ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT: ADOT-RS-14 (158) FINAL REPORT — PORTLAND CEMENT CONCRETE

UTILIZATION OF WASTE BOILER ASH IN HIGHWAY CONSTRUCTION IN ARIZONA

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December 1976

Prepared for:
Arizona Department of Transportation
206 South 17th Avenue
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in cooperation with
The U.S. Department of Transportation
Federal Highway Administration

HIGHWAYS DIVISION · RESEARCH SECTION ·

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MATERIALS DIV.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-AZ-RS-74-158-I-II		

4. Title and Subtitle	5. Report Date
Utilization of Waste Boiler Ash in Highway Construction in Arizona Part I - Portland Cement Concrete	December, 1976
	6. Performing Organization Code
7. Author(s) John C. Rosner, Ph.D., P.E. & M. Kent Hamm, P.E.	8. Performing Organization Report No.
9. Performing Organization Name and Address Engineers Testing Laboratories, Inc. P. O. Box 21387 Phoenix, Arizona 85036	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. HPR 1-14(158) 74-28
12. Sponsoring Agency Name and Address Arizona Department of Transportation 206 South Seventeenth Avenue Phoenix, Arizona 85007	13. Type of Report and Period Covered Final Part I September 1974 to December 1976
	14. Sponsoring Agency Code

15. Supplementary Notes

In cooperation with U.S. Department of Transportation, Federal Highway Administration

16. Abstract

Waste boiler ash (fly ash) is produced by several coal-fired power generating plants in and adjacent to Arizona. A literature search, laboratory test program and analysis of test data indicate that available fly ashes can be advantageously used as admixtures in portland cement concrete for highway construction. Compressive strength, flexural strength, resistance to sulfate attack and freeze-thaw durability are included in the laboratory test series. Test data are utilized in the development of a mix design procedure aimed at optimizing the proportions of fly ash and portland cement.

17. Key Words	18. Distribution Statement
Fly ash, Admixtures, Waste boiler ash, Recycling, Concrete design, Pozzolan	No restriction. This report is available to the public through NTIS, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	197	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

FINAL REPORT

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PART I - PORTLAND CEMENT CONCRETE

by

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and

M. Kent Hamm, P.E.

Submitted to

Arizona Department of Transportation

Highways Division

for

Research Project - HPR 1-14(158)

Sponsored by

Arizona Department of Transportation

in Cooperation with

U.S. Department of Transportation

Federal Highway Administration

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ACKNOWLEDGEMENTS

The writer(s) wish to thank Mr. Gene R. Morris and Mr. Ben W. Ong of the Engineering Research Division of the Arizona Department of Transportation for their fine cooperation during this project. Special thanks are also extended to Mr. Doug Forstie and Mr. Hal Emery of the Materials Division, Arizona Department of Transportation, for their assistance.

Appreciation is due to representatives of the various utilities for furnishing power plant and coal data vital to the preparation of Appendix A, particularly Mr. Dean Curtiss and Mr. Doug Nass of the Salt River Project, Mr. Thomas A. Shaw and Mr. Gilbert T. Gutierrez of the Arizona Public Service Company, and Mr. Michael L. Dina of the Southern California Edison Company.

Thanks go to Mr. Michael R. Christensen of Engineers Testing Laboratories for assistance in data reduction, analysis, and preparation of the final report.

Finally, the dedicated work of many individuals at Engineers Testing Laboratories in laboratory testing, data collection, data reduction and clerical work is appreciated.

IMPLEMENTATION STATEMENT

The search for more efficient construction material and the problem of industrial waste disposal have been combined in the development of uses for waste boiler ash (fly ash) produced by coal-fired power generating stations. Fly Ash is a pozzolan, a material with cementitious properties which can be utilized in many construction material applications. This report evaluates the use of fly ash that is available from four sources. Part I evaluates the use of fly ash in portland cement concrete. Part II evaluates the use of fly ash combined with lime in soil stabilization. Chapter 8, Part I presents a mix design procedure and Chapter 6, Part II presents Iso-Strength curves in mix design procedures. A first estimate of the mix proportions may be developed from the most appropriate family of Iso-Strength curves. Target strength should be retained after allowing for loss due to saturation. Cost data can be used to establish the proportions of lime and fly ash in an economical range. Mix design procedures as outlined in the report will be incorporated into ADOT pavement design and evaluated.

3/7/77

ABSTRACT

Waste boiler ash (fly ash) is produced by several coal-fired power generating plants in and adjacent to Arizona. A literature search, laboratory test program and analysis of test data indicate that available fly ashes can be advantageously used as admixtures in portland cement concrete for highway construction. Compressive strength, flexural strength, resistance to sulfate attack and freeze-thaw durability are included in the laboratory test series. Test data are utilized in the development of a mix design procedure aimed at optimizing the proportions of fly ash and portland cement.

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LIST OF ABBREVIATIONS AND SYMBOLS

AASHO	American Association of State Highway Officials
ACI	American Concrete Institute
ADOT	Arizona Department of Transportation
ASTM	American Society for Testing and Materials
A, B	Constants
Btu	British thermal unit
^{o}C	Degrees Celsius
cc	Cubic centimeters
CD	Coefficient of determination
CLC	Coefficient of linear correlation
cm	Centimeters
CM	Cementitious material
cy	Cubic yard
e	Natural logarithm base (2.718---)
ETL	Engineers Testing Laboratories, Inc.
^{o}F	Degrees Farenheit
F	Fly ash to portland cement weight ratio
FA	Fly ash
ft, ft^3	Feet, cubic feet
gal.	Gallons U.S.
gm	Grams
in.	Inch
Kg	Kilogram
K	Constant
KW	Kilowatt
k	Fly ash efficiency factor
KWH	Kilowatt-hour
lb.	Pound
MW	Megawatt
m, m^3	Meter, cubic meter
n	Number of samples
psig	Pounds per square inch gauge
PCA	Portland Cement Association

LIST OF ABBREVIATIONS AND SYMBOLS (continued)

PC	Portland cement
PC'	Portland cement equivalent
R	Flexural strength
s	Standard deviation
sk.	Sack (94 pounds portland cement)
σ	Compressive strength
σ_{cyl}	Compressive strength, molded cylinder
σ_{core}	Compressive strength, drilled core
σ_{28}	Compressive strength at subscript age
V_1	Within-test coefficient of variation
Vol.	Volume
W	Water (usually weight)
X	Independent variable
Y	Dependent variable

CONVERSION FACTORS

To convert from	To	Multiply by
Cubic foot	Cubic meter	2.832×10^{-2}
Cubic inches	Cubic meter	1.639×10^{-5}
Cubic yards	Cubic meter	7.646×10^{-1}
Foot	Meter	3.048×10^{-1}
Gallon (U.S. liquid)	Cubic meter	3.785×10^{-3}
Inch	Meter	2.540×10^{-2}
Pound-force	Kilogram-force	4.536×10^{-1}
Pounds per square inch	Kilograms per square centimeter	7.031×10^{-2}
Sack (U.S. cement)	Kilograms	4.264×10
Tons	Kilograms	9.072×10^{2}
Degrees Farenheit	Degrees Celsius	*

* $^{o}C = (5/9)\ (^{o}F-32)$

PROJECT SUMMARY

Coal-fired steam generating stations in and around Arizona produce millions of tons of waste boiler ash (fly ash) per year, most of which is not utilized in any way. Research has shown fly ash to possess pozzolanic properties thereby making it potentially useful, as a cementitious material, in a variety of construction applications.

The Arizona Department of Transportation, in October, 1974, commissioned Engineers Testing Laboratories, Inc. to undertake a study for the purpose of evaluating potential uses of fly ash in Arizona highway construction. The program was to serve the multiple objectives of developing a low cost construction material, utilizing a previously wasted by-product, and aiding in the conservation of the non-renewable resources, lime and portland cement.

The study was divided into two parts. Part I concerned the utilization of fly ash in portland cement concrete for Arizona highway construction. Included were a literature review, laboratory test program, engineering analysis of data, and the development of a mix design method. The laboratory procedures were directed toward evaluation of compressive strength, flexural strength, freeze-thaw durability and resistance to sulfate attack. Forty-eight mix designs were tested in the strength test series. A number of the mixes were then subjected to the durability and soundness test series. Strengths were determined to be predictable utilizing the proposed mix design method. Fly ashes from the four available sources were found to be beneficial admixtures for portland cement concrete.

An interim report was submitted to the Arizona Department of Transportation in January, 1976. The purpose of the

interim report was to present the preliminary fly ash concrete mix design procedure for review prior to the completion of the study.

Part II concerned the utilization of fly ash in soil stabilization for Arizona highway construction. The study program included a literature review, laboratory test series, engineering analysis of data and the development of a mix design procedure for lime-fly ash stabilized soil. Four typical Arizona soils were utilized in the test series, with fly ash from the four principal sources available in Arizona. Laboratory evaluations included combinations of zero to eight percent lime and zero to thirty percent fly ash for each soil type and fly ash source. Unconfined compressive strength, wet-dry durability and freeze-thaw durability were evaluated in the test series. The fly ashes were found beneficial in varying degrees, depending primarily on soil characteristics.

The two year project was completed with the general conclusion that available fly ash could be efficiently utilized in highway construction in Arizona.

CHAPTER 1. INTRODUCTION

The search for more efficient construction materials, and the problem of industrial waste disposal have been combined in the development of uses for waste boiler ash (fly ash) produced by coal-fired power generating stations. Fly ash is a pozzolan, a material with cementitious properties which can be utilized in many construction materials applications. The purpose of this report is to evaluate the use of fly ash in portland cement concrete.

The study has been conducted through literature search, laboratory testing and engineering analysis of the data developed. In carrying out the literature search, an effort was made to review all English language literature pertinent to the subject, with no regard for geographic origin. The laboratory studies utilized fly ash from the four principal sources which were found to be available to the Arizona construction market. Materials other than fly ash were each obtained from a single source thereby making fly ash quality the principal variable in the test program. Test series were designed to evaluate compressive strength, flexural strength, resistance to sulfate attack and resistance to deterioration from freezing and thawing.

Review of the literature and engineering analysis of the test data culminated in the development of a mix design procedure for normal weight portland cement concrete using fly ash as an admixture.

The results of the literature survey are presented in the chapter entitled Literature Review. Comment on the literature has been categorized by subject, for convenience (i.e., compressive strength, workability, durability).

References have also been organized by subject in the Subject Index to References immediately following the References near the end of the report.

Laboratory test procedures and results are presented in the middle chapters of the report along with analyses of of the data. The principal topics, strength and durability, are the subjects of separate chapters.

The mix design chapter includes an introductory evaluation of methods presently in use and a final section on evaluation of the proposed mix design method. The middle sections of the chapter can be independently used as a working outline for the proposed mix design method.

Information relative to the production and quality of fly ash from sources used in the study has been placed in an appendix since the evaluation of time variation in fly ash quality was not a principal objective of the program.

CHAPTER 2. LITERATURE REVIEW

2.1 Historical Development

2.1.1. Ancient Applications

In the third century B.C., the Roman builders made a significant discovery. Near Vesuvius were deposits of sandy volcanic ash, which when added to lime and water, made a cement which dried to rocklike hardness and even hardened under water. They called this material "pulvis puteolanus". By mixing this cement with sand and gravel they made concrete. First use of this material was as a filler between veneer finishes since durability to exposure was questioned. Nonetheless, some of the more daring builders of that time began using the material in exposed construction and surprisingly found the durability satisfactory. Thus, the material use spread widely. Structures, the Colosseum and the Basilica of Constantine, and distribution systems, the Clocaca Maxima and the Aquaducts, were just a few of the facilities built utilizing this new material. Many of these structures still exist today and attest to the durability of the new found material.

The Roman method of making cement, combining lime and pulverized volcanic ash, was essentially the only method employed until 1824, although numerous processes had been attempted. At that time, the first successful process of artifically combining and calcifying clay and limestone to form a hydraulic cement was realized. With the development of a manufacturing process to produce high quality hydraulic cement, known today as portland cement, the use of natural cementing agents declined rapidly.

The natural material employed by the Romans is classified today as a pozzolan. A pozzolan is defined as a siliceous or siliceous 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. Pozzolans may be either natural materials or synthetic materials which consist of glassy materials produced by rapid cooling of molten silicate mixtures. Fly ash, the finely divided residue that results from the combustion of ground or powdered coal and is subsequently collected from the flue gases, is an example of a synthetic pozzolan. Fossil fuel power plants are the major producers of the material.

Although fly ash was recognized as a pozzolanic material, little use was made of the product until the need arose for massive concrete structures possessing low permeability. Experience with portland cement concrete revealed that during the hydration process significant quantities of heat were generated. Release of this heat, during the later cooling period, cause the concrete to crack unless precautions were taken. Thus, the need arose to minimize the temperature rise during hydration and subsequent volume change without loss in strength. Pozzolanic cements which produce lower ultimate heat than portland cement and which liberate the heat at slower rates appeared to be advantageous. Additionally, it was recognized that during the hydration of portland cement a significant quantity of free lime was formed. The free lime present in the hardened concrete was susceptible to leaching from the concrete of hydraulic structures resulting in a more porous concrete. The incorporation of a pozzolanic material, which would chemically combine with the free lime to form a non-leachable cement component, was employed. These circumstances initiated a renewed interest in pozzolanic materials.

2.1.2. Use of Pozzolans in the United States

With development of the manufacturing process for portland cement, the abundance of suitable materials for processing, and superior quality control, concrete construction in the United States was almost exclusively confined to portland cement.

Use of pozzolanic materials was not seriously considered until governmental emphasis was directed toward implementation of large reclamation and hydro-electric programs. Most of these programs required construction of massive concrete structures. In 1911, the Bureau of Reclamation initiated an investigation into the use of pozzolans in concrete (20)*, and in 1915 the Bureau of Reclamation specified a natural pozzolan for the Arrowrock Dam. The first use of fly ash as a pozzolan by the Bureau of Reclamation was in the repair of the spillway tunnel at Hoover Dam in 1942. Following this project the Bureau of Reclamation began collecting fly ash samples from various locations and initiated an extensive testing program. As a consequence, fly ash was specified for use in Hungry Horse Dam. Numerous projects have since been constructed under Bureau of Reclamation authorization which contain fly ash as a pozzolan.

Initial use of fly ash by the Corps of Engineers was in the construction of Sutton Dam, West Virginia, in 1958 (102). Subsequently, fly ash has been used extensively by the Corps of Engineers. Concurrently the

*Numbers in parenthesis in this section and throughout the report correspond to source title listed in the Reference section.

Tennessee Valley Authority began using fly ash in concrete structures.

In most of the early applications, the minimization of the heat of hydration was the primary concern rather than the strength characteristic of the resulting concrete. Experience indicated that 25-30% substitution of portland cement by fly ash could be utilized while achieving an adequate strength level; however, the desired strength would not develop within the normal reference period, 28 days. Since construction for these projects extended over a considerable period of time, early strength development was not a requisite. However, on projects where the construction period was short, the knowledge of fly ash concrete possessing low early strength most certainly curtailed its utilization.

The major impetus to the use of fly ash in portland cement concrete is attributed to the research work of R. E. Davis, et al (16) published in 1937 and in later reports (15, 17, 18). Some of the significant findings of these researchers relative to the use of fly ash in concrete were:

1. Improved workability
2. Less segregation and bleeding
3. Water demand about the same or lower
4. Increased ultimate strength
5. Reduced shrinkage
6. Increased resistance to sulfates
7. Reduced heat of hydration
8. Reduced permeability

Interest and research in fly ash usage in concrete waned during the World War II period but renewed interest and extensive research was initiated in the late forties. During the early fifties, correlation of research and experience data was undertaken by committies of various technical societies and agencies (2, 9, 10, 13, and 99). In 1954, the American Society for Testing and Materials issued the first specification for fly ash usage in concrete. This initial specification viewed fly ash as only an admixture in portland cement concrete and specifically stated, "The use of fly ash as a direct substitute for portland cement is not within the scope of these specifications". Three years later, the Corps of Engineers issued a specification for pozzolans and the methods of sampling and testing pozzolans. Subsequently, an engineering manual establishing criteria for use of pozzolans was issued. Modifications were incorporated into the original ASTM specifications periodically; however, it was not until 1960 that a standard was issued to cover fly ash both as a pozzolan in portland cement concrete and as an admixture. With the issuance of recognized specifications, utilization of fly ash in portland cement increased; however, today approximately 42 million tons (3.8×10^{10} Kg) of fly ash are produced annually, whereas only 10% of the ash is utilized with only a minor percentage finding its way into concrete.

2.1.3. Highway Construction

The use of fly ash in portland cement concrete by the various highway agencies has been rather limited. First reported use was in the construction of twelve 488 ft. (149 m) test sections in Kansas in 1949. Available aggregate for this construction had long been considered responsible for severe map-cracking and abnormal expansion in concrete pavements. In an effort to reduce these effects, fly ash from the Chicago area was used to replace 25% of the portland cement in the standard mix. The fly ash was found effective in reducing surface cracking and eliminating map-cracking (94). In 1949, Larson (40), working for the State Highway Commission of Wisconsin, reported the results on a study of the effects of substitution of fly ash for portions of the cement in air-entrained concrete. His study lead to the installation of a 3.3 mi. (5310 m) test section. Field examination of the test section by Abdun-Nur (1) after 9 years of service indicated the pavement to be in good condition with no evidence of failure due to the concrete. Knowledge of the experimental work being conducted in Kansas spread to Nebraska and two experimental test roads, each approximately 6 mi. (9660 m) in length, were constructed utilizing fly ash. Results indicated the use of fly ash in the concrete presented no special problems in construction and the fly ash concrete was durable, high in strength and did not expand because of cement-aggregate reaction (95).

The Alabama State Highway Department has been the leader among the states in using fly ash in concrete pavements and structures with their first installation being in 1955. Their experience with fly ash has been so successful that to date over 660 mi. (1.06×10^6 m) of pavement have been constructed (28, 29, 30). Alabama is one of the few states which currently have a standard set of specifications for fly ash concrete. Alabama's experience (30) indicates that without regard to the benefits derived from the addition of fly ash to concrete, when based on the cost of the concrete without fly ash, the average cost of the fly ash mixture is less. Nevertheless, to date only eleven states have used fly ash in portland cement concrete.

2.1.4. Structural Uses

A rather limited amount of published data exists, relative to the use of fly ash as a pozzolan in structural concrete. Public contention that fly ash concrete possesses low early strength, a detriment to early form removal and rapid construction, may have accounted for the slow acceptance of fly ash concrete for structural uses. The leaders in the structural use of fly ash concrete have been the power utilities, particularly in the Chicago area. With their successful experience, architectural firms soon began specifying fly ash concrete for structures.

The Prudential Building in Chicago, a 41 story structure, contains a total of 100,000 cy (76,460 m^3) of fly ash concrete in the structural elements, ranging from the caissons to the light-weight concrete floors (33). It has been concluded that the use of fly ash was the prime factor for the remarkable absence of drying shrinkage cracks in the floors. Numerous other high-rise structures, John Hancock Center, Imperial Towers, Lake Shore Drive Apartments, Lake Point Tower and others, have incorporated fly ash in their construction. For the 5000 psi (350 Kg/cm^2) concrete specified for the Imperial Towers, only two cylinders fell below specifications, and the coefficient of variation was 2.88%. In the 20 story Lake Point Tower fly ash concrete designed for 7500 psi (530 Kg/cm^2) was used in all columns and shearwalls to the 17th floor. Twenty-eight day compressive strength test results indicated strength of 8100 psi (570 Kg/cm^2). Additional structures have been built incorporating fly ash concrete with the strength of 9000 psi (630 Kg/cm^2) and currently consideration is being directed to developing fly ash concrete possessing compressive strength as high as 11,000 psi (770 Kg/cm^2).

2.1.5 Specifications

As will be discussed later, fly ash varies from one power plant to another and from time to time in a given plant. Due to this variability, specifications have been established to use as a guide for assessing the general characteristics of the fly ash. The first specifications issued in 1954 by the American Society for Testing and Materials applied only to the use of fly ash as an admixture to concrete. Numerous modifications were later adopted and in 1960 specifications were issued relative to the acceptance of fly ash as a pozzolan. The current ASTM specification, Designation: C618-73, segregated all pozzolans into three classes; raw or calcined natural pozzolans, Class N; fly ash, Class F; and others, Class S. This specification is applicable for both the chemical and physical requirements of the pozzolanic material. The current ASTM specification forms the basis for all standard and/or special provision specifications issued by the state highway agencies. Table 2-1 contains the current ASTM specification for fly ash and the specifications issued by some of the state highway agencies and other public agencies. For the state specifications, entries have been designated only for those requirements which are in variance with the ASTM specification. In general, the state's specifications are more restrictive than the ASTM, particularly in regard to the loss on ignition requirement. Further, most of the states specify a maximum amount of fly ash which may be used in the concrete.

