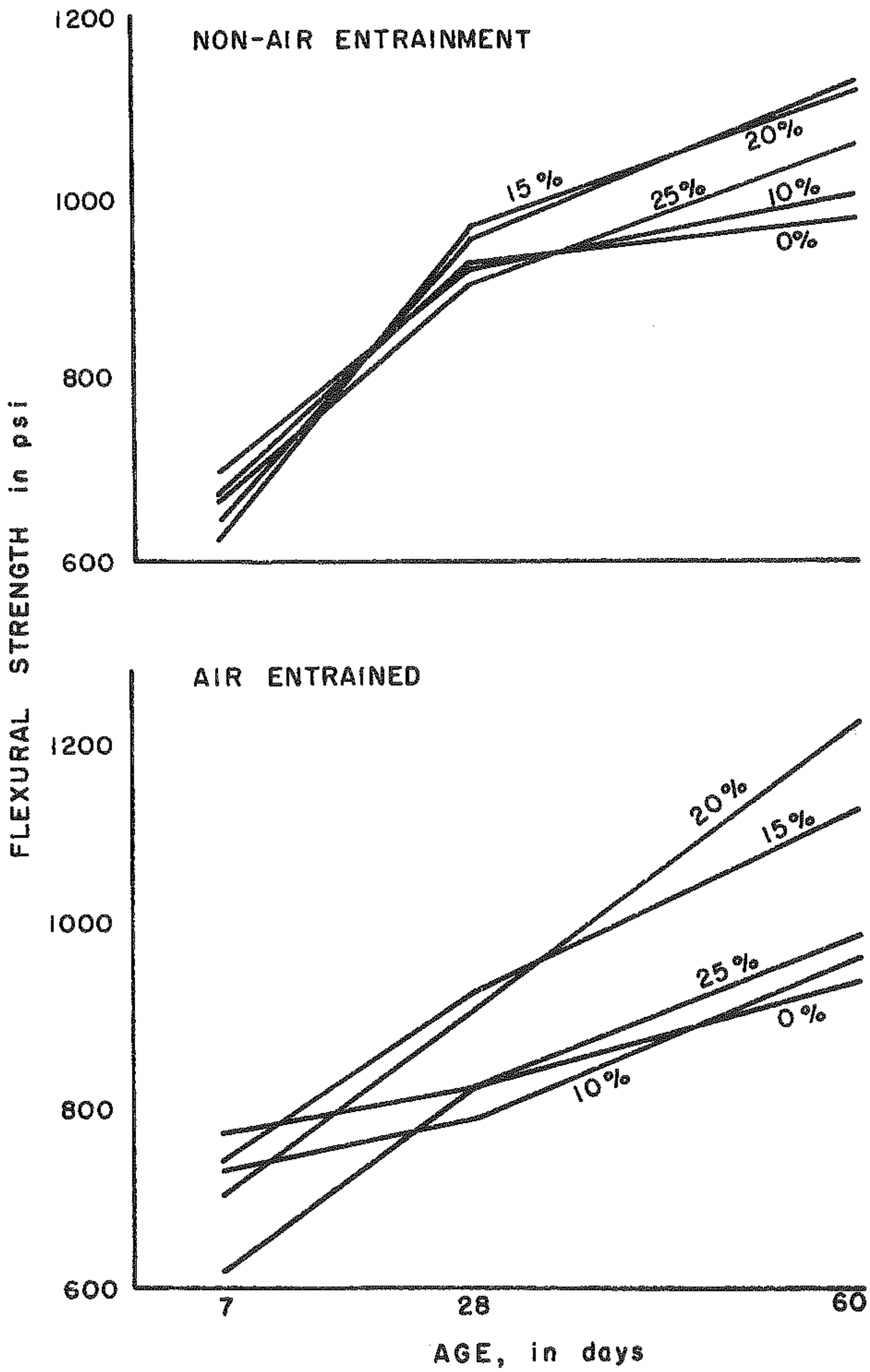

Fig. 10: Results of Flexural Strength Tests of Concrete with Various Percentages of the Sand Replaced with Fly Ash.