It is noted that a modification of ASTM Designation: C618-73 is presently under review by ASTM Committee C-9 and is to be voted upon for possible adoption. The review specification contains two classes for fly ash

TABLE 2-1. Specifications for Fly Ash

Property	ASTM C-618 Class F (6)	Std. Ala.	(1) S.P. Fla.	S.P. Ga.	S.P. Ind.	S.P. Ky.	S.P. Neb.	S.P. W.Va.	S.P. Mich.	S.P. Wisc.	Std. Minn.	(3) N. Dak. F1	F2	Corps of Engrs.	Federal
pH min.		7.0		7.0											
SiO_2 %				40.0											
Al_2O_3 %		15.0		15.0											
Fe_2O_3 %															
Sum of Oxides % min.	70.0										45.0	70.0	5.0	70.0	75.0
MgO % max.		5.0		3.0								5.0		5.0	5.0
SO_3 % max.	5.0	3.0		3.0							12.0		7.0	4.0	4.0
Moisture % max.	3.0	1.0												3.0	3.0
LOI % max.	12.0	6.0	6.0	6.0	8.0	6.0	6.0	6.0	4.0	5.0	5.0		6.0	6.0	6.0
Available Alk. as Na_2O % max.	1.5 (2)	1.5									3.0		2.5	1.5	2.0
CaO % max.											35.0		35.0		
Free Carbon % max.							3.0								
Fineness cm^2/cm^3 min.	6500			3000 (4)										6500	6500
Retained #325 % max.	34	25		20.0					10.0		30.0	20.0	30.0	(7) N.S.	N.S.
Multiple Factor	255.0											150	150	N.S.	N.S.
Pozz. Act. Index - 28 Days % min.	85										75		75	75	75
w/lime psi min.	800													900	900
Water Requirement % max.	105													(5)	(5)
Shrinkage % max.	0.03	0.09												N.S.	N.S.
Soundness % max.	0.50													.50	.50
Expansion 14 day % max.	0.02													N.S.	N.S.
FA Proportion Specified			20% by wt.	25% by wt.	100 lb. per cy no red. in PC	94 lb. per cy		equal vol. to 1 bag	used 72 lb. FA to repl. 47 lb. PC	used 75 lb. FA per cy	10% by wt.	(8) 15%	(8) 15%		

NOTES:

(1) Special Provision
(2) Optional test
(3) Sub-bituminous and lignite coal sources
(4) cm^2/gm
(5) This specification requires that a mortar of fly ash pozzolan and 103 percent of the water content of the control shall have a flow equal to or greater than that of the reference mortar.
(6) Uniformity requirements not presented
(7) Not specified
(8) Weight or volume replacement not specified

pozzolanic material: Class F, fly ash derived from anthracite or bituminous coal; and Class C, fly ash derived from lignite or subbituminous coal. The review specification for Class F fly ash is the same as the current specification given in Table 2-1 with the following exceptions:

a) Blaine fineness requirement has been eliminated;
b) Pozzolanic Activity Index with portland cement has been lowered to 75% minimum;
c) Autoclave soundness has been increased to 0.8% maximum; and
d) a uniformity requirement on the fineness, as measured by the percent retained on the #325 sieve, has been added.

As this review specification has not been approved, the above are presented only for informational purposes and distribution of the Class C requirements is considered inappropriate at this time.

Other Federal agencies, Federal Housing Administration, Federal Aviation Administration and U. S. Department of the Navy, have issued their own specifications, but all cite the ASTM specification as a guide.

2.2 Fly Ash Characteristics

2.2.1 Chemical and Physical Properties

Tests indicate that, generally, the strength developed in fly ash-portland cement mortars is related to the carbon content of the fly ash, the fineness of the fly ash measured by the amount passing the #325 sieve, and the water requirement for mortars containing fly ash as compared to similar mortars without fly ash (11). However, the loss on ignition shows no correlation with compressive strength of the mortar (5).

Nevertheless, if fuel oil is burnt concurrently with the coal, small changes in loss on ignition, not directly caused by unburnt coal, may severely retard cement hydration (73).

Differences in SiO_2, Al_2O_3, CaO, MgO, or the sum of SiO_2 and Al_2O_3 contents of fly ash appear to have little significant bearing on the properties of either mortar or concrete (5). However, the SO_3 content of the fly ash appears to have an influence on the early compressive strength; higher SO_3 contents result in higher strengths (5).

2.3 Fly Ash in Portland Cement Concrete

2.3.1 General

Available references relative to the use of fly ash in portland cement concrete are listed in the Reference section of this report. The literature has been reviewed and summarized in logical categories which are then presented in the section entitled Subject Index to References, immediately following the References. In addition, outstanding or particularly relevant comment from the literature has been summarized in this section.

The literature available on the use of fly ash is voluminous. The scope of the presentation here is necessarily limited to highly selective comment on each topic.

2.3.2 Compressive Strength

One-to-one replacement of a portion of the portland cement with fly ash generally results in reduced early strength. However, for a well designed mix, strength beyond 28 days may exceed that of the normal portland cement mix (4, 39). Fly ash must be added in greater quantity than the cement removed to maintain equivalent early age strength (4, 100). In general, curing conditions have the same effect on the compressive strength of fly ash concrete as on normal concrete (9). A definite relationship exists between compressive strength and water requirement for a mortar of fixed consistency (11). The strength of fly ash concrete batched with Type II cement is lower at early age, but higher at late age than similar concrete batched with Type I cement (100).

2.3.3 Flexural Strength (Modulus of Rupture)

High flexural strength in concrete pavement containing fly ash can be obtained with mixes of relatively low cement factor (28). Investigators generally agree that portland pozzolan cement has greater tensile strength than standard portland cement concrete (7).

2.3.4 Workability

Fly ash concrete shows less tendency to separate than concrete not containing fly ash (15, 31), is more plastic, and bleeds less (15). Fly ash in concrete mixes also retards the rate at which the concrete hardens, an advantageous characteristic in hot weather applications where the concrete is exposed to sun and air. However, this retarding effect is not tolerated for cool and cold weather applications and in areas under cover such as basements and floors in homes (87). One study indicates that the addition of finely divided mineral admixtures to concrete without a reduction in cement often entails an increase in the total water content of the concrete and may result in an increase in drying shrinkage and absorptivity as well as a decrease in strength (4). Another study indicates that an 8% sand replacement with fly ash results in a mix of greater workability, even at low slumps (less than 2 inches), for pavements resulting in less shrinkage for a given workability (28, 30). In certain cases, concrete with fly ash has been requested by the concrete finishers who had previously worked with fly ash concrete (30).

2.3.5 Water Reduction

The amount of mixing water required to produce a concrete mix having a given degree of workability is generally less for fly ash mixes than for straight portland cement concrete (8). In one study, mixes with 70 to 188 pounds of fly ash per cubic yard (42 to 112 $\frac{Kg}{m^3}$) required 1 to 2½ gallons less water per cubic yard (0.005 to 0.012 $\frac{m^3}{m^3}$) than comparable non-fly ash mixes of the same consistency (100).

2.3.6 Time of Set

A 25% cement replacement with fly ash can produce concrete that remains workable approximately 2 hours longer at 70°F (21°C) and approximately 4 hours longer when the concrete temperature is 50°F (10°C) (69).

2.3.7 Curing Conditions

Studies indicate that the 28 day strengths of concrete made with or without fly ash respond in the same manner to a given storage condition; moist, dry or cold (10,100). However, fly ash mixes with standard moist curing produce slightly lower strengths prior to 28 days and appreciably higher strengths at lager ages compared to mixes with the same 28 day strength, Type I cement, and no fly ash (10). The fly ash blend also suffers greater strength reductions at the later ages from low temperature curing than the straight Type I cement (10).

2.3.8 Air-Entraining Admixture Demands

Concrete containing fly ash requires larger quantities of air-entraining admixture (AEA) than do concretes not containing fly ash. The increase in AEA with increasing quantities of fly ash varies with quality of fly ash. Both test data and field experience indicate that fly ash concrete requires more AEA than non-fly ash concrete to achieve the same air content (100).

2.3.9 Volume Change

Generally, researchers agree that the use of fly ash in reasonable quantities will not cause excessive drying shrinkage (9, 17, 28). A few studies report drying shrinkage to actually be less for fly ash mixes than for conventional concrete (8, 20, 97). It is also reported that autoclave expansion is considerably lower for fly ash mixes than for straight cement mixes (17).

2.3.10 Creep

A replacement of 15% cement with fly ash (by weight) is found to be the optimum value with respect to creep for the use of fly ash in structural concrete. Creep-time curves for plain and fly ash concretes are similar. Increase in creep with fly ash content is negligible up to 15% replacement, above which creep increases slightly with increasing fly ash content. The probable mechanism of creep is the same for fly ash and normal concrete (44).

2.3.11 Permeability

Concrete is less permeable when a portion of the portland cement is replaced with fly ash (8). Proper use of fly ash as an admixture can reduce permeability from one-sixth to one-seventh that of equivalent concrete containing no fly ash (4).

2.3.12 Freeze-Thaw Durability

The effect of fly ash on the freeze-that durability of concrete is in dispute. Many studies report that fly ash has no effect on the freeze-thaw durability of concrete or that the effect is inconclusive from the tests performed (9, 100). Some reports state that fly ash mixes have freeze-thaw durability characteristics similar to normal concrete mixes if the air contents and compressive strengths are comparable (4, 46). Other reports conclude that fly ash mixes excell over normal mixes in freeze-thaw durability (17, 95). Most studies indicate freeze-that durability to be highly dependent on air content (4, 28, 40, 46, 95, 100).

2.3.13 Sulfate Resistance

All studies reviewed indicated that the resistance of concrete to sulfate attack is improved by the addition of fly ash (4, 8, 17, 20, 28, 39, 73, 100). The effectiveness of fly ash in improving the sulfate resistance of concrete increases as the severity of the exposure to sulfates is increased (4). Special cements for sulfate resistance or for use in marine works may be unnecessary with the correct proportioning of fly ash and portland cement (73).

2.3.14 Surface Scaling

The studies reviewed conflict over the effects of fly ash in concrete on surface scaling. The conclusions range from adverse effect on resistance to surface scaling for all fly ash-portland cement combinations (97) to equal or greater resistance to scaling compared to normal concrete so long as the carbon content of the fly ash remains low (25).

2.3.15 Alkali Reaction

Studies indicate that fly ash is effective in reducing alkali reaction and corresponding mortar expansion (8, 95). Fly ash is more effective in reducing reaction at later ages than at earlier ages (8). However, the use of small amounts of fly ash (less than 10% replacement) along with potentially alkali-reactive combinations may actually increase the rate and severity of alkali-aggregate reaction (65).

2.3.16 Corrosion of Reinforcing Steel

Most sources agree that the addition of fly ash to concrete does not decrease the protection against corrosion of steel reinforcing bars when compared to normal concrete (38, 74, 83, 85). In one study the corrosion potective properties are enhanced by the inclusion of fly ash (39).

2.4 Proportioning Techniques

Several techniques are available for the proportioning of mixes to include fly ash. These techniques utilize a previously tested and proven portland cement concrete mix design by changing the proportions of the different constituents and adding fly ash (46, 53). Strength and workability are held constant between the normal and fly ash mixes (12, 88, 89).

CHAPTER 3. MATERIALS

3.1 General

All materials utilized in the study, excepting the fly ashes, were typical of materials presently used in the manufacture of portland cement concrete in the Phoenix area. Ash from several of the sources had not been used commercially for concrete production in combination with other materials used in the study. In all cases, materials were obtained from normal production runs at commercial production facilities and were not specially produced for use in this study.

Since the study was primarily concerned with variations in concrete characteristics attributable to the use of fly ash as a pozzolanic admixture, it was desired to eliminate, insofar as possible, variations due to constituents other than fly ash. Aggregate, cements and admixtures, therefore, were each obtained from a single source and generally in one purchase lot. All of the materials used (except fly ash) have a history of satisfactory performance in local usage and the general behavior of each of the constituents (except fly ash) has been reasonably well established.

The materials used in the course of the study are described in the following paragraphs. Information on the sources from which materials were obtained is presented in Table 3-1.

3.2 Aggregates

3.2.1 Coarse Aggregate

Coarse aggregate was obtained from alluvial Salt River deposits located in the South Central section of Phoenix, Arizona. The pit-run material in these deposits is typically quite coarse, with an excess

TABLE 3-1. Materials Sources

Material	Source	Remarks
Fly Ash	1. Cholla Power Plant 2. Four Corners Power Plant 3. Navajo Power Plant 4. Mohave Power Plant	Arizona New Mexico Arizona Nevada
Portland Cement	Phoenix Cement Company	Type V* Type II Type IP
Coarse Aggregate	Arizona Sand and Rock (Salt River Source)	ADOT ** Specification 706
Fine Aggregate	Arizona Sand and Rock (Salt River Source)	ADOT Specification 706
Air Entraining Agent	W. R. Grace and Company	Daravair Darex AEA
Water	Phoenix Municipal Water Supply	

* Type II portland cement was used in all fly ash-portland cement concrete mixes. Types IP and V were used for comparative data in selected areas of the study.

** Arizona Department of Transporation

of relatively large rock exceeding 8 inches (20.3 cm.). Crushing is required for balanced production of most aggregate gradations. Some portion of oversize rock is generally wasted in production; nevertheless, aggregate typically contains a large proportion of crushed rock (as compared to screened river run rock). Salt River aggregate is considered, in most respects, one of the better concrete aggregates available in Arizona.

Table 3-2 presents a summary of results derived from tests of the coarse aggregate used in the study. As indicated in Table 3-2, the coarse aggregate was found to be non-reactive when tested in accordance with ASTM C-289 procedures. In the past, Salt River aggregates have occasionally shown a potential for alkali reactivity when tested by this procedure, and reactivity has been experienced in actual use with high alkali cements. This problem has been alleviated with introduction of the production and use of low alkali cement in Arizona, and Salt River aggregate has a long and extensive history of satisfactory performance when used with low alkali cements.

3.2.2 Fine Aggregate

Fine aggregate, obtained from the same source as the coarse aggregate, is predominantly a screened and washed material. Test results of representative samples from the aggregate used in batching the concrete for the study are presented in Table 3-3.

3.3 Portland Cement

The portland cements utilized in the study were produced by Phoenix Cement Company - Division of Amcord, Inc. at a facility located near Clarkdale, Arizona. The cements used

TABLE 3-2. Coarse Aggregate Characteristics

Bulk Specific Gravity (SSD)	Bulk Specific Gravity (OD)	Absorbtion %	Gradation			Dry Rodded Unit Wt. lb./ft^3	Abrasion %	Sodium Sulfate Soundness (Five Cycles) %		Potential Alkali Reactivity
			Sieve Size	% Finer						
AASHO Designation: T84				T27	Spec*	T19	T96	T104	Spec**	ASTM Designation: C289
			1½ in.	100	100					
2.68	2.66	0.75	1 in.	98	95-100					
			3/4 in.	73						
2.68	2.66	0.82	1/2 in.	29	25-60	101.7	13	0.84	12 max.	Aggregate Considered Innocuous
			3/8 in.	14						
2.68	2.66	0.87	1/4 in.	5		101.5				
			#4	1	0-10					
			#8		0-5					

* "Spec" denotes AASHO Designation: M80-70, Size #57, as adopted by ADOT.

** "Spec" denotes AASHO Designation: M80-70.

TABLE 3-3. Fine Aggregate Characteristics

Bulk Specific Gravity (SSD)	Bulk Specific Gravity (OD)	Absorbtion %	Gradation			Sand Equivalent %	Organic Impurities	Fineness Modulus	Sodium Sulfate Soundness (Five Cycles) %	
			Sieve Size	% Finer						
AASHO Designation: T84				T27	Spec*	T176	T21	M6	T104	Spec**
			3/8 in.	100	100					
			1/4 in.	99						
2.65	2.62	0.99	#4	96	95-100	92				
			#8	85						
			#10	81						
2.65	2.62	1.01	#16	70	45-80	91	#1 (clear)	2.76	4.4	10 max.
			#30	45						
			#40	32						
2.65	2.62	0.97	#50	22	10-30	92				
			#100	6	2-10					
			#200	1	0-4					

* "Spec" denotes AASHO Designation: M6-65 as adopted by ADOT.

** "Spec" denotes AASHO Designation: M6-65.

were commercially classified as Types IP, II and V as defined in ASTM Designations: C595 and C150. Type II cement was used in all fly ash concrete batched for the study. Types IP and V were used for comparative purposes in selected portions of the study. Type IP blended cement was used in comparison specimens prepared for compressive strength, flexural strength, sulfate soundness and freeze-thaw testing. Type V sulfate resistant cement was used for comparative specimens in the sulfate soundness test series.

The results of physical and chemical tests performed on samples of cement from the shipments used in the test concrete are presented in Tables 3-4 and 3-5. The cement shipment dated November 14, 1974, was used in the compressive and flexural strength specimens. The later shipment, November 21, 1975, was used for durability and soundness test specimens. The slight difference in cement characteristics, indicated by the data of Tables 3-4 and 3-5, was recognized. Cement from only one shipment was utilized in any given test series. No testing was performed on the Type IP and Type V cements since these cements were not utilized in the batching of fly ash concrete.

3.4 Fly Ash

Fly ash from four sources was utilized in the study. The sources and general locations were:

Four Corners Power Plant	- near Fruitland, New Mexico
Navajo Power Plant	- near Page, Arizona
Mohave Power Plant	- near Laughlin, Nevada
Cholla Power Plant	- near Joseph City, Arizona

Coal used at these plants was obtained from bituminous-to subbituminous sources in Arizona and New Mexico. Information on coal sources and quality is included in Appendix A.

TABLE 3-4. Type II Portland Cement
Physical Test Results

Test Procedure	Shipment Received 11/14/74	Shipment Received 11/21/75	ASTM: C150 Specification
Blaine Fineness, cm^2/gm ASTM: C204	3423	3972	2800 min.
Compressive Strength , psi ASTM: C109			
Age 4 days	3110	-	
7	3230	4140	2500 min.
28	5200	5380	
60	5930	6380	
90	6420	6960	
Autoclave Expansion, % ASTM: C151	0.04	0.13	0.80 max.
Setting Time, Gillmore ASTM: C266			
Initial, Min.	310	193	60 min.
Final, Hr.	7.75	5.22	10 max.
Normal Consistency, % ASTM: C187	26.5	25.0	
Specific Gravity ASTM: C188	3.14 3.13	3.12	
Air Content, % ASTM: C185	5.6	6.0 4.9	12 max.

TABLE 3-5. Type II Portland Cement Chemical Test Results

Constituent	Shipment Received 11/14/74 %	Shipment Received 11/21/74 %	ASTM: C150 Specification %
Silicon Dioxide (SiO_2)	21.12	21.14	Min. 21.0
Aluminum Oxide (Al_2O_3)	3.29	3.48	Max. 6.0
Ferric Oxide (Fe_2O_3)	2.38	2.66	Max. 6.0
Calcium Oxide (CaO)	62.13	60.80	–
Magnesium Oxide (MgO)	4.03	4.18	Max. 5.0
Sulfur Trioxide (SO_3)	2.50	2.10	Max. 3.0
Loss on Ignition	1.96	3.66	Max. 3.0
Insoluble Residue	0.79	0.55	Max. 0.75
Tricalcium Aluminate ($3CaO{-}Al_2O_3$)	4.69	4.72	Max. 8.0

Test results from samples of the fly ash used in the study specimens are presented in Table 3-6. Periodic sampling and testing of fly ash from each of the sources were performed during the course of the study; however, such sampling and testing were unscheduled and incidental to this study. The data were accumulated for the purpose of providing information on the variation of fly ash properties. Test data relating to the periodic sampling as well as a discussion of the methods of fly ash recovery at each plant are presented in Appendix A.

The data of Table 3-6 apply to samples which represent only the fly ash used in the strength and durability test specimens. Data in Appendix A apply to all samples, and include the results presented in Table 3-6.

The test results indicate that each fly ash failed in some respect to meet the ASTM Designation: C618 for Class F Pozzolan. The failures occurred in the areas of fineness (Blaine surface area and % passing the #325 sieve) and Pozzolanic Activity Index.

3.5 Water and Admixtures

3.5.1 Water Source

The water used in batching concrete test specimens was obtained from the City of Phoenix municipal water supply (laboratory tap water) except where applicable test specifications required distilled water. In general, concrete strength and freeze-thaw specimens were batched with tap water. Sulfate soundness specimens and cement quality specimens were batched with distilled water. No testing was performed on water used in the course of the test program. Table 3-7, however, presents typical data from analyses of the Phoenix water supply.

TABLE 3-6. Fly Ash Used in Strength and Durability Test Specimens

Property *	Cholla	Four Corners	Navajo	Mohave	ASTM: C 618 Class F Specifications
SiO_2 %	58.4	58.4	52.7	52.6	
Al_2O_3 %	31.4	31.4	20.5	16.3	
Fe_2O_3 %	1.3	0.8	4.9	5.5	
Sum of oxides %	91.1	90.6	78.1	74.4	70.0 min.
MgO %			2.0	2.5	-
SO_3 %	0.3	0.3	0.5	1.13	5.0 max.
Moisture %	0.01	0.04	0.02	0.02	3.0 max.
Loss on Ignition %	0.34	0.44	2.77	0.77	12.0 max.
Available Alkalies					
As Na_2O %	0.28	0.52	1.31	1.14	1.5 max.
CaO %	4.5	3.3	8.7	16.4	-
Fineness					
Surface Area cm^2/cm^3	4560	5000	6835	9145	6500 min.
Retained #325 %	36.2	29.8	34.4	36.2	34 max.
Multiple Factor %	12.3	13.1	95.3	27.9	255.0 max.
Pozzolanic Activity Index:					
Cement, % control	60.0	56.0	67.0	84.0	85 min.
Lime, psi	-	-	-	-	800 min.
Water requirement					
% of control	102	98.5	-	-	105 max.
Shrinkage,					
Increase %	0.077	-	-	-	0.03 max.
Soundness,					
Autoclave %	0.048	0.048	0.053	0.13[illegible]	0.5 max.
Expansion - 14 day %	-	-	-	-	0.02 max.
Air-Entraining Admixture ml.	1.68	1.44	-	-	Not applicable
Specific gravity	2.07	1.92	2.12	2.46	Not applicable

*ASTM: C618 Test Series for Class F Pozzolan

3.5.2 Admixtures

No admixtures other than an air entraining agent were used in the concrete. The air entraining admixtures used are described in Table 3-8.

TABLE 3-7. Phoenix Water Supply - Typical Analysis

pH	7.4 - 8.0
Chloride	20 - 465 mgs/l*
Alkalinity, Carbonate	0 - 2 mgs/l
Bicarbonate	110-145 mgs/l
Hardness	120-600 mgs/l
Calcium	22-120 mgs/l
Magnesium	11-67 mgs/l
Total Solids	190-1420 mgs/l
Nitrate	10-180 mgs/l
Fluoride	0.2-1.4 mgs/l
Iron	0-0.1 mgs/l
Sulfate	1-200 mgs/l
Sodium	20-240 mgs/l
Note: The water actually used in the mixes was not tested. This data represents typical values encountered in the City of Phoenix water supply.	

*Milligrams per liter, which is equivalent to parts per million (by weight).

TABLE 3-8. Air Entraining Admixtures

Air Entraining Agent	Manu-factured by	Description	Remarks
Darex AEA	W. R. Grace & Co.	Purified, sulfonated hydrocarbon w/cement catalyst	Used in control batches A1, A2, B1, and B2
Daravair	W. R. Grace & Co.	Concentrated aqueous solution of completely neutralized vinsol resin	Used in all other mixes
Note: Products were not analyzed. Descriptive information was supplied by the manufacturer.			

CHAPTER 4. MIX DESIGNS AND LABORATORY PROCEDURES

4.1 Concrete Mix Designs

4.1.1 General

To meet the objectives of the study, several series of mix designs were developed as a basis for the batching of normal portland cement "control mixes" as well as fly ash concrete mixes. The principal variable in both types of mixes was the volume of cementitious material (portland cement and fly ash). In general the mix designs were developed in accordance with the following considerations:

Coarse aggregate - volume was maintained constant for all mixes, 12.00 $\frac{ft^3}{cy}$ (.0444 $\frac{m^3}{m^3}$).

Fine aggregate - volume was varied from 5.61 to 7.83 $\frac{ft^3}{cy}$ (0.208 to 0.290 $\frac{m^3}{m^3}$) to accommodate changes in cementitious material.

Water - volume was varied from 28.2 to 33.9 $\frac{gal}{cy}$ (0.140 to 0.168 $\frac{m^3}{m^3}$) to maintain workability in the range of 3 $\pm$ 3/4 in. (7.6 $\pm$ 1.9 cm) slump.

Cement and fly ash - total and relative volumes were varied to achieve a suitable range of test data.

Fly ash was the only constituent which varied as to source; four sources were utilized, as described in Chapter 3. Batch weights for all test mixes are included in Appendix B. Mix designs were developed and controlled using absolute volume calculations.

4.1.2 Control Concrete Mixes

Seven control mixes were designed and batched for the study. The first three mix designs (numbers A, B and C) contained 2.90 cubic feet of Type II portland cement per cubic yard (0.107 $\frac{m^3}{m^3}$). This volume, for purposes of relative comparison was designated as 100% cementitious material volume, equivalent to 570 pounds or 6.1 sacks per cubic yard (338 $\frac{kg}{m^3}$). Control mixes 0-0, 0-1, 0-2 and 0-3 were designed with 100%, 90%, 80% and 70% respectively, of the basic control volume of portland cement. This provided a range of control mixes containing from 570 down to 400 pounds or 6.1 to 4.3 sacks of Type II portland cement per cubic yard of concrete (338 to 237 $\frac{kg}{m^3}$).

4.1.3 Fly Ash Concrete Mixes

Several fly ash mixes were studied for each of the four fly ash sources. A coded numbering system was developed to aid in identifying the numerous mix designs. Each mix was identified by a three digit code (such as C-3-2). The first digit identified fly ash source:

C - Cholla
F - Four Corners
M - Mohave
N - Navajo

The second digit identified the volume of cementitious material relative to the base control volume of 2.90 cubic feet per cubic yard (0.082 $\frac{m^3}{m^3}$).

1 - 100%

2 - 110%

3 - 120%

4 - 130%

5 - 140%

The third digit represented the ratios of fly ash and portland cement to the base control volume of cementitious material:

% Control Volume	Third Code Digit	% Fly Ash By Vol.	% Cement By Vol.
100	1	10	90
	2	20	80
	3	30	70
110	1	15	95
	2	25	85
	3	35	75
120	1	25	95
	2	35	85
	3	45	75
140	1	50	90
	2	60	80
	3	70	70

Thus, the mix code C-3-2, for example, would identify the mix as containing Cholla fly ash, 3.48 cubic feet (0.0985 $\frac{m^3}{m^3}$) total cementitious material or 120% of 2.90 cubic feet (0.0821 m^3), 1.02 cubic feet (0.0289 $\frac{m^3}{m^3}$) fly ash or 35% of 2.90 cubic feet (0.0821 $\frac{m^3}{m^3}$), and 2.46 cubic feet (0.0696 $\frac{m^3}{m^3}$) portland cement or 85% of 2.90 cubic feet (0.0821 $\frac{m^3}{m^3}$). Other mixes could be similarly identified, with the exception of those containing

Type IP Cement. The Type IP mixes were identified as follows:

IP-0-0	100% control cementitious material
IP-0-1	90%
IP-0-2	80%
IP-0-3	70%
IP-1-0	110%
IP-2-0	120%
IP-3-0	130%

The proportions of pozzolan to portland cement were not determined for the Type IP, therefore no reference to such proportions is made in this study.

It was generally necessary to mix more than one batch to obtain the concrete necessary for all testing and specimens. A letter (A or B) added as a fourth digit to the mix code identified succeeding batches of the same mix design (i.e., C-3-2A, C-3-2B).

4.2 Concrete Batching and Sampling

4.2.1 Mixing

Concrete for test specimens was batched and mixed in accordance with the Standard Method of Making and Curing Concrete Test Specimens in the Laboratory, AASHO Designation: T126-70 (ASTM Designation: C192-69). Mixing was accomplished in a five cubic foot power-driven revolving drum, tilting mixer. Mortar adhering to the mixer was compensated for by "buttering" the mixer immediately prior to batching. Consistency and air content were determined for each batch. Consistency was determined in accordance with the Standard Method of Test for Slump of Portland Cement Concrete, AASHO Designation: T119-70 (ASTM Designation: C143-69). Air content was determined in accordance with the Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method, AASHO Designation: T152-70 (ASTM Designation: C231-68). Batches not meeting the requirements for air content or consistency were rejected with the exception that water was occasionally added to low-slump batches and mix proportions were recalculated accordingly.

4.2.2 Compressive Strength Test Specimens

Compressive strength test specimens were cast in 6 in. (15.2 cm) diameter by 12 in. (30.5 cm) high cylindrical metal molds. Sampling and casting of specimens were accomplished in accordance with the procedures of AASHO Designation: T126-70. Consolidation was accomplished by rodding. Cylinders were stored in the moist room prior to stripping and moist curing. After stripping, cylinders were stored in a moist room in accordance with the recommendations for Moist Cabinets and Rooms Used in the Testing of Hydraulic Cements and Concrete, AASHO Designation: M201-70 (ASTM Designation: C511-68). Three test cylinders were cast for each planned test age.

4.2.3 Flexural Strength Test Specimens

Specimens for determination of flexural strength were cast in 6 x 6 x 20½ in. (15.2 x 15.2 x 52.1 cm) metal molds in accordance with the requirements of AASHO Designation: T126-70. Consolidation was accomplished by rodding. Three beams were cast for each test age. Prior to stripping, beams were stored in the moist room. Curing was accomplished in a moist room in accordance with the provisions of AASHO Designation: M201-70 (ASTM Designation: C511-68).

4.2.4 Freeze-Thaw Specimens

Specimens for durability tests in the freeze-thaw apparatus were cast in 3 x 3 x 15 in. (7.6 x 7.6 x 38.1 cm) metal molds. Specimens were cast in companion groups of three and cured in accordance with the provisions of ASTM Designation: C666-73, Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing. Concrete was batched separately from that used for strength determination specimens.

4.2.5 Sulfate Soundness Test Specimens

The specimens for determination of resistance to sulfate attack were cast in metal 1 in. (2.54 cm) cube and 1 x 1 x 11 in. (2.54 x 2.54 x 27.9 cm) bar molds. The batching, specimen molding and curing were in accordance with a non-standardized procedure which is outlined in detail in the section on durability testing (Chapter 6).

4.3 Curing and Testing

4.3.1 Curing

Cylinders and beams for compressive and flexural strength testing were cured until test age in a standard moist room as mentioned previously. Temperature and humidity in the moist room were automatically controlled and recorded.

4.3.2 Strength Testing

Compressive strength testing was performed in accordance with the requirements of AASHO Designation: T22-66 (ASTM Designation: C39-66). Third point loading was used for the determination of flexural strengths, in accordance with AASHO Designation: T97-64 (ASTM Designation: C78-64).

CHAPTER 5. COMPRESSIVE AND FLEXURAL STRENGTH

5.1 Compressive Strength

5.1.1 Test Results

Compressive strength test data are tabulated in Appendix B. Each reported value represents an average of three test results. Batch weight, air content, slump, unit weight and temperature are included with the strength data for convenience of reference.

Figures 5-1a, b and c present age-strength curves representing all compressive strength data tabulated in Appendix B. The curves are organized in accordance with test series designations. Detailed batch information on each series is presented in Appendix B and an explanation of the series designation meanings in Chapter 4. It should be noted here that many factors which are constant in the mix designs of this study, are variables in the general case. Such factors include consistency, air content, coarse aggregate content, aggregate quality, portland cement quality and conditions of curing.

Each set of curves in Figures 5-1a, b and c represents concrete mixes with the same proportions of portland cement and fly ash. The mix designs produced a general range of 28 day compressive strengths varying from 2200 to 4720 psi (155 to 332 Kg/cm^2).
The primary differences in the curves reflect strength variations caused by differences in fly ash characteristics from the various sources. Some trends are apparent. The Navajo fly ash concretes consistently exhibit the highest strengths, and Cholla the lowest, at early ages (up to 28 days). At later ages (60 and 90 days) this trend is not

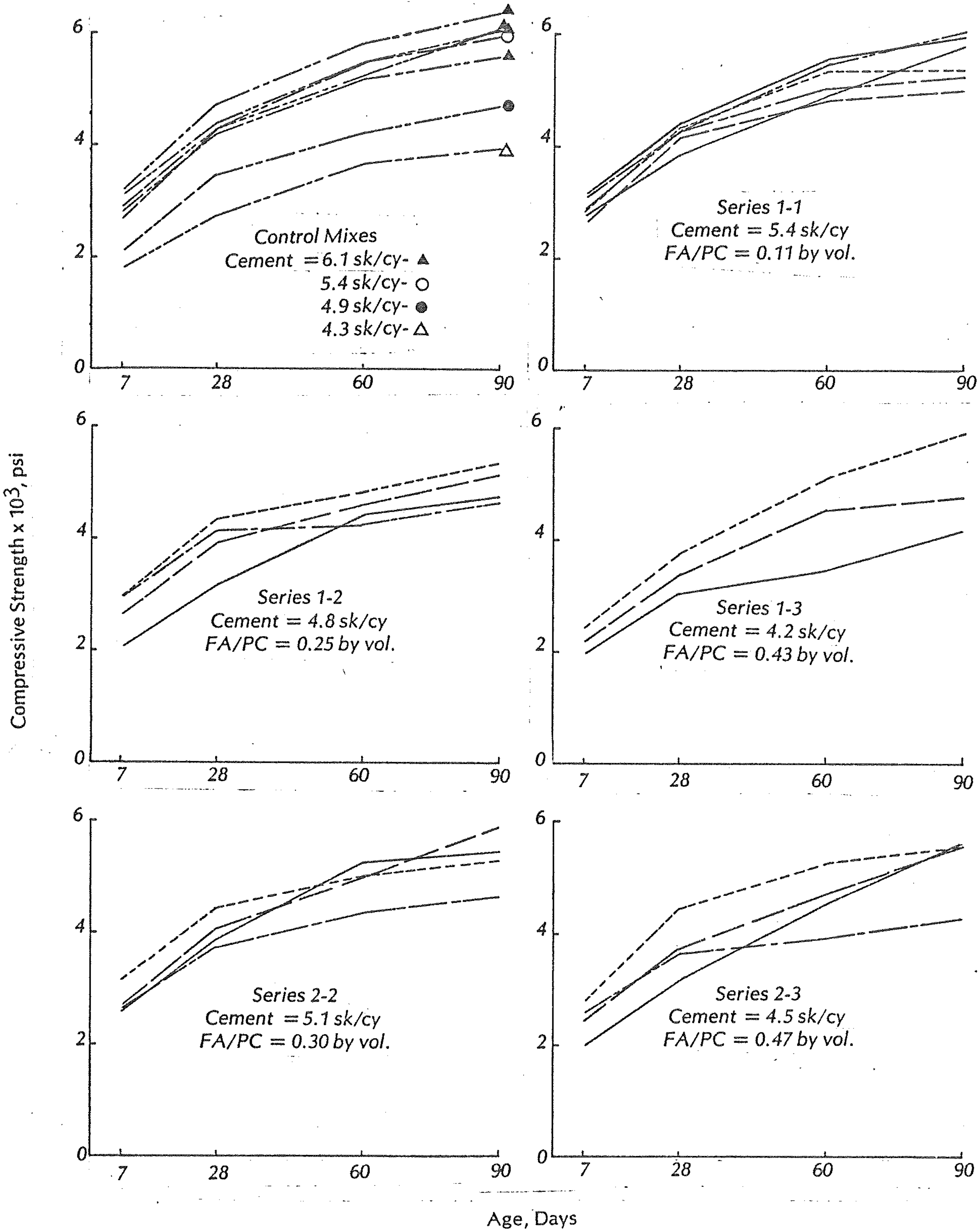


FIGURE 5-1A. COMPRESSIVE STRENGTH VS. AGE

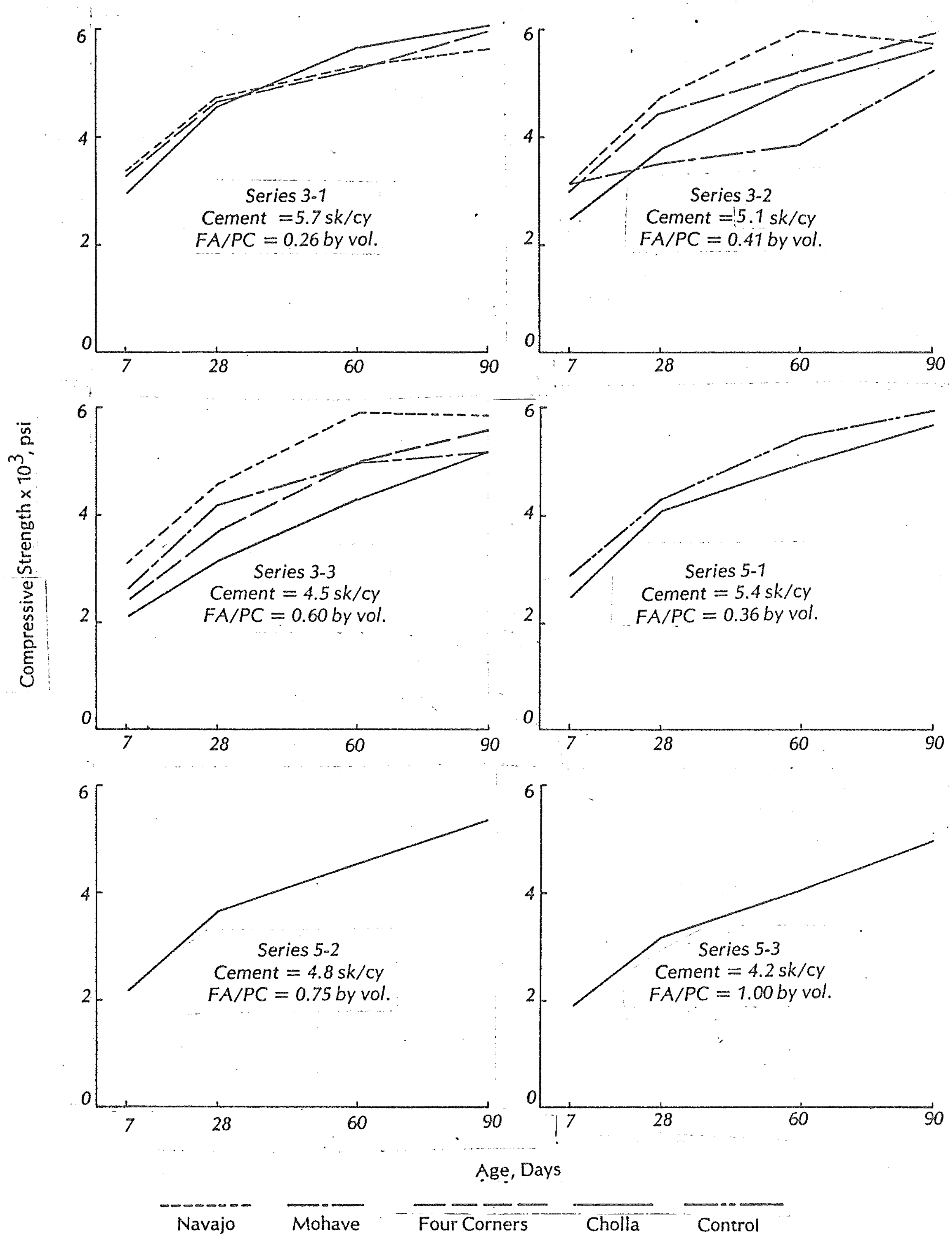


FIGURE 5-1B. COMPRESSIVE STRENGTH VS. AGE

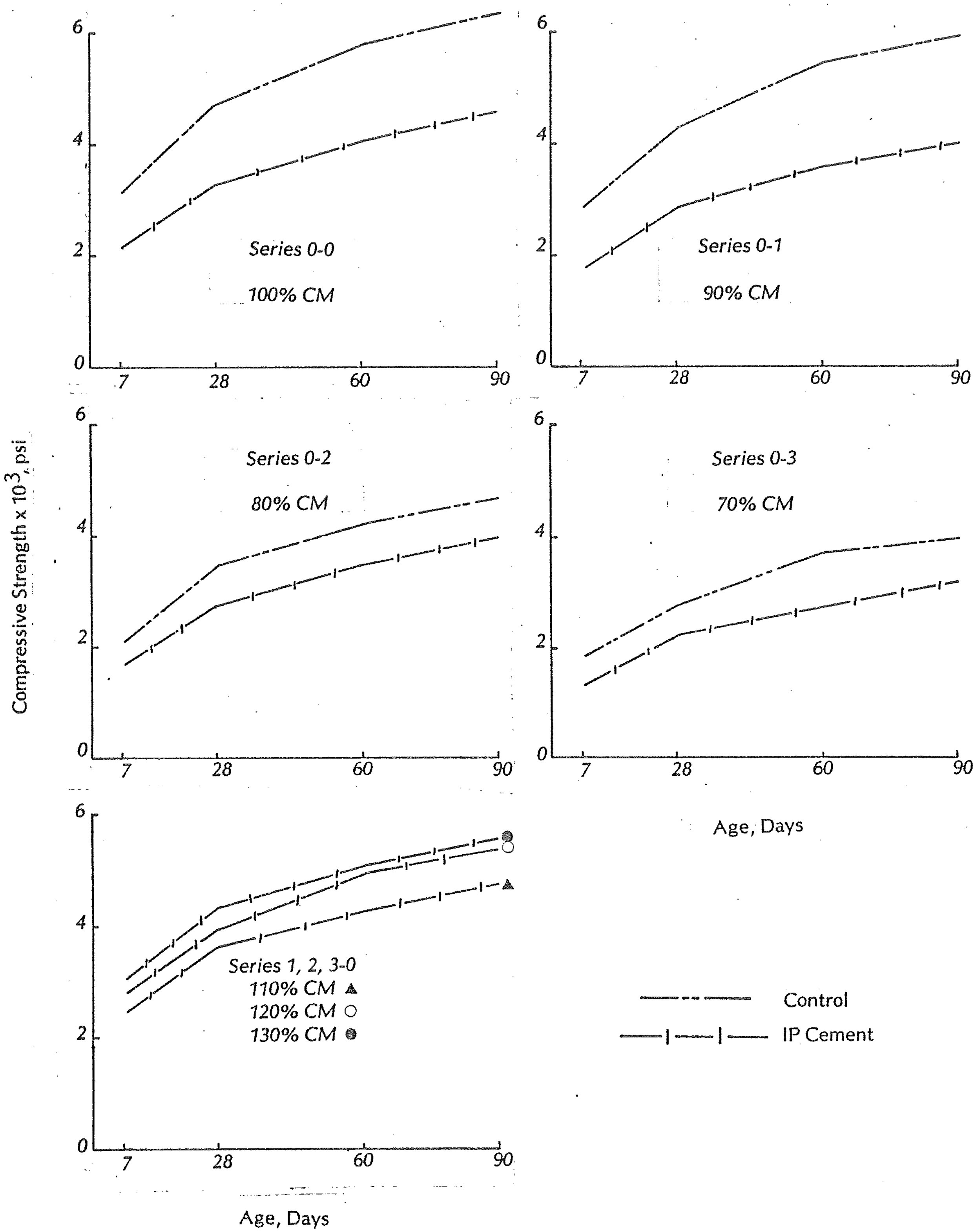


FIGURE 5-1C. COMPRESSIVE STRENGTH VS. AGE dominant. The Cholla fly ash concrete generally shows a strong late-age gain relative to the three other sources.

Strength gain with time is discussed further in the following paragraphs. The statistically derived comparisons and evaluations are essentially correlations and are not necessarily intended to represent cause-effect relationships. This fact should not handicap the usefulness of the analysis.

5.1.2 General Age-Strength Relationship

The projection of early age compressive strengths to later age predictions is a continuing problem in concrete quality control. The pace of construction is frequently such that 28 day, or later, compressive strength test results are often of little practical value for quality control during construction, or even for the development of mix designs. Specifications, nevertheless, are generally developed around 28 day compressive strengths, and acceptance based on these relatively late age test results. To avoid serious problems with regard to acceptance of in-place non-specification concrete, as well as potential safety hazards posed by low strength concrete supporting subsequent superstructure, strength projections must be based on early age test results, general knowledge of the uniformity of the concrete batching and handling procedures, and intuition. The problem is well known, widely recognized and has been discussed thoroughly in many volumes of published literature.

The compressive strength data developed during the course of this study were analyzed to determine if the strength gain with age of fly ash concretes could be reliably predicted. Data available included 7, 28, 60 and 90 day compressive strengths for all mix designs studied. Three expressions for the prediction of compressive strength were examined. The consideration of these mathematical models is, in itself, an exercise which gives considerable insight into strength gain.

The first expression was of the general form

$Y = AX^B$, in which:

- Y = Compressive strength at desired age, psi
- X = Age at which compressive strength is desired, days
- A = Constant coefficient
- B = Constant exponent

This expression was examined since concrete strength gain with time appears generally to develop in accordance with a relationship of this type.