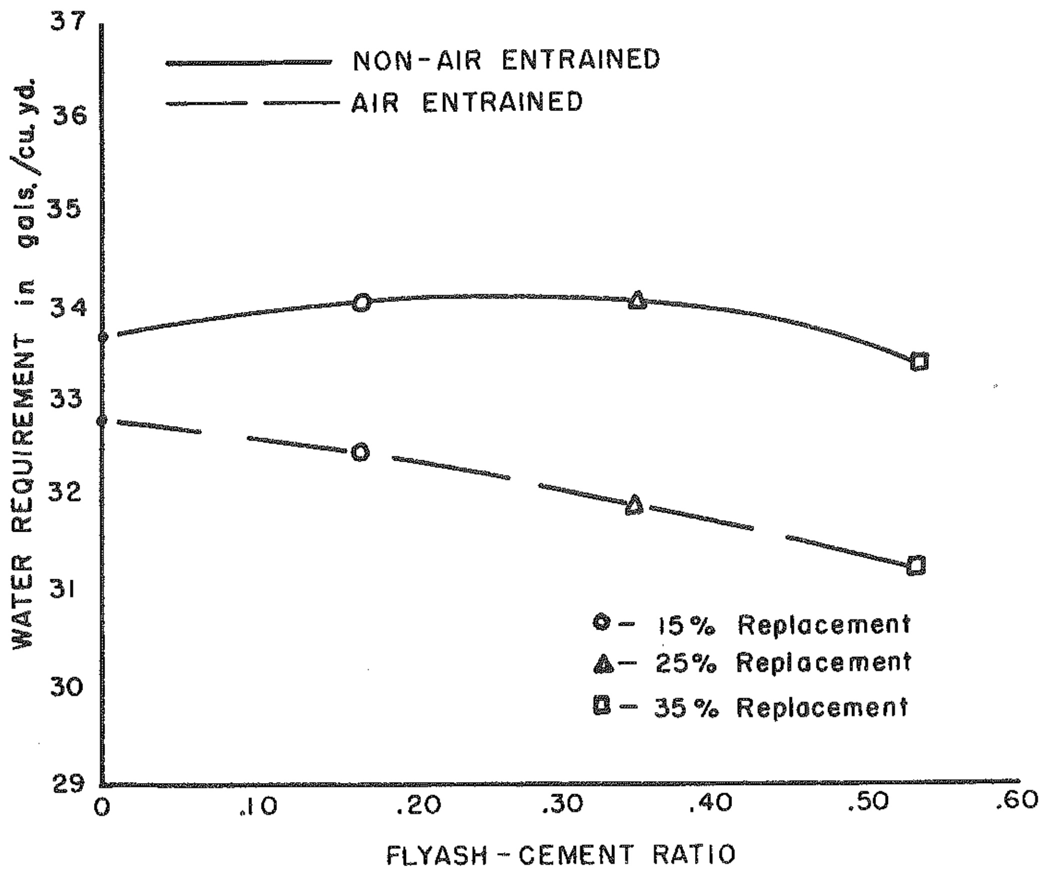

Fig. 11: Relationship of Water Requirement to Cement Replacement Expressed as Fly Ash-Cement Ratio.