The second expression analyzed was of the general form

$Y = X + AX^B$, in which:

- Y = Compressive strength at age 28 days, psi
- A = Constant coefficient applicable to 28 day prediction only
- X = 7 day compressive strength, psi
- B = Constant exponent applicable only to 28 day prediction

This expression differs from the first in that the independent variable is a strength value rather than an age; further the dependent variable is not an explicit function of time.

The third expression studied was of the general form

$$Y = A + BX_1 + CX_2, \text{ in which:}$$

Y = Compressive strength, psi
A, B, C = Constants
X_1 = Portland cement content, lb./cy
X_2 = Age, days

The last expression has been included here since it has been noted in the reference literature.

There are numerous relationships which can be examined in any attempt to develop a mathematical model to explain concrete strength gain. Various logical transformations of the selected independent variables add further to the variety of possibilities. The development of the "best" such model was not a purpose of this study. The models included in this study were selected on the basis of common usage or presentation in the existing literature. The purpose herein is to provide a basis of judgment for the predictability of fly ash concrete compressive strength.

5.1.2.1 Age Regression Model

The expression $Y + AX^B$ was analyzed by fitting all test data (7, 28, 60 and 90 day compressive strengths) utilizing a least squares analysis to obtain "best fit". The constants "A" and "B" were determined for each test series as were the coefficients of determination for the data-fit. The coefficients of determination were found to be above 0.950 for about 92% of the 48 test series data points and above 0.980 for about 77% of the data points. The relatively high values of the coefficients of determination indicated that the strength gain with age could be well represented by a general geometric regression. Most of the data which exhibited lower correlation occurred in the Mohave fly ash mix design series. The general shapes of age-strength curves for the Mohave series (Figures 5-1a, b and c) illustrate the slightly erratic results.

The constants "A" and "B" in the general regression equation naturally varied widely for the different mix design series. To determine whether or not a reliable strength prediction could be developed, further regression analyses on the constants "A" and "B" were performed, utilizing geometric, linear and exponential regression functions. The 7 day compressive strengths were used as the bases for these analyses. In the case of each regression, three relationships were examined; 7 day compressive strength vs "A"; 7 day compressive strength vs "B"; and "A" vs "B". A minimum of 90% of the variation in "A" was found to be explainable by either of the three regressions. The geometric function yielded the best correlation for "A". The best predictions of "B" were developed from the linear regression expression, utilizing "A" as the dependent variable, rather than 7 day strength. Results indicated that 74% to 96% of the variation in "B" could be explained by the model; correlation was slightly less positive than for the constant "A".

The expression for the prediction of later age compressive strengths based on 7 day test results would be:

$$\sigma_X = AX^B$$

in which

σ_X = Compressive strength at desired age, psi

X = Age at which compressive strength prediction is desired, days

and the "best fit" values of "A" and "B" were found to be:

Fly ash mixes $A = 5.471 \times 10^{-3} \sigma_7^{1.595}$

$B = 4.875 \times 10^{-1} - 1.313 \times 10^{-4} A$

Control mixes $A = 1.651 \times 10^{-1} \sigma_7^{1.157}$

$B = 3.889 \times 10^{-1} - 6.180 \times 10^{-5} A$

Type IP mixes $A = 8.510 \times 10^{-2} \sigma_7^{1.248}$

$B = 4.096 \times 10^{-1} - 9.056 \times 10^{-5} A$

where σ_7 = compressive strength at age seven days, psi.

Compressive strengths were predicted for 28, 60 and 90 day ages using the power curve and constants derived above. Actual vs predicted values of 28 day compressive strength are presented in the scatter diagram Figure 5-2. The data indicate reasonably good correlation, with nearly all data falling within the $\pm$ 10% range. The points falling marginally within the $\pm$ 10% range are predominantly from the Mohave fly ash series.

It should be noted here that the resultant relationships are not presented as the best possible representation of the strength-time relationship nor are the relationships necessarily universal. The purpose here is to present a reasonably reliable model for compressive strength prediction which can be used to evaluate two questions:

1) Is the compressive strength of fly ash concrete predictable?

and 2) How do the strength-time characteristics of fly ash and normal concretes compare?

The data indicate the answer to the first question appears to be in the affirmative. The fly ash test mix designs appear to be predictable within the range of accuracy expected of normal portland cement concrete. Examining Figure 5-2 it appears that the Control and Type IP mixes fit more closely to the 45^{o} "perfect prediction" line than

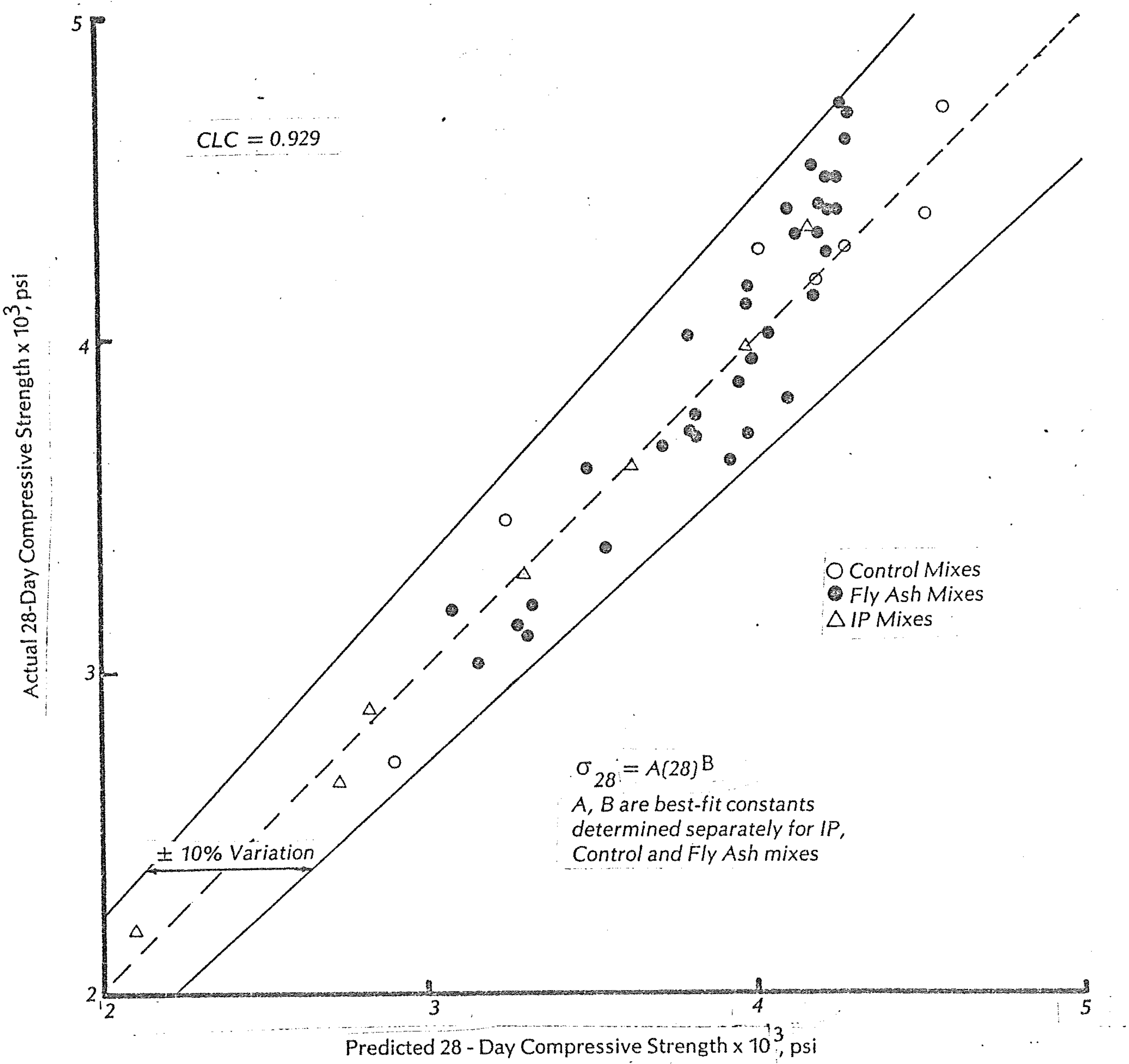


FIGURE 5-2. ACTUAL VS. PREDICTED 28-DAY COMPRESSIVE STRENGTHS

do the fly ash mixes. It should be remembered, however, that the constants in the regression equation were developed separately for Control, Type IP and Fly Ash mixes. Separate determination of constants for each fly ash source would probably improve correlation for the fly ash mixes. However, the data as presented serve to demonstrate the general answer to the questions of compressive strength predictability.

The resultant relationships, presented in Figure 5-3, illustrate the apparent general strength gain behavior exhibited by the test mixes, and analysis thereof can provide insight regarding the second question. The data developed indicate that at relatively low compressive strengths the fly ash concretes realize a greater strength gain than do normal concretes when compared with equal 7 day strengths. Conversely, the data indicate that for a given late-age strength (28 to 90 days) the normal concrete must have a higher seven day strength. This is consistent with much of the current general knowledge available regarding fly ash concrete strength gain. Higher strength mix designs lead to a reversal in this trend as indicated by the set of curves originating at a seven day strength of 3000 psi (211 Kg/cm^2). Again, general experience in the field of fly ash mix designs seems to indicate the fly ash concretes are less efficient in the higher strength ranges. It should not be implied that the strength gain beyond 90

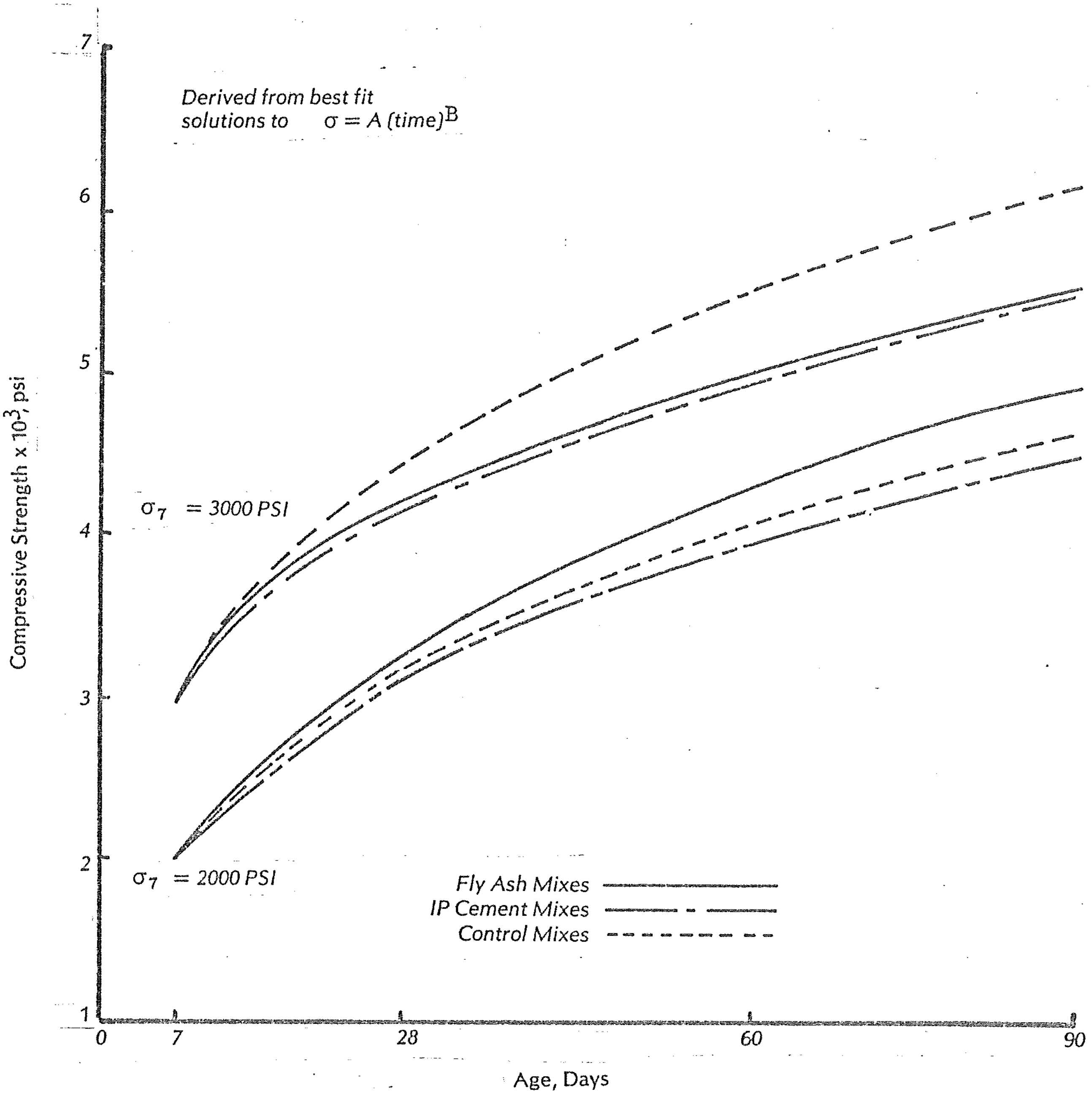


FIGURE 5-3. RELATIVE STRENGTH GAIN

days would continue at the rates indicated by the curves. The curves represent only the best fit to the available data from 7 to 90 days and may not be extended without new evaluations of the curve constants utilizing data points in the later (beyond 90 days) ages.

The curves of Figure 5-3 represent the best fit of the data developed from the tested mix designs; conclusions based on the curves should be developed only with full knowledge of the particular mix designs included in the study.

5.1.2.2 7 Day vs 28 Day Compressive Strength Model

The relationship:

$$\sigma_{28} = \sigma_7 + 30\sqrt{\sigma_7}$$, in which σ_7 and σ_{28}

are 7 and 28 day compressive strengths, is frequently employed (at least in the geographic area common to this study) as a means of estimating 28 day compressive strength from the 7 day test result. This appears to have been derived from a transformed polynomial regression using 7 day strength as the independent variable. The expression was evaluated in its usual form; the results of the evaluation can best be summarized by reference to the upper scatter diagram of Figure 5-4. The control (normal concrete), IP cement and fly ash mixes are presented identifiably for comparison. The relative linearity of the predicted vs actual compressive strengths is indicated by the

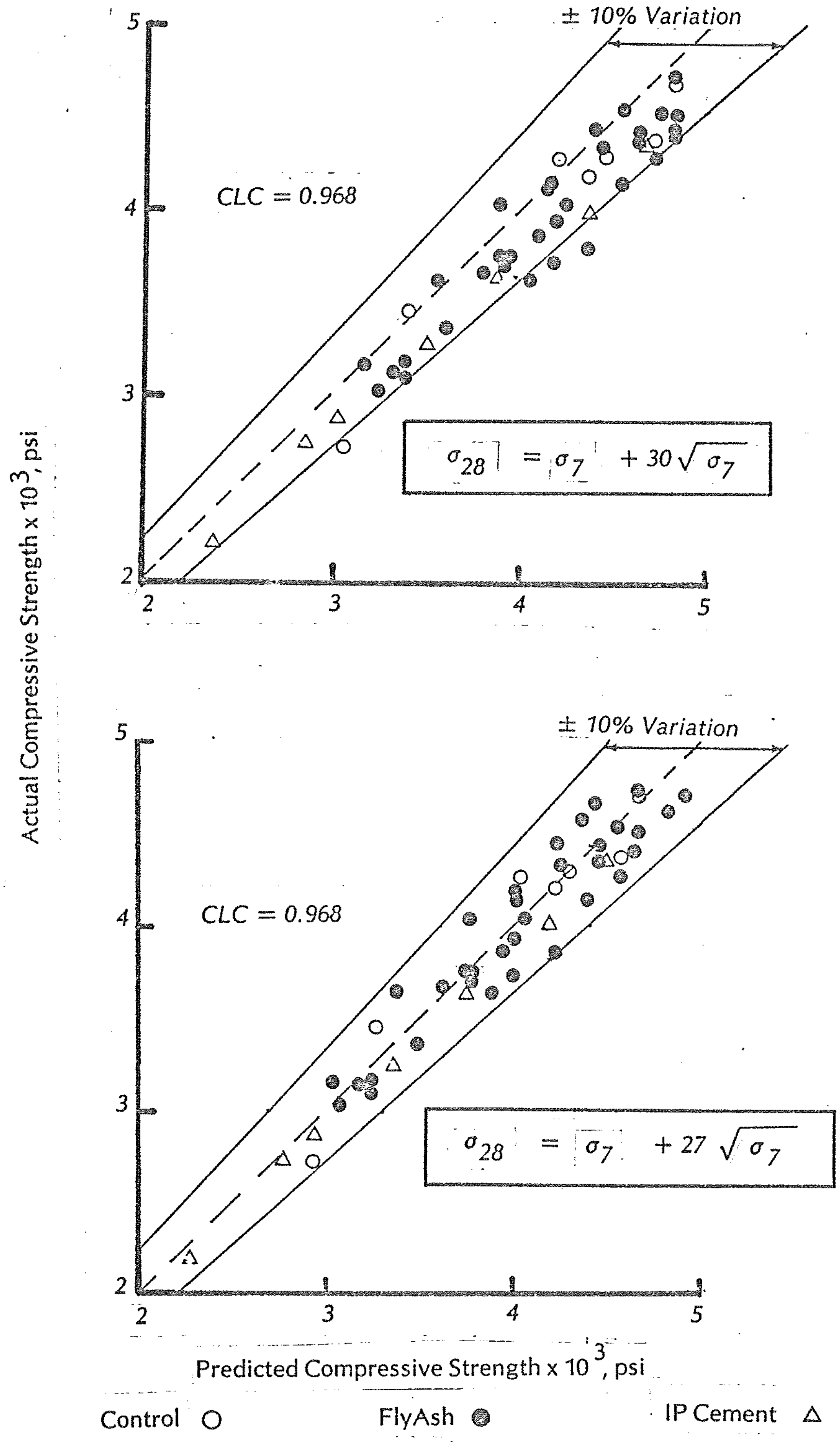


FIGURE 5-4. ACTUAL VS. PREDICTED COMPRESSIVE STRENGTH

coefficient of linear correlation given on the figure. The coefficient of linear correlation for the scatter diagram can in this case be interpreted as the coefficient of correlation for the original data points to the model equation. The coefficient of determination therefore, indicating the percentage of variation accounted for by the model equation, can be taken, for practical purposes, as the square of the coefficient of linear correlation. Thus the model equation appears to account for about 94% of the variation in 28 day compressive strength.

The upper portion of Figure 5-4 includes all data developed in the course of this study; and the coefficient of linear correlation (CLC) includes all data with no distinction for mix type. Actual strength appears to consistently fall short of the predicted value; therefore, a logically indicated but arbitrary change of constant from 30 to 27 was similarly evaluated with better results. The lower scatter diagram of Figure 5-4 illustrates the latter evaluation. The relationship appears to be reasonably valid for projection of 28 day compressive strengths within a range of error of $\pm$ 10%.

The likely rationale behind the development of the equation can readily be seen by reference to Figure 5-5. The corresponding 7 and 28 day compressive strengths are plotted on the scatter disgram for all mix designs studied. The distribution of data points

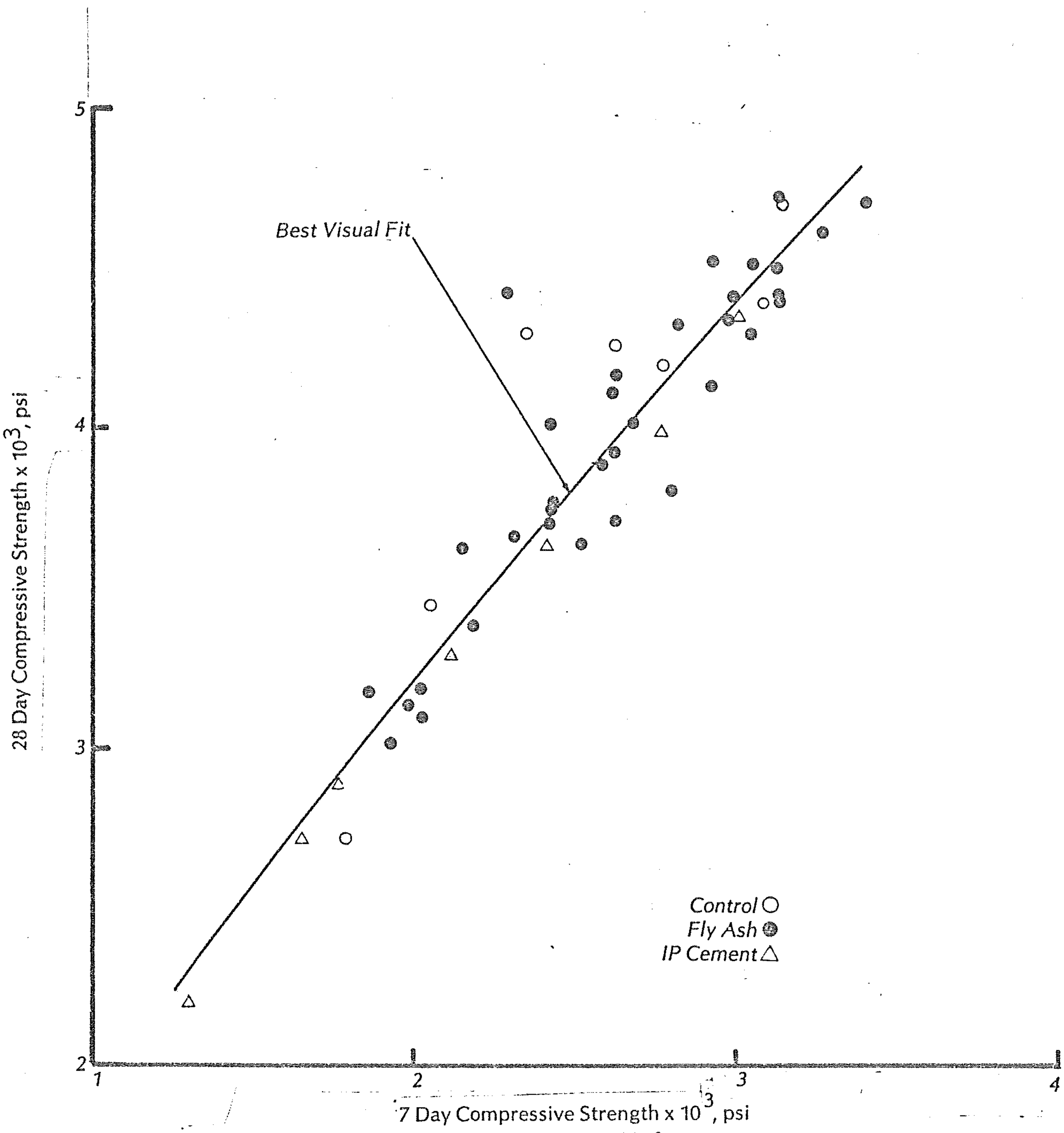


FIGURE 5-5. 7 DAY VS. 28 DAY COMPRESSIVE STRENGTH

suggests that the relationship might be approximated by a best fit polynomial. The least squares best fit solution to the general polynomial equation ($Y = A + BX + CX^2$, transformed by $X_1 = X^2$) yielded the solution:

$$\sigma_{28} = -16,670 - 5.9\ \sigma_7 + 711\sqrt{\sigma_7}$$

based on control mix data only. Small changes in data distribution result in large changes in individual coefficients. This best fit solution increased the reliability of prediction to a slight degree. The best fit solution to the general polynomial appeared to account for about 97% of the variation in 28 day compressive strength. The slight increase in reliability gained by this refinement is not of practical value considering the increased complexity of the expression.

Solutions could be examined for the polynomial relationship in various degrees, and with various logical transformations of the independent variable, to find the best representation of the data. Comparisons between fly ash and normal concrete behavior could also be developed at all ages. This approach would be one of the nearly limitless avenues of investigation, mentioned earlier, that could result from the data developed in this report. The purpose of this brief section, however, was merely to examine the 7 to 28 day strength gain of fly ash concrete relative to the frequently used predicter equation.

5.1.2.3 Cement Content and Age Regression Model

One additional method of predicting compressive strength was evaluated. The equation

$$\sigma = (9\ PC - 2200) + 2350 \log T_C$$

in which

σ = compressive strength of fly ash concrete at desired age in psi

PC = portland cement in lb./cy

T_C = age in days at which strength prediction is desired

appears in the literature (Ref. 39).

Compressive strengths predicted on the basis of this relationship were in all cases higher than the actual test value as indicated in the upper half of Figure 5-6. The expression as presented in the literature, was based on fly ash mixes with a uniform 150 pounds of fly ash per cubic yard (89.0 kg/m^3); mix designs in the present study contained from 34 to 261 pounds of fly ash per cubic yard (20.2 to 154.9 kg/m^3). It would be expected that predicted strengths for the mixes near the control value of 150 lb./cy (89.0 kg/m^3) would correlate with actual strengths. The plotted data points represent fly ash mixes with 135 to 165 pounds of fly ash per cubic yard (80.1 to 97.9 kg/m^3). Nearly all data, however, is outside (below) the 10% error

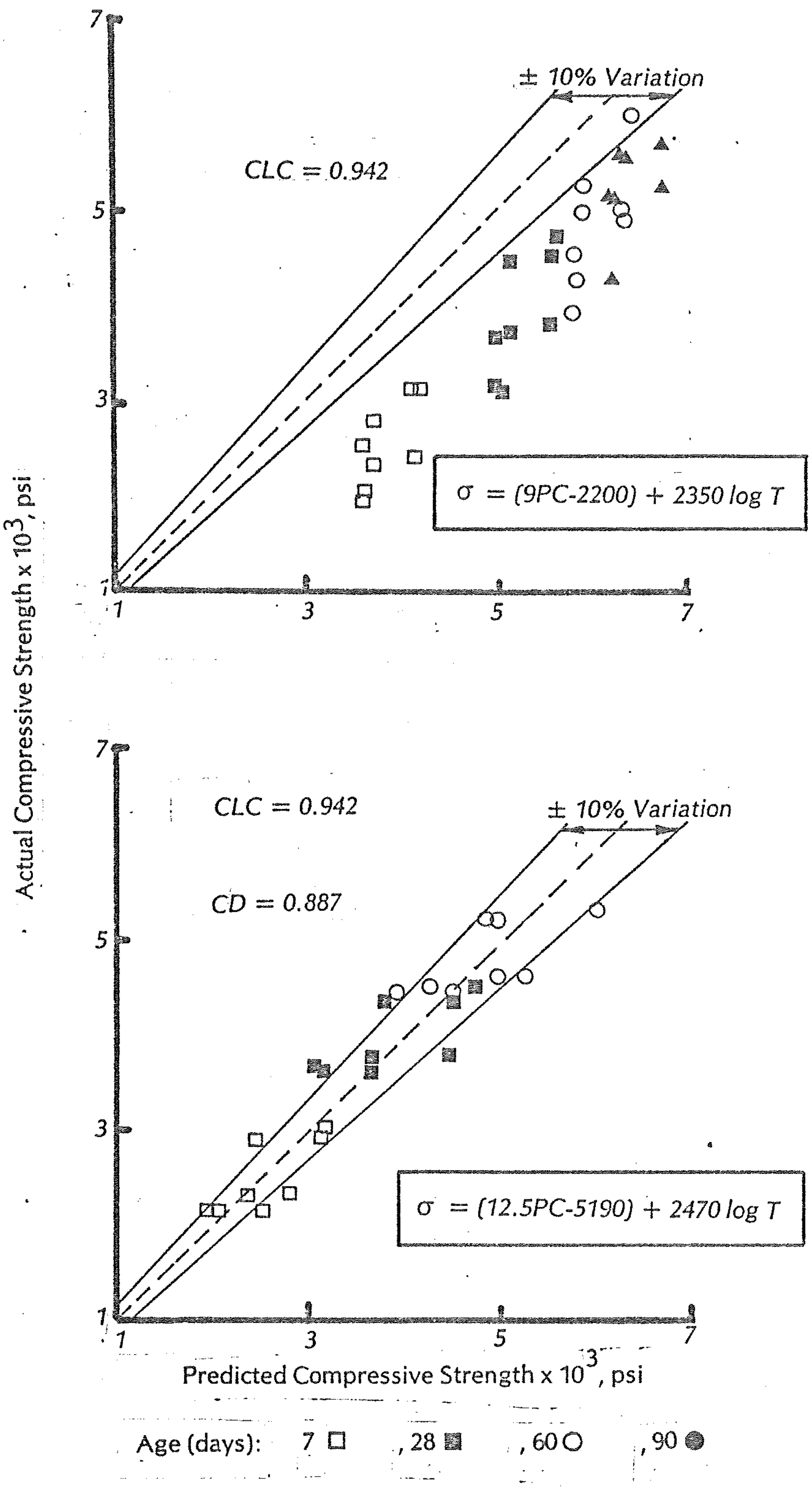


FIGURE 5-6. ACTUAL VS. PREDICTED COMPRESSIVE STRENGTH

curves, indicating strongly that the relationship, if true in general form, is not true in specific form for the fly ash mixes developed in this study.

In order to evaluate the applicability of this general form of multiple linear regression (with two independent variables, cement content and age) the general equation was solved, utilizing the least squares method to obtain best fit. All fly ash concrete data available from this study was included. The best fit relationship was found to be:

$$\sigma = (12.5\ PC - 5190) + 2470 \log T_C$$

with the terms defined as previously. The coefficient of determination was computed, indicating that approximately 89% of the variation in compressive strength is explained by the resultant expression. The relatively high degree of correlation might imply that variables other than age and portland cement content are unimportant to the prediction. Certainly this is not a valid conclusion; the remaining variables are included in the values of the best fit constants. Any such expression therefore can only be utilized with a full knowledge of those variables which are missing specifically from the expression but are included in the constants of the solution. Analysis of relationships such as discussed here may have their principal value in simply establishing that the dependent variable is reasonably predictable.

5.2 Flexural Strength

5.2.1 Test Results

Flexural strength test results are tabulated in Appendix B, along with compressive strength and mix design data. Each reported value represents an average of three test results.

All flexural strength test data are presented for comparison on the age-strength curves of Figures 5-7a, and 5-7b. The mix designs tested produced 28 day flexural strengths in the approximate range of 450 to 720 psi (31.6 to 50.6 Kg/cm^2).

The flexural strength-age relationships appeared generally to be normal and predictable. The flexural strength curves, however, indicate a drop in strength from 60 to 90 days for a few test series which, when first encountered, is disturbing. The slope of the strength gain curve is relatively flat in the region beyond 28 days and particularly beyond 60 days. Normal variations in test data tend to be exaggerated when they occur within the flatter regions of strength gain. A 50 psi (3.5 Kg/cm^2) variation (or "error") in the test result tends only to increase or decrease the slope of the aging curve in the 0 to 28 day region. A similar variation in the 60 to 90 day range may not only change the slope of the aging curve, but can change the sign of the slope, thus indicating a loss of strength with age. The strength may in reality have remained constant; the apparent anomoly in the slope of the aging curve reflects only the inability to measure precisely the magnitude of the variable (strength). Variations from the "true" value would be expected to be compensating in some cases and additive in others. The uniformity of test data will be discussed in another

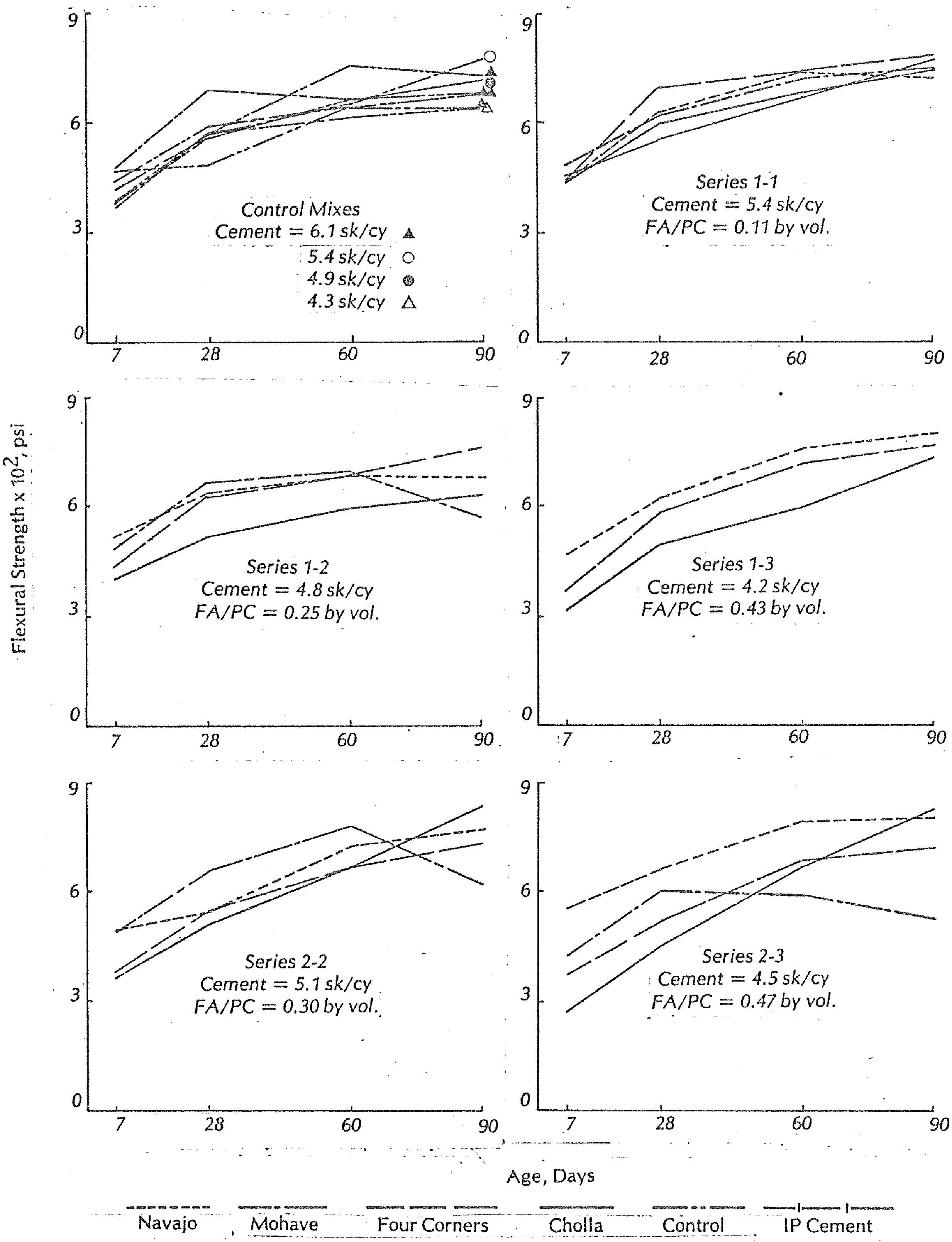


FIGURE 5-7A. FLEXURAL STRENGTH VS. AGE

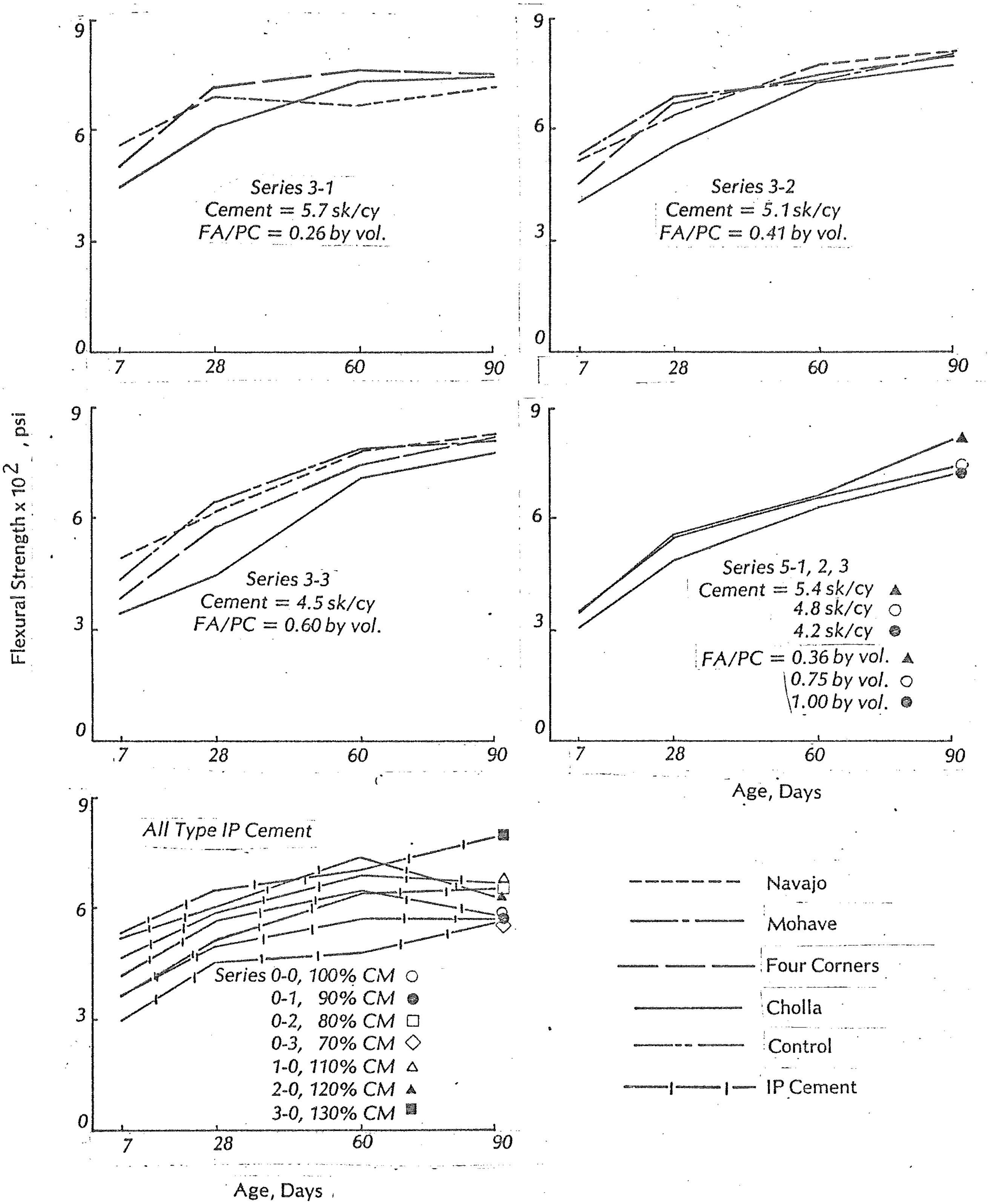
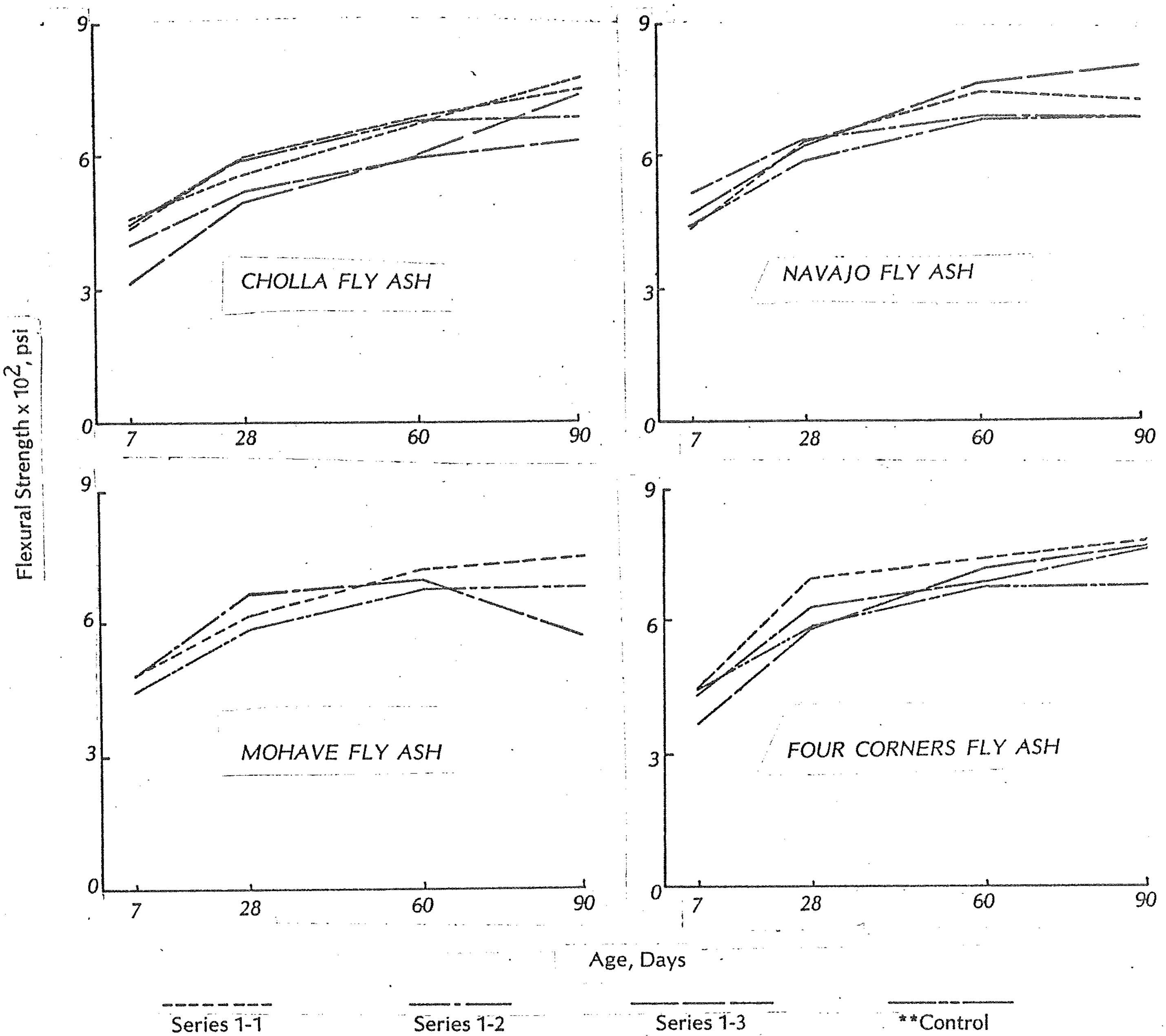


FIGURE 5-7B. FLEXURAL STRENGTH VS. AGE

section; however, it can be stated here that the flexural strength may not be repeatable to the degree of accuracy necessary to precisely establish the slope of the aging curve (beyond 28 days) unless large numbers of data points are used. The preceding is intended only to qualify the significance of the shape of the aging curves in the flatter portions. There are some apparent anomalies in the flexural strength-age curves which appear to be beyond the range of expected error. The Mohave fly ash series 1-2, 2-2 and 2-3 demonstrate a marked loss of strength from 60 to 90 days. Review of the batch data provides no apparent explanation. Compressive strengths from molded cylinders and cores do not confirm the apparent deterioration of the 90 day specimens. The conclusion appears to be that some sort of laboratory error occurred in the molding or handling of these particular flexural beams (batching error is ruled out since other cylinders and beams were molded from the same batch).