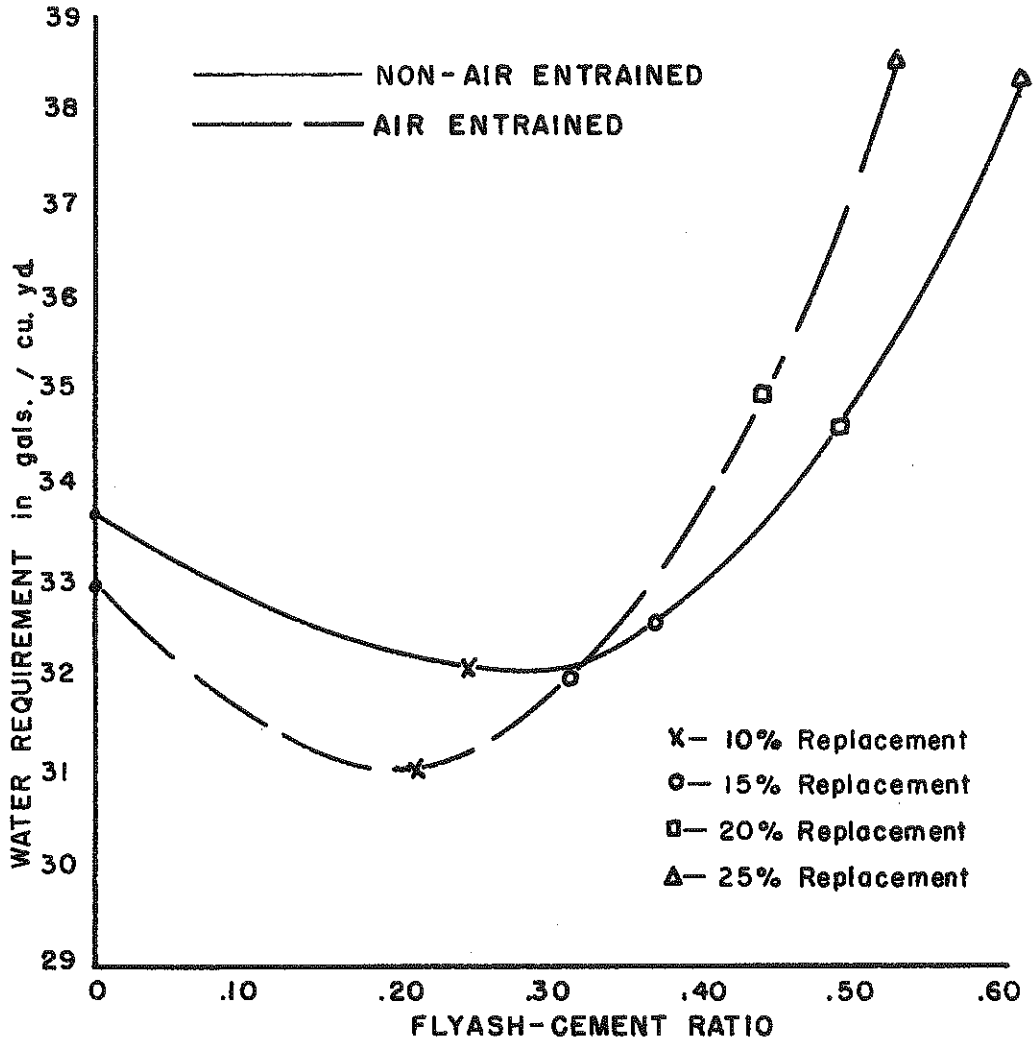

Fig. 12: Relationship of Water Requirement to Sand Replacement Expressed as Fly Ash-Cement Ratio.

mixes (Fig. 12) the curve shows an early drop followed by a sharp rise. In all cases the reduction in required water is probably due to the lubricating effect of the fly ash spheres; they can be assumed to act in the mix very much like minute ball bearings. This action is less marked in the cement replacement -- perhaps merely because fly ash is physically more like cement than sand -- and reaches an early point of diminishing returns in the sand replacement. This point is probably reached when the ball bearing action has attained its maximum effectiveness throughout the mix and the high specific surface of the fly ash begins to require more water than the sand would have required, in order to coat the individual particles.

What these trend lines imply, essentially, is that water requirement will not vary appreciably for any replacement of cement with fly ash, but that for sand replacement in the range of about 20 to 30 percent -- which seems from the data thus far developed to be the most practicable range -- the required water will be appreciably increased if a harsh mix is to be avoided.

Durability - Concrete Beams

The most striking feature of Figures 13 and 14 is their implicit argument for the advantages of air entrainment. Other than that, they illustrate what has been well known from previous investigations: the addition of fly ash has a mildly depreciative effect on freeze-thaw durability but -- at least in air entrained mixes -- this is ordinarily negligible. The most significant effect here seems to be that shown in the lower portion of Figure 13, where the 25 percent sand replacement specimens failed with somewhat alarming speed. In contrast, there is only very slight variation among the corresponding specimens of cement replacement in Figure 14.