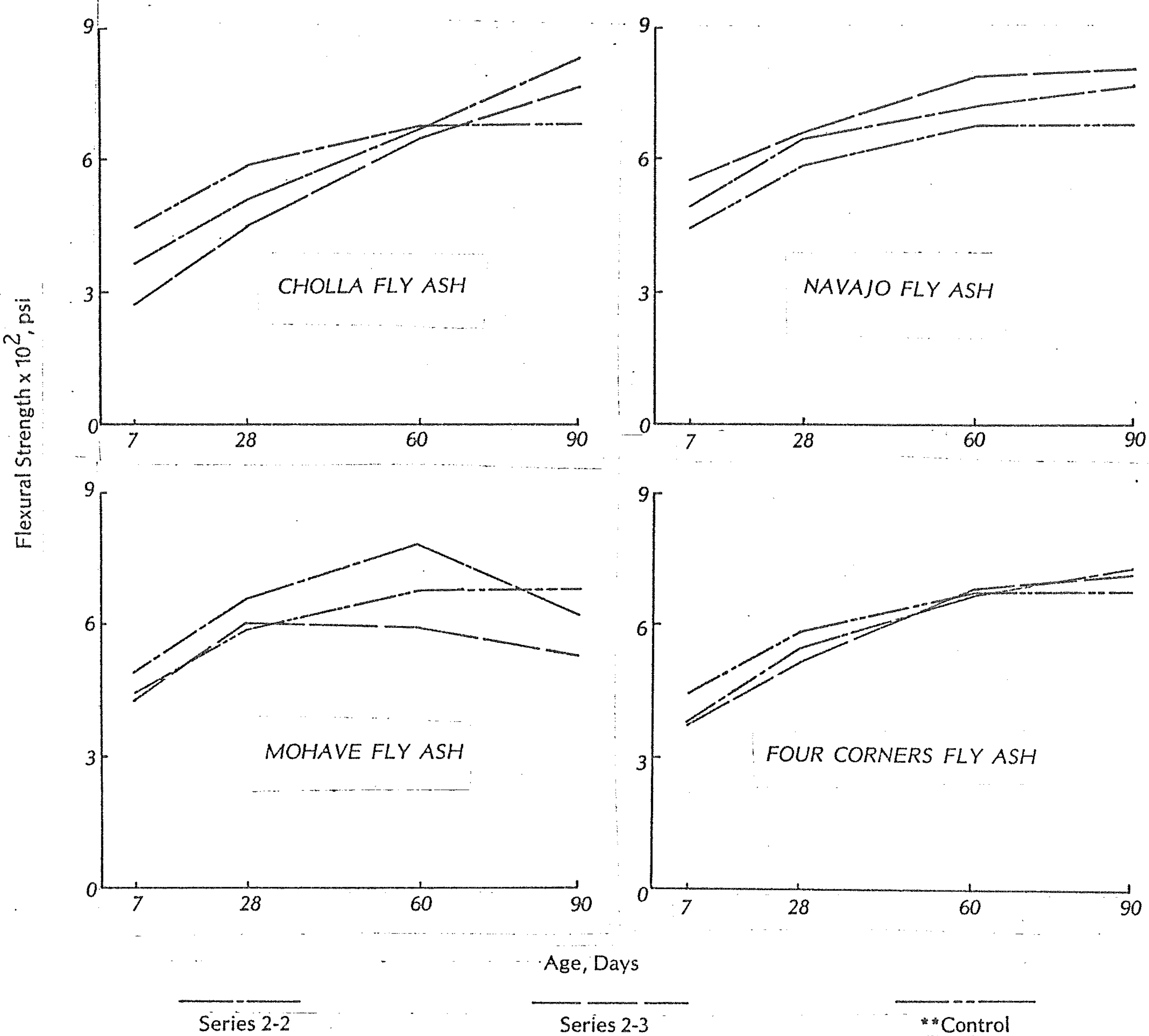
Comparisons of the flexural strength characteristics of the fly ash and control concrete mixes are illustrated in Figures 5-8, 5-9, 5-10 and 5-11. Each Figure represents a series of mixes with a common volume of cementitious material (portland cement plus fly ash). The control mix is a 6.1 sack (338 Kg/m^3) normal concrete. It should be recalled in considering the Figures that all of the concrete mixes were batched to maintain a common workability (slump). The exact constituents of each mix vary as explained elsewhere in this report and as tabulated in Appendix B. The control mix curve represents an average of the four similar control mixes. It appears from the curves that a particularly strong



Mix Series	PC* lb./cy	FA* lb./cy	FA/CM % Vol.	Vol. CM ft^3 /cy
**Control	571	0	0	2.90
1-1	515	39	10	2.90
1-2	457	78	20	2.90
1-3	402	112	30	2.90

*Average Values. See Appendix B for exact batch weights.
**Control mix averages A, B, C and 0-0.

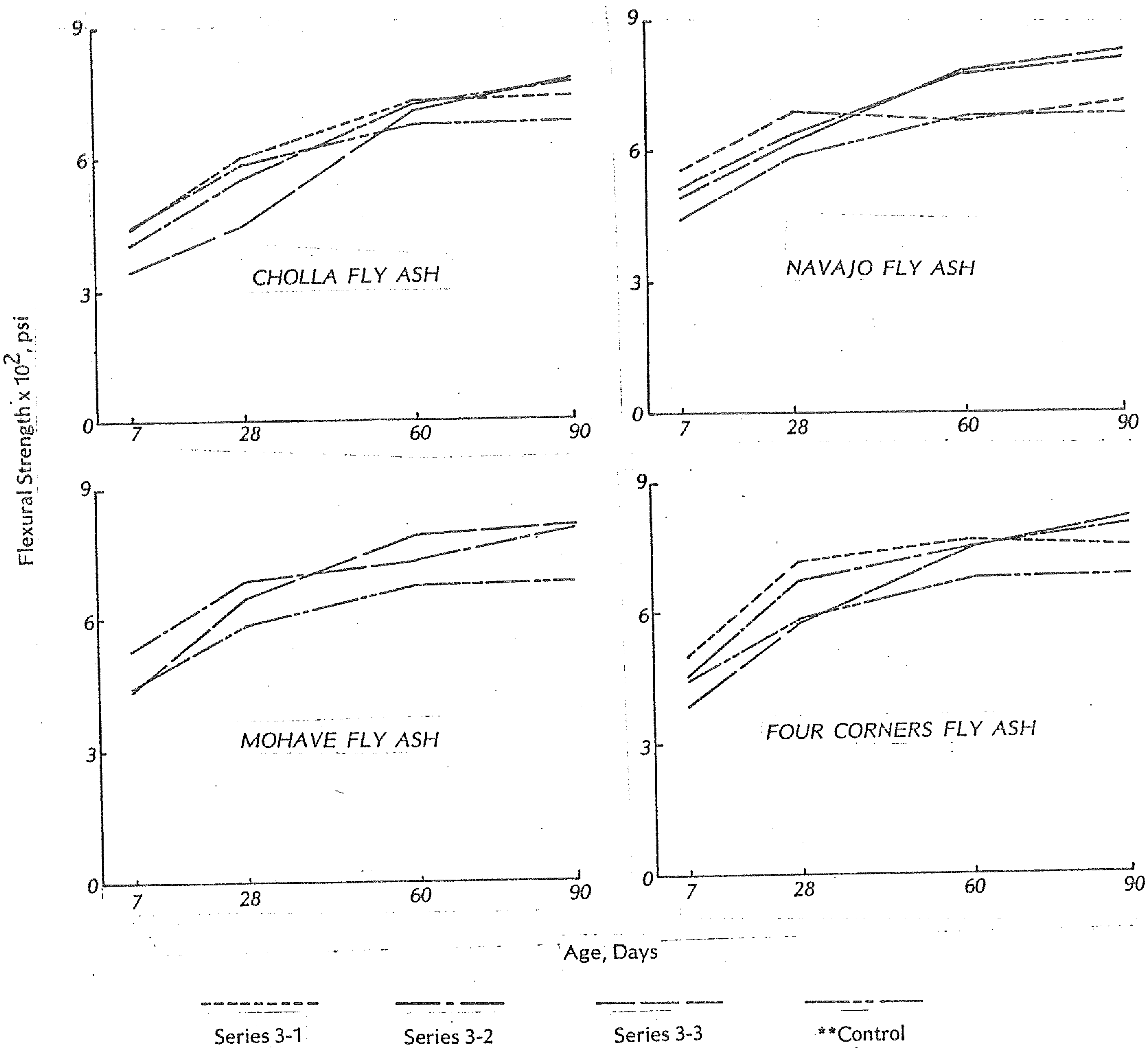
FIGURE 5-8. COMPARATIVE FLEXURAL STRENGTH, 100% CM SERIES



Mix Series	PC* lb./cy	FA* lb./cy	FA/CM % Vol.	Vol. CM ft^3/cy
**Control	571	0	0	2.90
2-2	486	98	23	3.19
2-3	428	136	32	3.19

*Average Values. See Appendix B for exact batch weights.
**Control mix averages A, B, C and 0-0.

FIGURE 5-9. COMPARATIVE FLEXURAL STRENGTH, 110%, CM SERIES

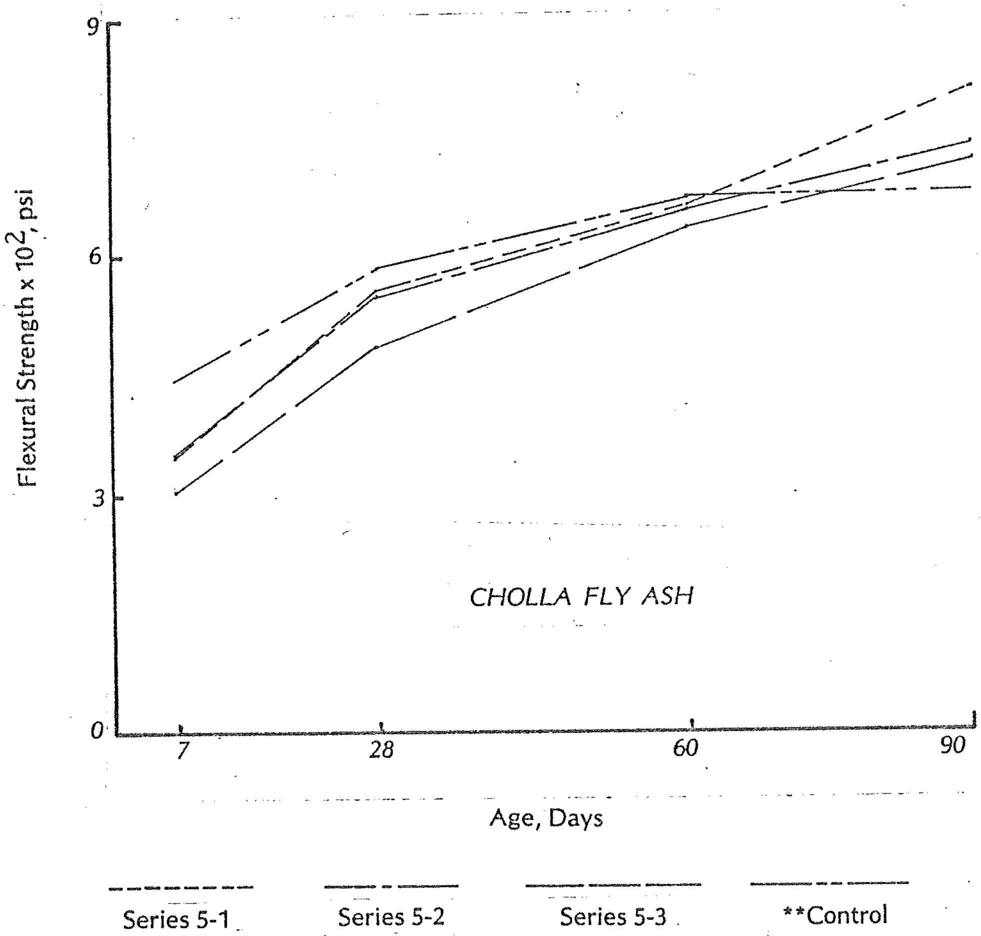


Mix Series	PC* lb./cy	FA* lb./cu	FA/CM % Vol.	Vol CM ft^3 /cy
**Control	571	0	0	2.90
3-1	541	93	21	3.48
3-2	485	136	29	3.48
3-3	429	175	38	3.48

* Average Values. See Appendix B for exact batch weights.

** Control mix averages A, B, C and 0-0.

FIGURE 5-10. COMPARATIVE FLEXURAL STRENGTHS, 120% CM SERIES



Mix Series	PC* lb./cy	FA* lb./cy	FA/CM % Vol.	Vol. CM ft^3 /cy
**Control	571	0	0	2.90
5-1	509	197	36	4.06
5-2	452	224	43	4.06
5-3	396	261	50	4.06

*Average Values. See Appendix B for exact batch weights.

**Control mix averages A, B, C and 0-0.

FIGURE 5-11. COMPARATIVE FLEXURAL STRENGTH, 140% CM SERIES case could be made for the use of fly ash when the design criterion is flexural strength. The data imply that the fly ash mixes present an advantage even on a straight volume replacement basis. This contrasts somewhat with the situation for compressive strength for which an increased volume of cementitious material (portland cement plus fly ash) is required to maintain any given strength level. The data of Figures 5-8, 5-9, 5-10 and 5-11 also indicate that the advantage of the fly ash concretes becomes more significant at later ages. This suggests that increased economic advantage may be possible if design requirements can be based on strengths attained at ages beyond the usual 28 days.

5.2.2 Age-Strength Predictions

Concrete mix-design methods are generally developed on the basis of compressive strength as the target criterion. Certain uses, however, require flexural strength as the more rational basis for performance evaluation. It is frequently necessary, therefore, to estimate the relationship between flexural and compressive strengths in order to develop a suitable mix to meet a flexural strength criterion. To this end several simplified approaches were examined in this study. In addition, the general shape of the strength-age curve was examined to some extent. The data developed appear to indicate that flexural strength is somewhat more erratic and less predictable than compressive strength (the term "flexural strength" here includes the methods of measurement as well as the strength).

The scatter diagram of Figure 5-12 illustrates the relationship between flexural and compressive

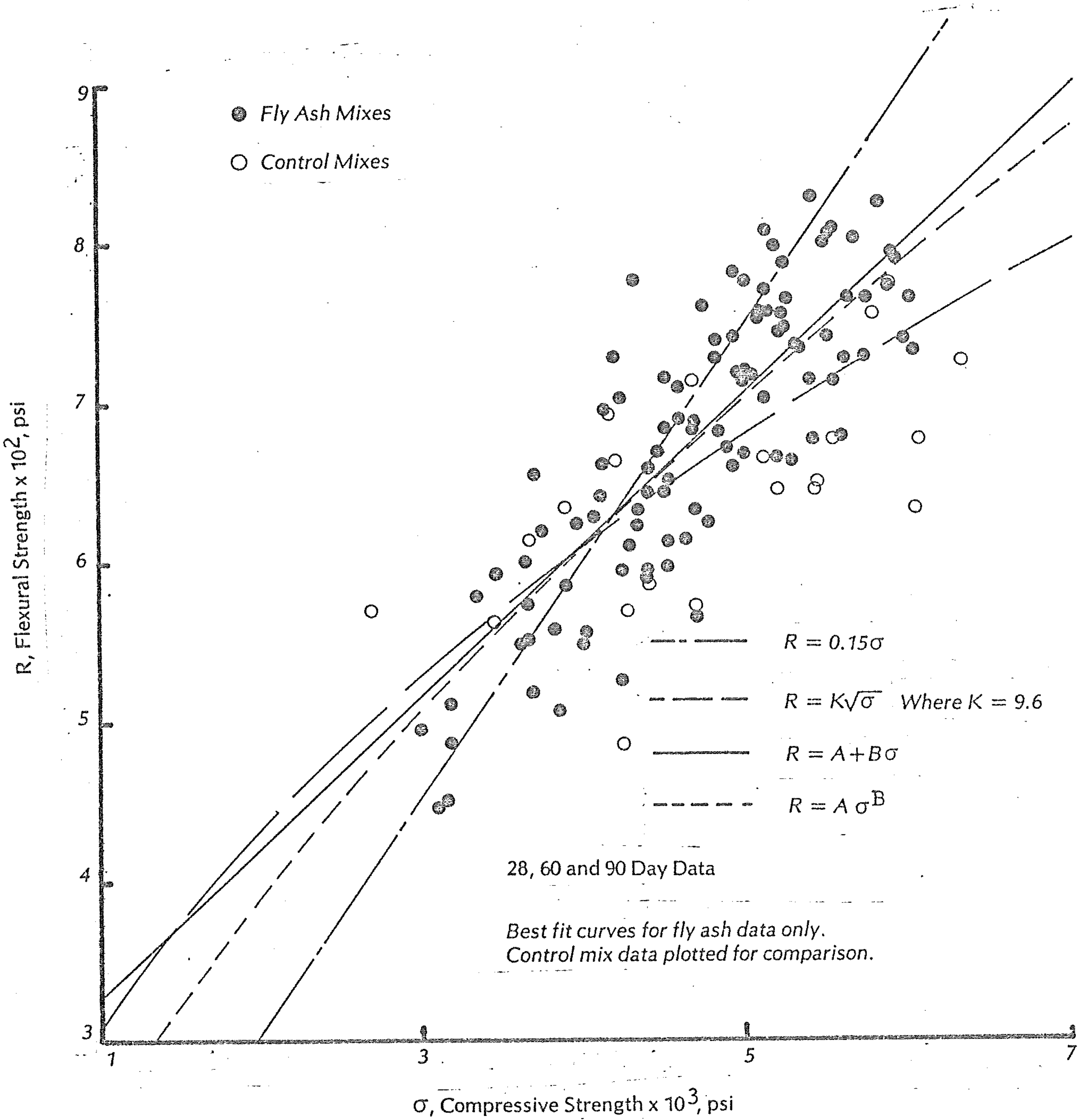


FIGURE 5-12. FLEXURAL AND COMPRESSIVE STRENGTH COMPARISON

strengths for all the data of this study except IP mixes. The distribution of data points is such that the best fit curve is not visually apparent. Data scatter obviously suggests that compressive strength may not be an extremely reliable predictor of flexural strength (for the mix designs under study). Four equations were studied, as possible predictors of flexural strength based solely on compressive strength. The relationships evaluated included:

(1) $R = 0.15\sigma$
(2) $R = k\sqrt{\sigma}$
(3) $R = A + B\sigma$
(4) $R = A\sigma^{B}$

in which:

R = flexural strength (modulus of rupture), psi
σ = compressive strength, psi
A, B = constants
K = constant (generally used value 8 to 10)

(flexural and compressive strengths are compared at similar age)

Equations (1) and (2) are relationships frequently used in estimating flexural strength. Equations (3) and (4) are simply the general expressions for which (1) and (2) represent particular solutions. The least squares best fit solutions were found for (3) and (4) to be:

(3) $R = 269 + 0.0852\sigma$
(4) $R = 3.99\sigma^{0.606}$

The curves representing all four relationships are indicated on the scatter diagram, Figure 5-12. Equations (3) and (4), for all practical purposes, yield identical results. The solution to equation (3) is obviously range dependent since it does not pass through the origin.

The statistical parameters indicate that the predictor equations account for approximately sixty percent of the variation in flexural strength. The scatter diagrams of Figure 5-13 illustrate the predictions comparatively. Control mix data are plotted with the fly ash concrete data for the purpose of visually illustrating the scatter of both normal and fly ash concrete mixes, with regard to the predictor expressions.

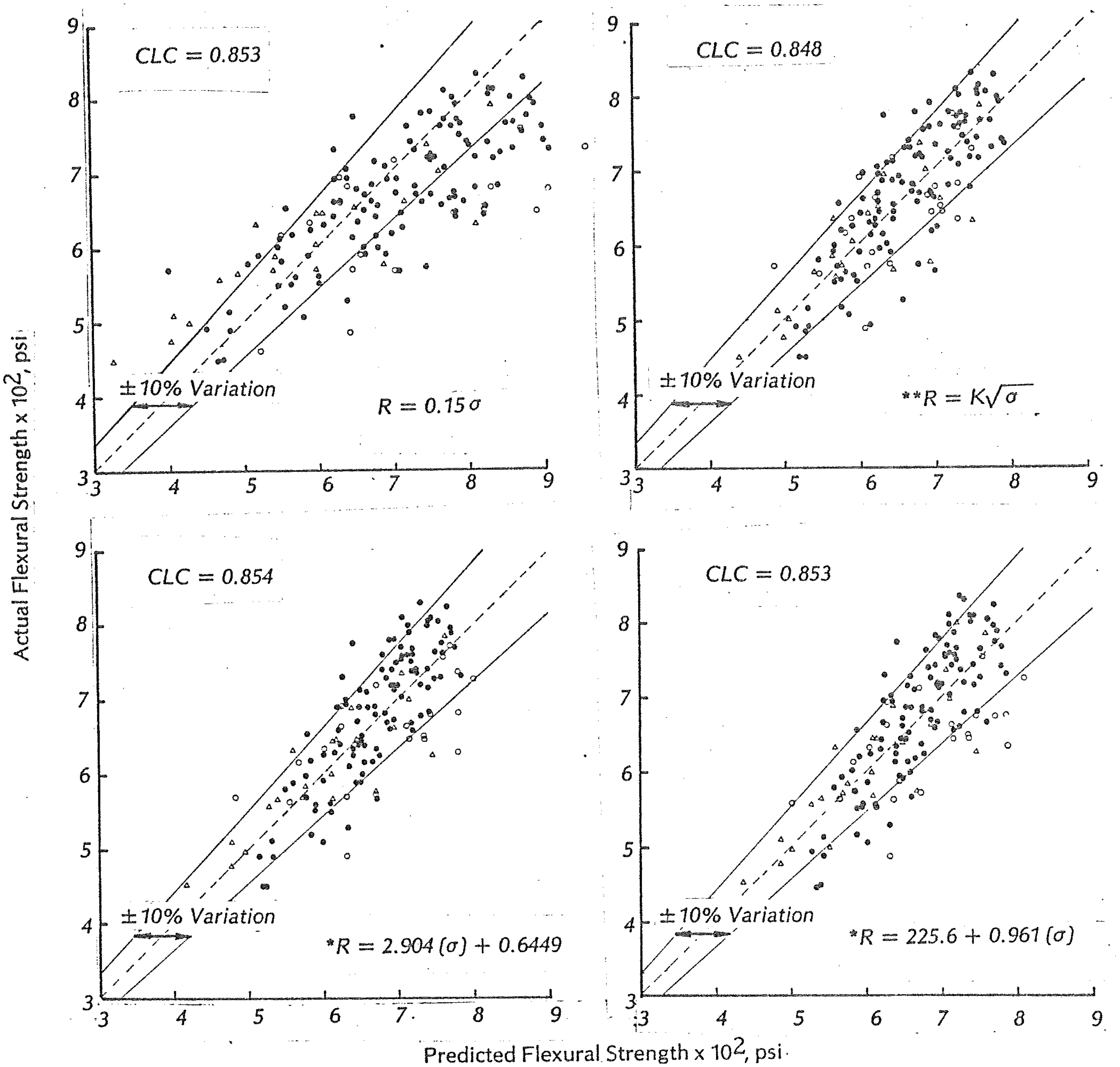
5.2.3 Relative Performance

The test data appear to support some interesting and definite conclusions with regard to flexural strength. Two important relationships are apparent from the data in Figures 5-8, 9, 10 and 11:

1. Fly ash apparently tended to increase late age flexural strength, even on a one-to-one volume replacement basis.

2. The flexural strength advantage of the fly ash concretes became more apparent at ages well beyond 28 days.

The first of these conclusions can best be illustrated by reference to Figure 5-8. The curves represent concrete mixes with identical volumes of cementitious material. The control mix contains



● Fly Ash Mixes   △ IP Cement Mixes   ○ Control Mixes

*Best fit equations

**K@ 28 days = 9.4, K@ 60 days = 9.8, K@ 90 days = 10.2 (for fly ash mixes only)

28, 60 and 90 day data plotted for all equations

FIGURE 5-13. FLEXURAL STRENGTH PREDICTOR EQUATIONS. CORRELATIONS BASED ON FA DATA ONLY. CONTROL DATA PLOTTED FOR COMPARISON.

2.90 cubic feet of cementitious material (CM) per cubic yard (0.107 m^3/m^3). Fly ash contents range from 10 to 50 percent of total cementitious material by volume. The curves of Figure 5-8, therefore, represent concretes in which part of the portland cement has been replaced on a one-to-one volume basis by fly ash. At age 7 days the normal concrete control mix exhibits superior strength in the majority of cases. By age 28 days the fly ash mixes indicate a strength advantage and by 60 and 90 days age the advantage of the fly ash mixes has become more evident. The economic implications of this behavior are obvious since less expensive fly ash has replaced portland cement on a one-to-one basis with a net increase in strength. This is in contrast to the situation regarding compressive strength wherein a larger volume of fly ash is necessary to replace a given amount of cement to maintain a comparable strength level.

The age at which the fly ash concrete flexural strength advantage becomes apparent varies depending primarily on fly ash source. There appears to be some indication that the fly ash concretes would continue to gain strength significantly beyond age 90 days; there are, however, no test data to support this possibility. The trend for late gain in strength is indisputable considering all the curves. At age 7 days about 35 percent of the fly ash test strengths exceed the control strength. By age 90 days 85 percent of the fly ash test strengths exceed the control strength, with a steady gain for intermediate ages.

No other general conclusions appear to be justified from the available data. It is interesting to note in the 120 percent CM series (Figure 5-10) that the relative strength positions of the various mixes are very uniformly ordered. The 90 day strengths increase, in every case, with increasing value of the FA to CM ratio. This relationship is found to reverse itself between 7 days and 90 days of age. Each group of curves in the 120 percent CM series behaves in this manner, without exception. This pattern, however, is not repeated in the other series. The very obvious conclusions indicated by Figure 5-10 appear to be refuted by the remainder of the data. This illustrates the potential hazard involved in attempting generalizations from limited data.

5.3 Core Compressive Strength

5.3.1 General

The results of compressive strength tests on drilled cores were used to evaluate long term strength of all mix designs developed in the study. A secondary purpose was accomplished in that data were developed for a direct comparison of drilled core with molded cylinder compressive strengths. Drilled cores, 2½ to 3 inch (6.35 to 7.62 cm) diameter, were obtained from the flexural strength beams after flexural strength testing. Drilling was performed on the same day compressive strength testing was performed; beam remnants remained in the moist room until cored. The 60 day and 180 day cores were drilled from the 60 day flexure beams. The 90 day and 360 day cores were drilled from the 90 day flexure beams. The ratio of length to diameter of cores was maintained in the range of 1.8 to 2.3.

5.3.2 Test Results

A tabulation of test data is presented in Appendix B.

The compressive strengths are plotted on the curves of Figures 5-14 along with 60 and 90 day cylinder strengths for comparison. Tabulated and plotted strength values generally represent an average of three test values; in some instances only one or two cores could be obtained due to cracking or unusual breaking of the flexure beams. Core strengths representing less than three test values are so indicated in the Appendix.

Some variation is evident between the core and cylinder compressive strengths. Core strengths varied from 860 psi (60.5 Kg/cm^2) below to 770 psi (54.1 Kg/cm^2) above cylinder strengths for the 60 day tests. The 90 day cores varied from 1220 psi (85.8 Kg/cm^2) below to 740 psi (52.0 Kg/cm^2) above the cylinders. Compressive strengths of cores and cylinders are compared and analyzed in Figure 5-15. About 81% of the data points on the scatter diagram lie within a range of variation of $\pm$ 10% from a direct one-to-one comparison.

A straight line of the form $Y = A + BX$ was fitted to the data using the least squares best fit.

The solution, shown on Figure 5-15, indicates that about 76% of the variation in core strength can be accounted for by the assumed straight line relationship with compressive strength. The curve (straight line) which represents the best fit to the data indicates that core strength is typically slightly lower than cylinder strength within the range of values under study. The best fit straight line in Figure 5-15 is obviously range dependent since any universal relationship between core and cylinder