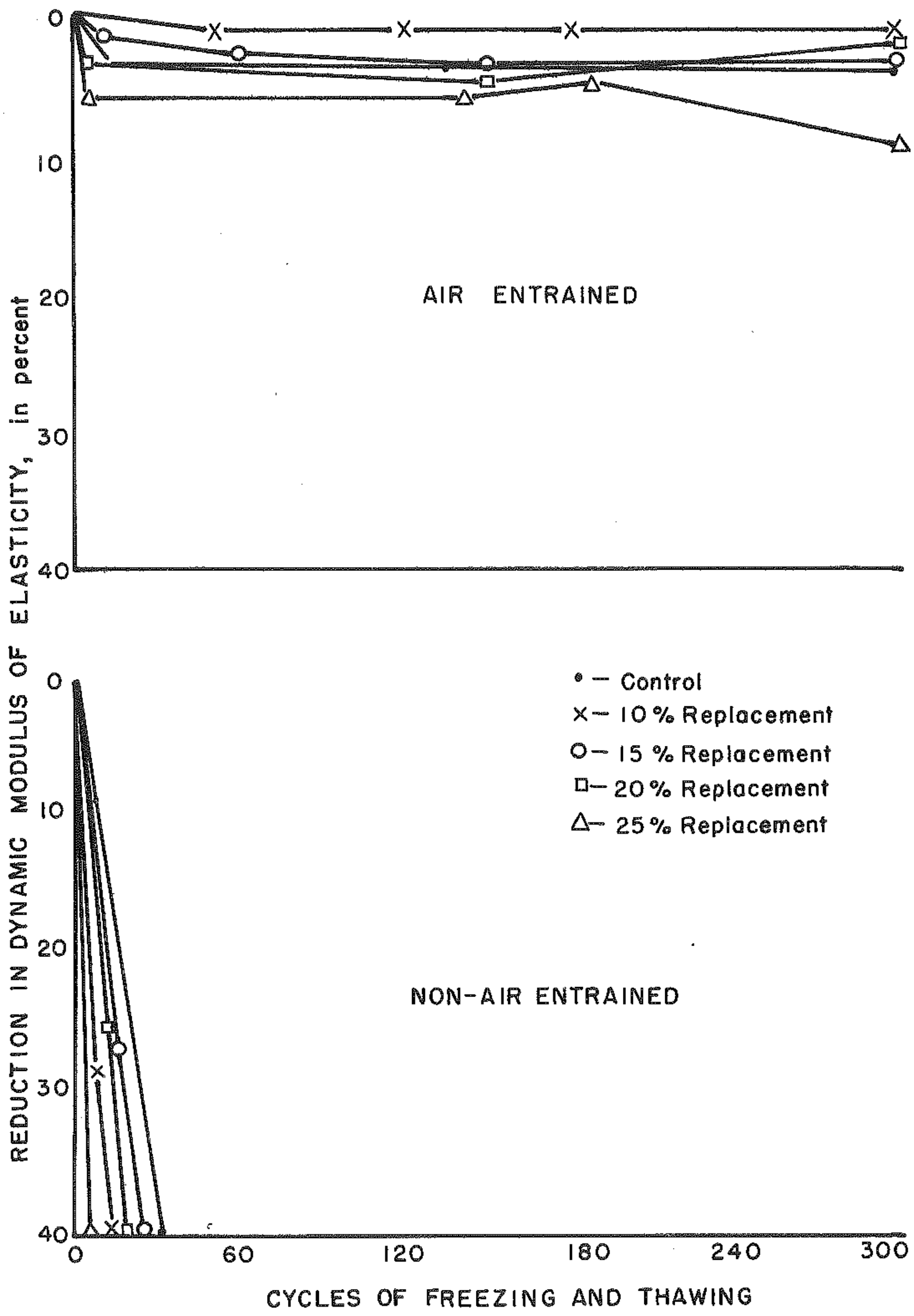

Fig. 13: Reduction in Dynamic Modulus of Elasticity of Concrete Having Various Percentages of the Sand Replaced with Fly Ash.

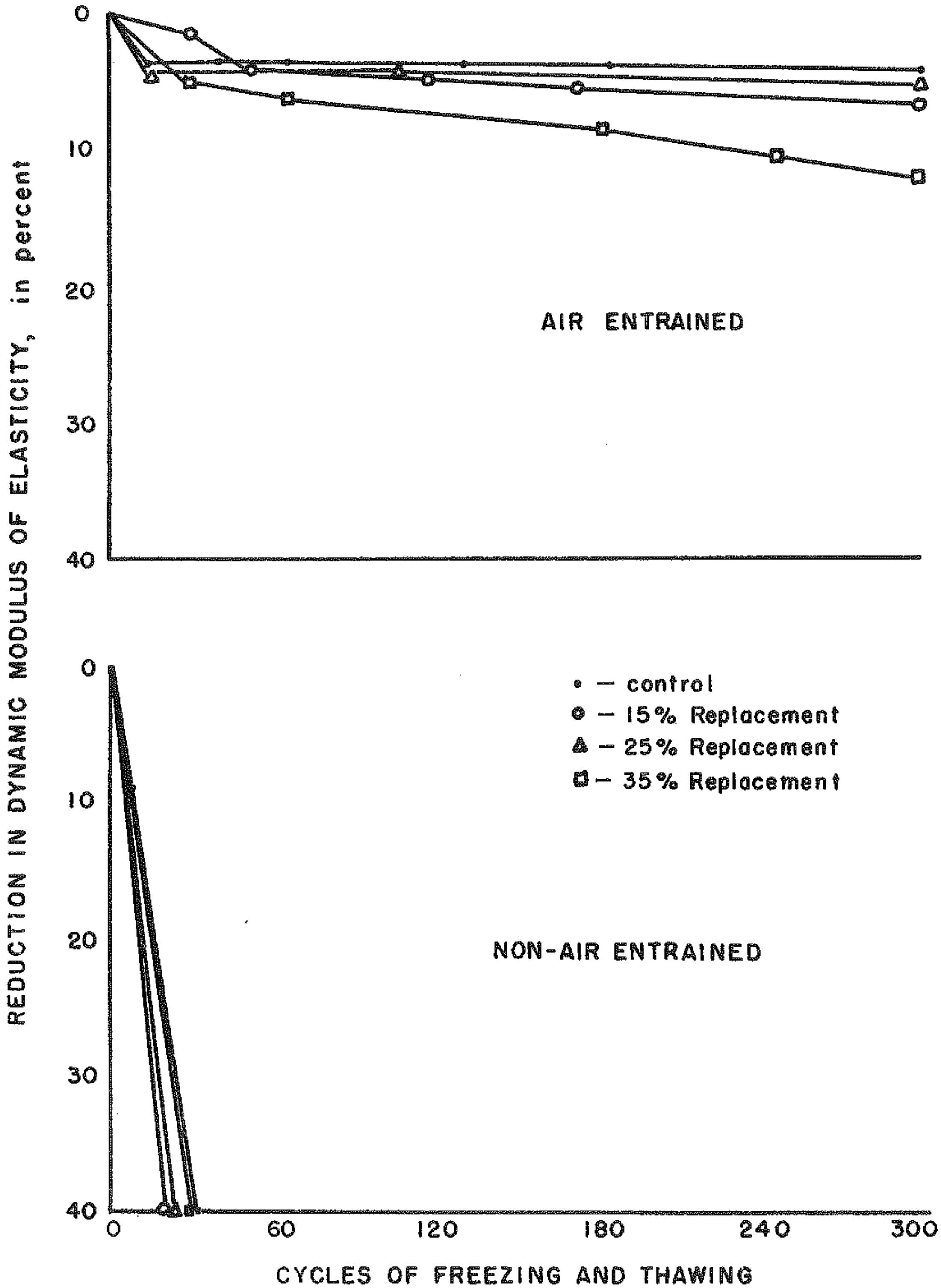

Fig. 14: Reduction in Dynamic Modulus of Elasticity of Concrete Having Various Percentages of the Cement Replaced with Fly Ash.

In general it can be concluded that air entrainment seems almost mandatory for mixes with any appreciable portion of sand replaced with fly ash -- at least when freeze-thaw durability is necessary.

Mortar Cubes and Briquettes

Sand replacement here makes a better showing than cement replacement, for undoubtedly the same reason as in the concrete specimens: in sand replacement the actual cement factor remains unaltered; in cement replacement it is lowered. Here, as might be expected, these effects are more readily apparent than in concrete and they demonstrate rather convincingly one of the major premises of the over-all study: that fly ash will react with lime to form cementitous compounds and that the bonds thus formed, although weaker than those of portland cement, can add to the ultimate strength of the concrete. At least this seems to be the only satisfactory explanation of the tendency shown to some degree in all the strength tests and to a rather pronounced degree in the tests on mortar cubes and briquettes, as indicated by the curves in Figures 15 and 16. There seems to be no question about the fact that these curves indicate that fly ash can produce cementation where sand can not (Figure 16), although its merits as a cement replacement are not quite as convincing.

Conclusions

There seems to be slight doubt that this partiqular fly ash -- and it should be repeated here that fly ashes differ -- could in many ways offer an effective and inexpensive substitute for at least some of the sand in air entrained concrete. If its use does not require high transportation costs, it could well produce an improved concrete at a lower total expense.

Furthermore, as a replacement for up to 25 percent of the cement in air entrained concrete it could provide a material which, if given curing periods of 28 days or longer, would be perfectly acceptable for many uses, and considerably less expensive than standard concrete.

Finally, although the study was not undertaken to gauge the relative effects of the pozzolanic reaction and of the change in mechanical properties brought about by the use of the fly ash, the results present convincing evidence that the pozzolanic reaction was, at least in large part, responsible for increases in strength when sand was replaced. It would be hard to explain otherwise the tests on mortar cubes and briquettes, where a 20 percent replacement of sand produced after sixty days of curing a compressive strength value almost double that of the control specimens.

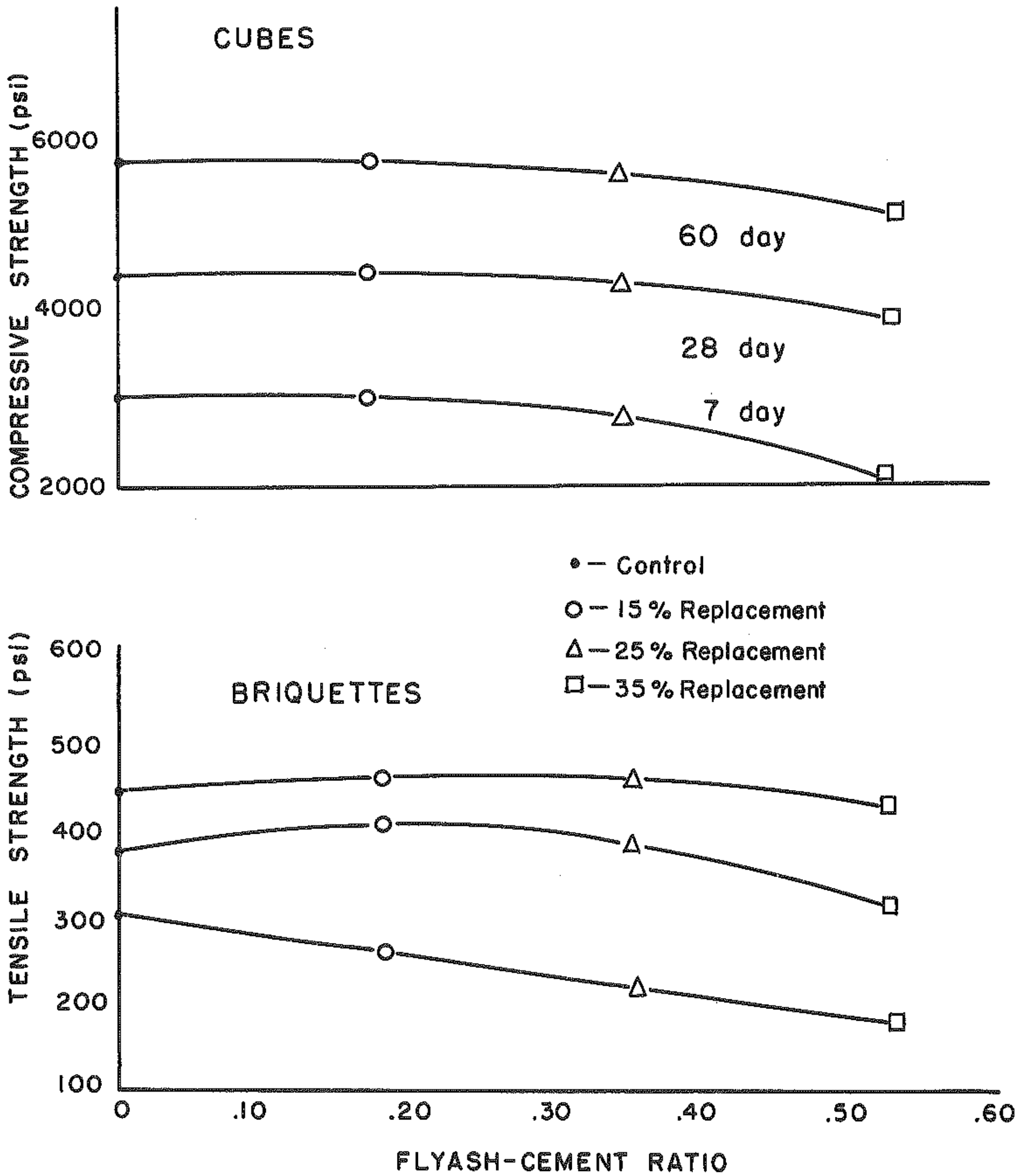

Fig. 15: Relationship of Compressive Strength of Mortar Cubes and Tensile Strength of Briquettes to the Percentage of Cement Replaced with Fly Ash.

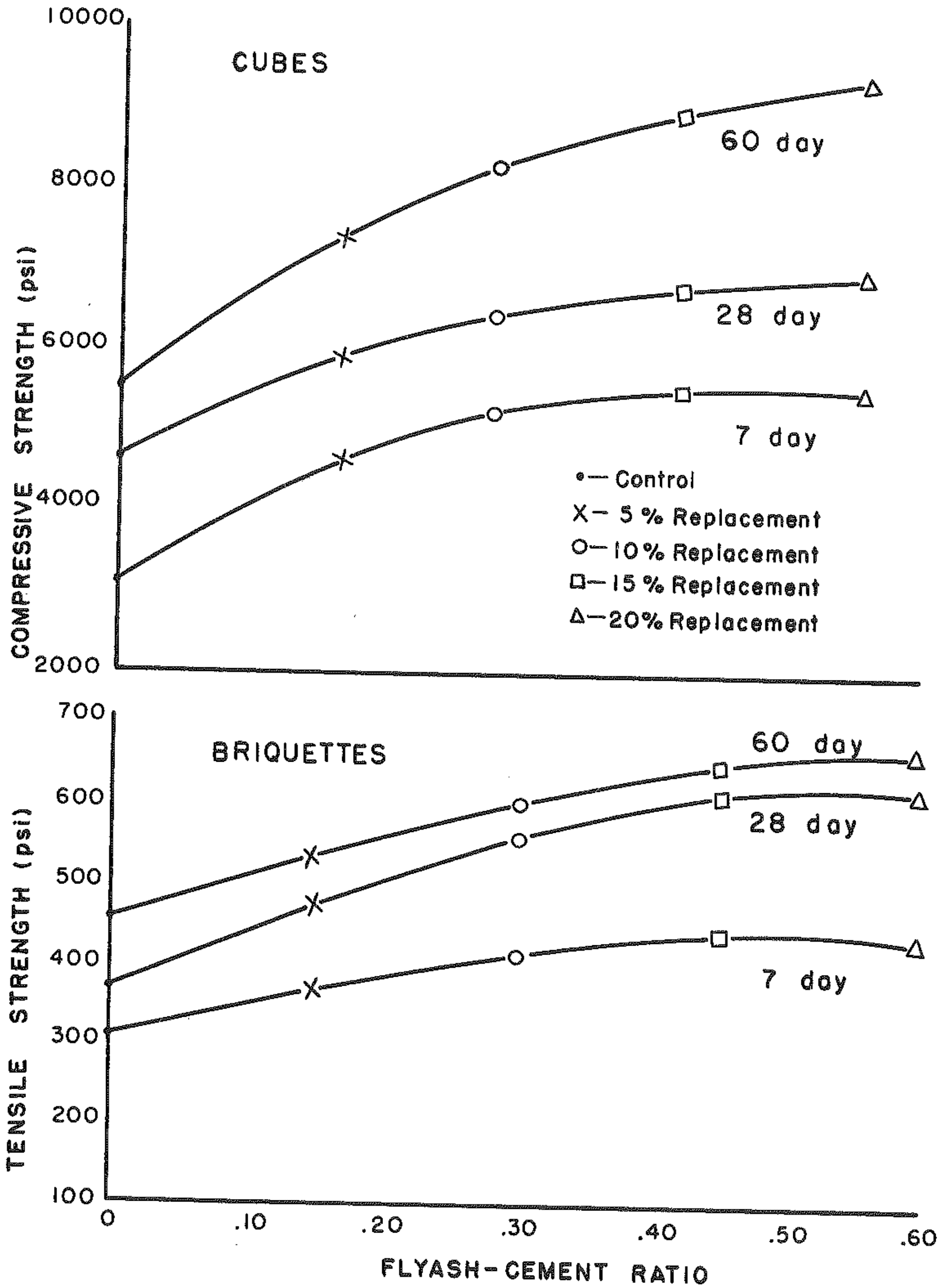

Fig. 16· Relationship of Compressive Strength of Mortar Cubes and Tensile Strength of Briquettes to the Percentage of Sand Replaced with Fly Ash.

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