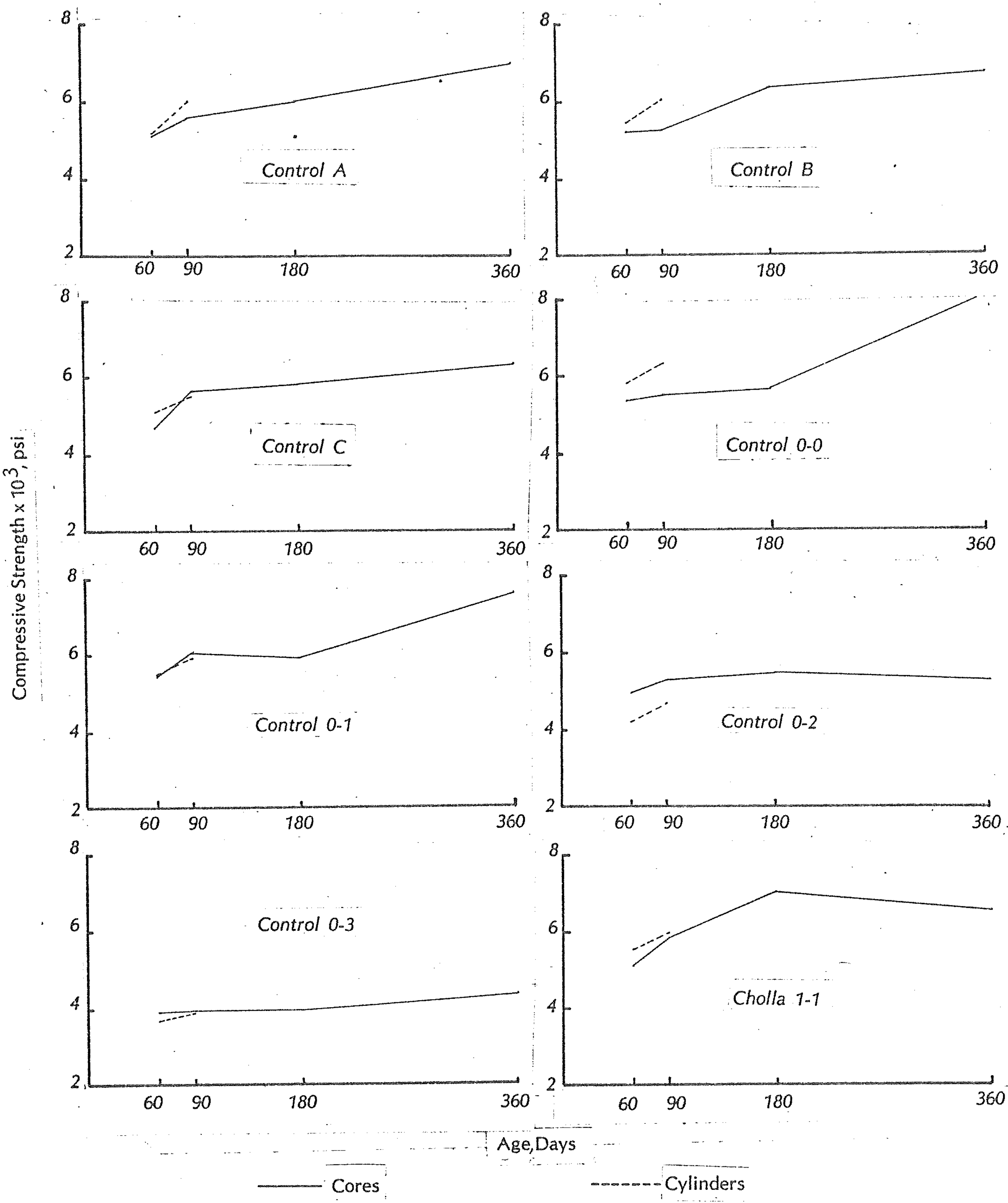


FIGURE 5-14A. LONG TERM STRENGTH GAIN

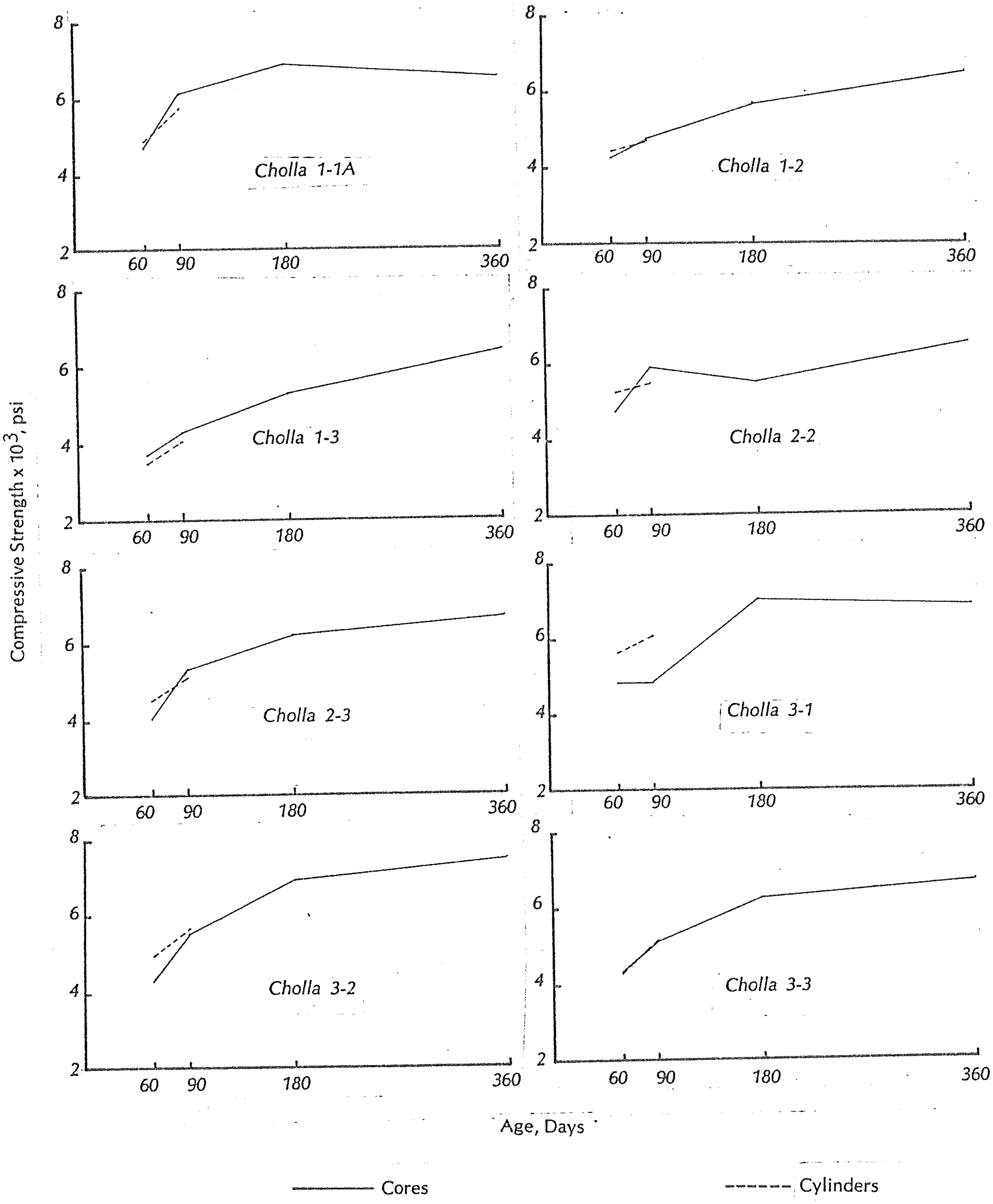


FIGURE 5-14B. LONG TERM STRENGTH GAIN

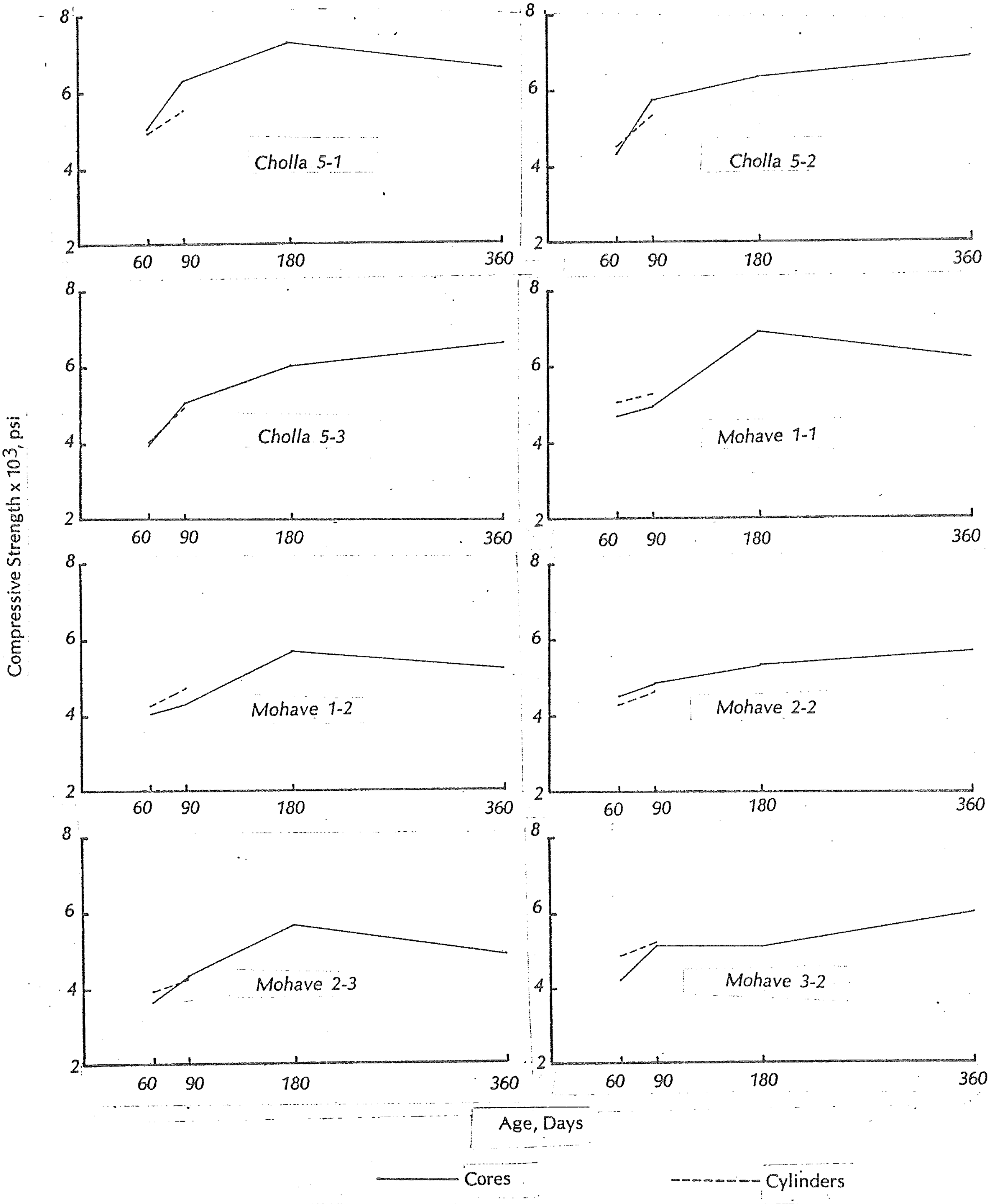


FIGURE 5-14C. LONG TERM STRENGTH GAIN

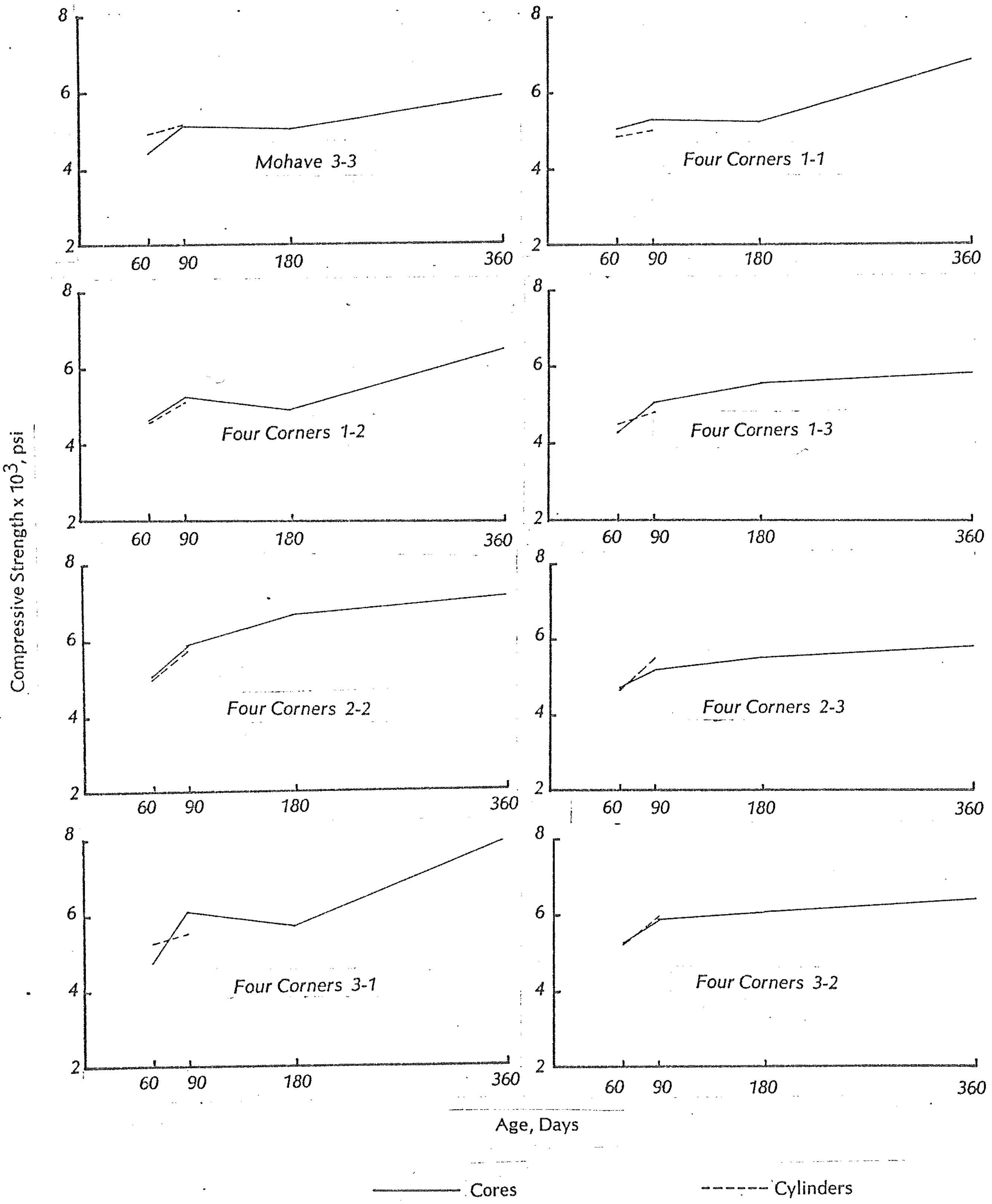


FIGURE 5-14D. LONG TERM STRENGTH GAIN

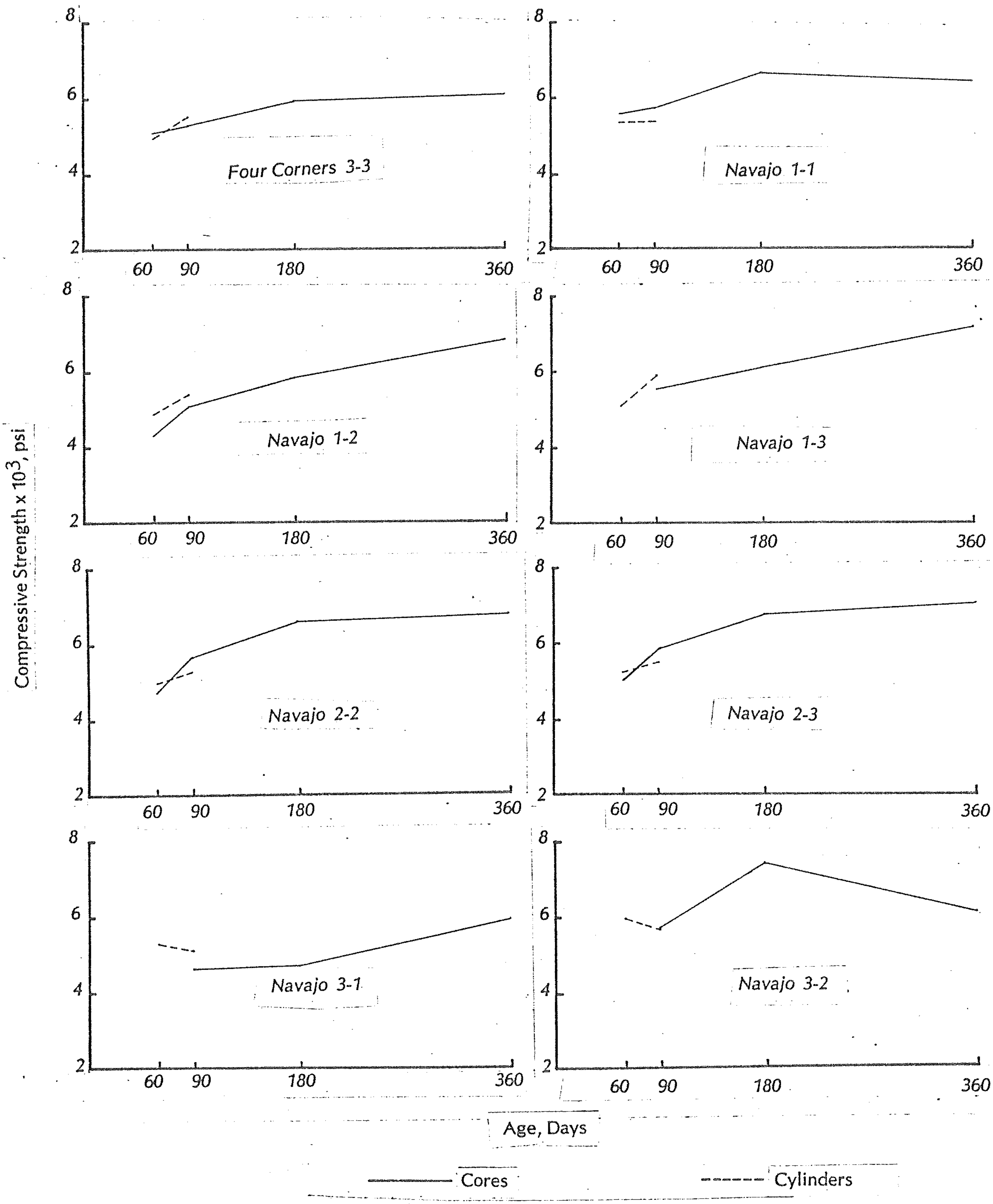


FIGURE 5-14E. LONG TERM STRENGTH GAIN

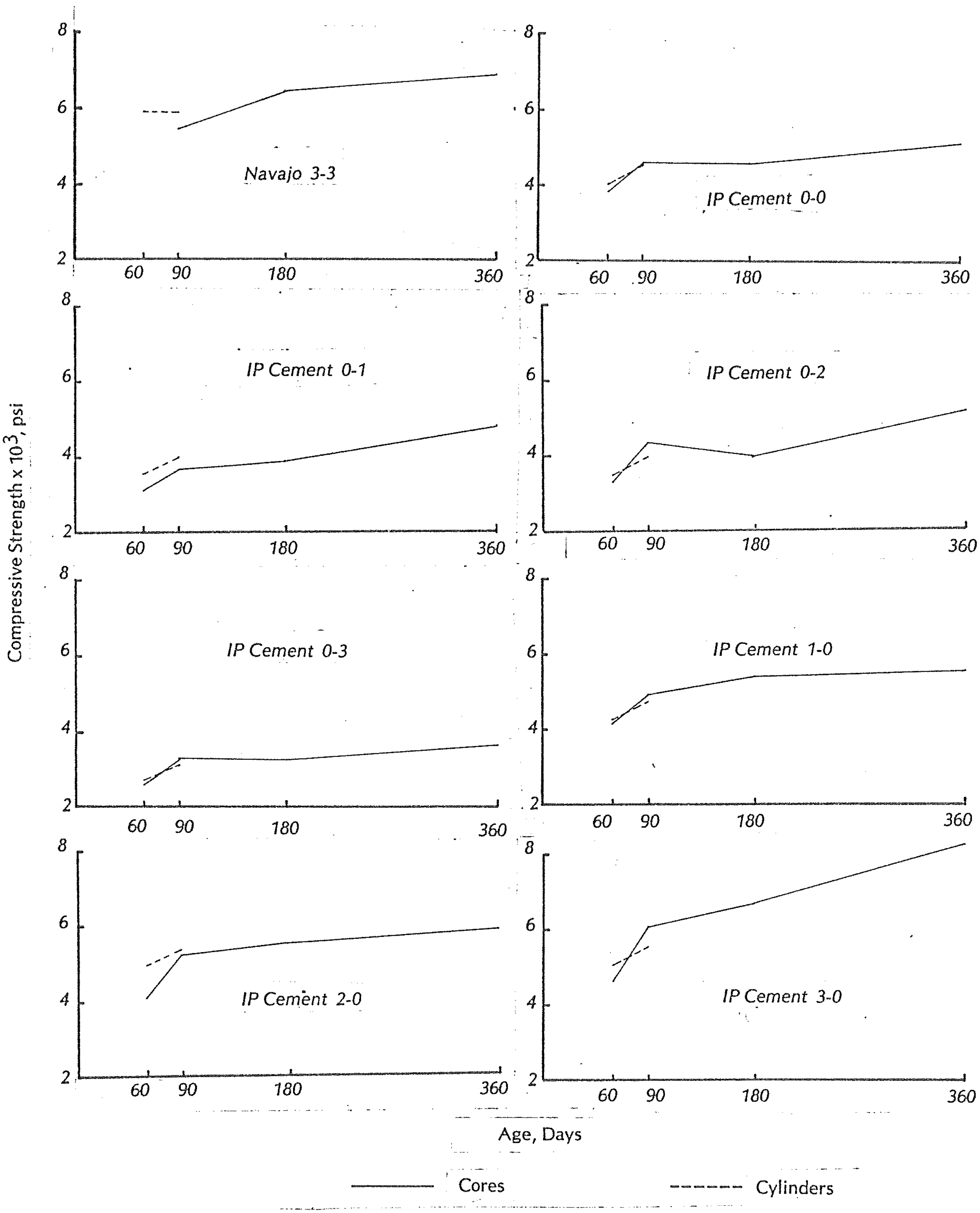


FIGURE 5-14F. LONG TERM STRENGTH GAIN

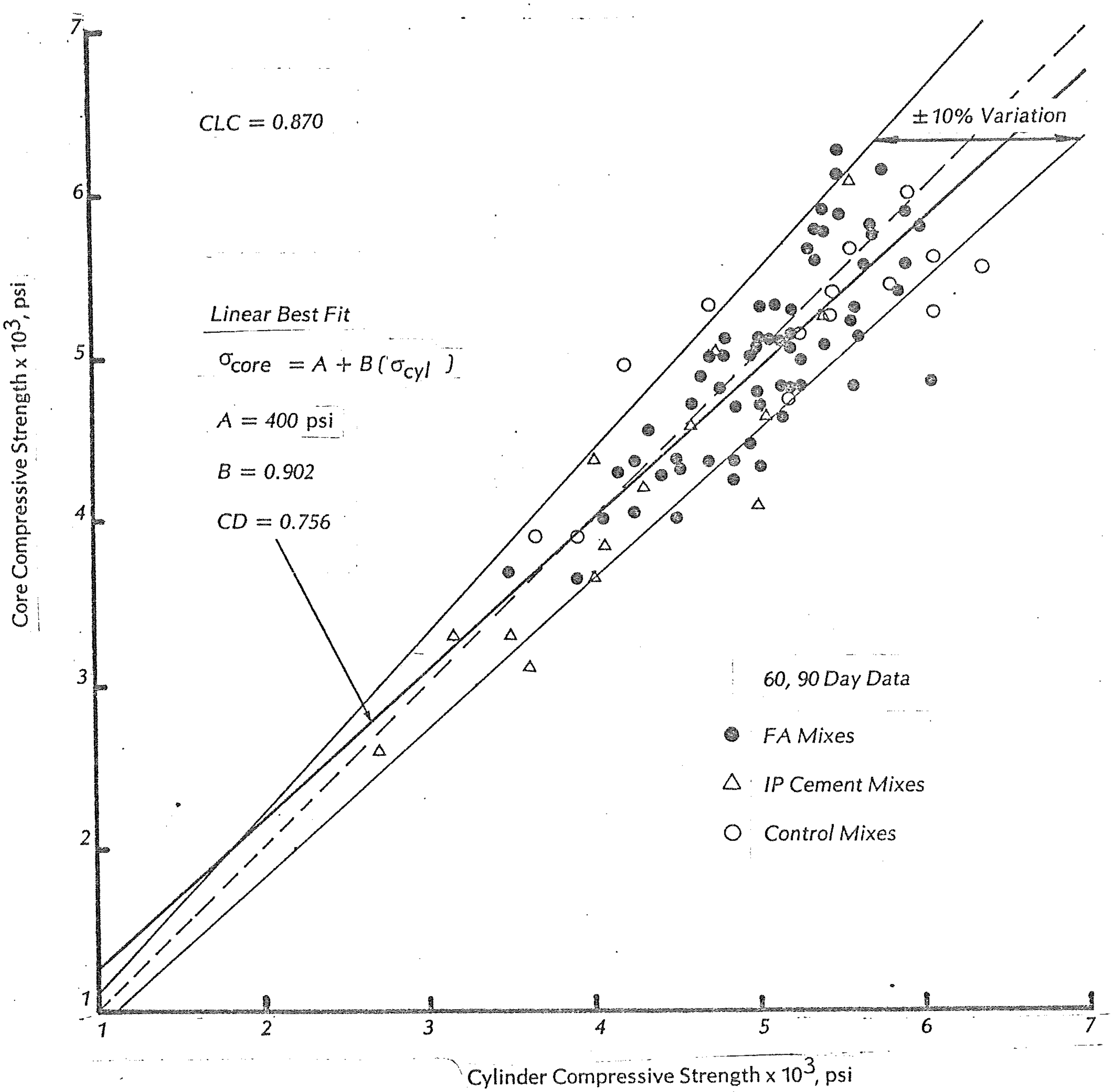


FIGURE 5-15. CORE AND CYLINDER COMPRESSIVE STRENGTH COMPARISON.

strengths must pass through the origin. The expression is sufficient, however, for the purpose of establishing a correlation for the 60 and 90 day test values.

5.3.3 Late Age-Strength Gain

The slopes of the age-strength curves were analyzed to determine the late age-strength gain characteristics of each mix type. The age-strength curves were assumed to be straight lines in the range of 60 to 360 days age. Six data points were available to establish the best fit aging curve; two points each were available at 60 and 90 days (core and cylinder) and one point each at 180 and 360 days. The data were used as obtained; no attempt was made to correct core data to equivalent cylinder data or vice versa.

The best fit straight line was fitted to each set of data points using the least squares method. The slope was determined for each best fit line based on strength gain as a percent of 60 day compressive strength. Slopes were then averaged for the control series and for the series corresponding to each fly ash source. Average values of the 60 to 360 day aging curve slopes are tabulated in Table 5-1. The data indicate a strength gain for the control mixes of 0.091% per day (using 60 day strength as a base). The fly ash concretes are slightly higher in all cases. The data strongly suggest that the fly ash concretes continued to gain strength at a rate significantly higher than for the normal portland cement concretes. A close study of the data does indicate that for some series the rate of strength gain is dependent on the magnitude of the 60 day compressive strength. The control mixes appear to have a slightly increasing rate of strength gain as the magnitude of

TABLE 5-1. Average Rates of Compressive Strength Gain for Cylinder and Core Specimens from 60 to 360 Days Age

Mix Series	Average Rate of Compressive Strength Gain as % 60 Day Strength, per day	Relative Rate
Control	0.091	100
Cholla	0.153	168
Four Corners	0.107	118
Mohave	0.099	109
Navajo	0.093	102
All Fly Ash	0.119	131
IP Cement	0.123	135

the 60 day strength increases. The reverse is true for the Cholla and Navajo series. The remaining series indicate no apparent relationship (rate of gain is independent of the base 60 day strength). The data are sufficiently separated to indicate confidence in the conclusion suggested by the rate-of-gain averages; the rate of strength gain was generally higher for fly ash mixes than for straight portland cement mixes in the 60 day to 360 day range. Finally, the rate of strength gain appeared to differ significantly for the various fly ash sources. The rate of late age-strength gain correlated inversely with the rate of early age-strength gain.

5.3.4 Evaluation of Coring

The discussion regarding the general reliability of drilled cores for use in determining compressive strengths is only incidental to the primary purposes of this study. Some degree of uncertainty exists within the industry as to the true correlation between the compressive strengths of drilled cores and cast cylinders. Field comparisons generally are made, of necessity, between cast cylinders which have received moist room curing, and drilled cores which have been obtained from the field cured structure. In addition, ages are frequently not comparable. The first step in developing the general relationship between core strengths and cylinder strengths is to establish the relative performance of the two specimen types when aged and cured under comparable conditions. The 60 and 90 day beam remnants presented an opportunity to make such a comparison using specimens and data already available.

The cores were smaller in diameter than would be ideal for the purpose. Beams were nominally six inches thick, thereby limiting the length of the cores. Holding the length-to-diameter ratio to about two then established the diameter at about three inches. Since maximum aggregate size was one and one-half inches the normally specified minimum core size would be three inches (twice the size of largest aggregate). Only the largest diameter cores met this usual minimum diameter requirement.

In addition the core lengths were somewhat variable due to the cracking and chipping which occasionally occurred and necessitated trimming.

Due to the variations from standard in diameter and length-diameter ratio, the core results as presented do not have the control normally expected of research data. The data should nevertheless be of value in evaluating the general correlation between cylinders and cores since the usual variables of age and curing conditions have been controlled.

Two criteria should be considered in comparing the core and cylinder compressive strengths, the shape and position of the best fit curve through the data points and the scatter of the data relative to the best fit curve. The data on Figure 5-12 indicates that the best fit curve, comparing core strength to companion cylinder strength, deviates by a maximum of about 3% from the 45° line which would indicate a one-to-one comparison. The cores tested in this study appear to be very nearly the equivalent of cylinders, overall, for compressive strength determination. The coefficient of determination indicates the equation of the best fit straight line accounts for 76% of the variation in core strength; the data scatter is such that all data are contained within ± 27% of the 45° one-to-one comparison line. The best fit line indicates good correlation, very nearly one-to-one; the data scatter, however, is greater than should be expected and may reflect the variations in core geometry.

A further comment on the reliability of the core strength data will appear in a following section on data reliability.

5.4 Data Uniformity and Reliability

The concrete strength values presented in Appendix B, are, in each case, averages of more than one test result. Reported values for cylinder compressive strengths and flexural strengths represent averages of three test results. Core compressive strength values represent averages of three test results generally; however, the results of only one or two cores were reported in cases where it was not possible to obtain additional undamaged core samples. Ideally, companion samples would provide identical test results; however, it must be recognized that some variability is present in test results obtained using present methods of batching, sampling, curing and testing. Test results are not precisely reproduceable even though reasonable standards of care were exercised in maintaining "constant" control parameters. This is due partly to inherent variability in the mix constituents, batching procedures and test methods, and partly, possibly, to variables which have not yet been identified or recognized as important to the end results. Raw strength test data were evaluated to determine uniformity of sampling and testing, assuming the validity of the usually accepted assumption that the concrete strength test result is a normal random variable.

The within-test standard deviation and coefficient of variation were determined in accordance with well known statistical quality control procedures, published by the American Concrete Institute (ACI). The coefficient of variation is a dimensionless expression of the relative degree of uniformity. Since the data include a broad range of strength values, the coefficient of variation provides a more convenient measure than the more common standard deviation (which has the units of the variable being evaluated). Table 5-2 presents a tabulation of the within-test coefficients of variation for all compressive and flexural strength test results. It is recognized that in some cases the number of data points is less than normally considered desirable for statistical evaluation. Available data varied from six groups of three samples each for the Mohave fly ash mixes to twelve groups for the Cholla fly ash mixes.

It is further recognized that the statistical evaluation procedure utilized here was developed to describe the relative uniformity of quantities of concrete produced to meet a specific target strength. The method as herein used is for the purpose of describing the relative uniformity of quantities of concrete produced with certain common classes of constituents. These departures from usual statistical practice should not diminish the value of Table 5-2 as a reasonably reliable comparative representation of data uniformity and reliability.

Table 5-3 is reprinted from ACI Standard 214-65. The data are presented in the ACI Standard as typical of the variation that can be expected with varying degrees of control. The purpose in reproducing the Table in this report is only to compare the degree of uniformity of data developed in this study to a widely used standard of performance.

TABLE 5-2. Relative Uniformity of Laboratory Test Data

Concrete Type	*	Molded Cylinder Compressive Strength				Flexural Strength				Drilled Core Compressive Strength			
		Age, Days				Age, Days				Age, Days			
		7	28	60	90	7	28	60	90	60	90	180	360
Control Mixes	n	7	7	7	7	7	7	7	7	7	7	7	7
	$\bar{R}$	97	180	264	226	54	45	80	79	393	634	309	666
	s_1	57	106	156	133	32	29	47	57	265	455	183	450
	V_1	2.2	2.7	3.1	2.4	7.6	4.9	7.3	8.2	5.3	8.6	3.3	6.9
Cholla Fly Ash Mixes	n	12	12	12	12	12	12	12	12	12	12	12	12
	$\bar{R}$	88	140	174	183	47	49	60	62	483	654	527	581
	s_1	54	83	103	108	28	30	35	41	285	451	324	415
	V_1	2.3	2.1	2.2	2.0	7.5	5.7	5.4	5.5	6.4	8.3	5.1	6.2
Four Corners Fly Ash Mixes	n	8	8	8	8	8	8	8	7	8	7	8	7
	$\bar{R}$	96	171	219	226	32	67	77	51	300	714	519	511
	s_1	57	101	129	133	19	40	46	33	177	422	307	324
	V_1	2.2	2.5	2.7	2.5	4.5	6.4	6.4	4.3	3.6	7.8	5.4	4.9
Mohave Fly Ash Mixes	n	6	6	6	6	6	6	6	6	6	6	6	6
	$\bar{R}$	102	128	126	138	48	80	74	60	435	570	707	335
	s_1	60	76	74	82	28	47	43	35	257	337	418	198
	V_1	2.1	1.9	1.6	1.7	5.9	7.3	6.1	5.2	6.0	7.0	7.2	3.5
Navajo Fly Ash Mixes	n	8	8	8	8	8	8	8	8	4	8	8	8
	$\bar{R}$	129	169	206	181	39	72	63	80	713	454	424	523
	s_1	76	100	122	107	23	42	38	56	421	307	251	309
	V_1	2.6	2.3	2.3	1.9	4.6	6.6	5.1	7.4	8.5	5.6	4.0	4.6
IP Cement Mixes	n	7	7	7	7	7	7	7	7	7	7	7	7
	$\bar{R}$	29	136	199	187	46	39	29	69	346	336	329	214
	s_1	17	80	117	111	27	23	17	41	204	199	194	126
	V_1	0.8	2.4	2.9	2.5	6.4	4.2	2.7	6.5	5.5	4.3	4.1	2.3

* n = Number of sets of companion specimens.
$\bar{R}$ = Average range of strengths. For all sets of a given age group (psi)
s_1 = Within-test standard deviation (psi).
V_1 = Within-test coefficient of variation (%).

Statistical determinations performed in accordance with methods of ACI 214-65.

TABLE 5-3. Standards of Concrete Control

Class of operation	Coefficients of variation for different control standards			
	Excellent	Good	Fair	Poor
Over-all variations: General construction	Below 10.0	10.0 to 15.0	15.0 to 20.0	Above 20.0
Laboratory control	Below 5.0	5.0 to 7.0	7.0 to 10.0	Above 10.0
Within-test variations: Field control	Below 4.0	4.0 to 5.0	5.0 to 6.0	Above 6.0
Laboratory control	Below 3.0	3.0 to 4.0	4.0 to 5.0	Above 5.0

Notes: (1) These standards represent the average for 28-day cylinders computed from a large number of tests. Different values for other than average concretes can be expected.

(2) From ACI Standard 214-65.

It should be noted that the data of Table 5-3 were developed from compressive strength test results. Widely accepted standards of uniformity for flexural strength, core compressive strength, or other concrete characteristics have not been developed.

The within-test coefficients of variation for the compressive strength data are, with only one exception, in the "excellent" range established in Table 5-3. The coefficients for the flexural strength data are considerably higher. If the highest and lowest values in each group of data are discarded, the geometric range in coefficients is nearly identical (factors from low to high of 1.81 and 1.90) for the two groups of data. The compressive strength and flexural strength samples were prepared from the same batches of concrete. It can reasonably be concluded that similar care was exercised in sampling and testing since there was no change in equipment or personnel. It was not a purpose of this study to develop a relationship for the variability of flexural strength vs compressive strength testing. The data suggest strongly, however, that there is considerably more variation inherent in the present procedures used for evaluating flexural strength than in those used for evaluating compressive strength. No attempt was made to verify the universality of this conclusion, either by testing or literature search.

The data of Table 5-2 indicate that the uniformity of fly ash mixes (including the Type IP mixes) may be slightly superior to that of the normal concrete control mixes. It is probably not valid to attach more than qualitative significance to this since a few anomalies appear to exist. The Mohave fly ash mixes, for example, exhibit the greatest degree of uniformity (lowest coefficients of variation) for compressive strength test results; however, these same mixes exhibit the greatest degree of variation (highest coefficients of variation) for flexural strength test results. (There is reason to believe that a laboratory error may exist for the Mohave flexural strength data. Data are unexplainably erratic, including a decline in strength with age for some test series). The data indicate that the addition of fly ash to concrete does not produce erratic strength results and probably contributes somewhat to increased uniformity, and therefore predictability, of strength.

The parameters presented in Table 5-2 relative to the reliability of core compressive strengths indicate a degree of uniformity approximately comparable to the flexural strength data. Cores were extracted from flexure beams previously stressed to failure in the flexure test; there was some risk, therefore, that cores might be unsuitable for subsequent compressive strength testing due to internal micro-cracks. The statistical evaluation, however, appears to indicate that the drilled cores were, in general, suitable for evaluation of compressive strength. It is probably reasonable to assume that the size of samples is a major factor in the difference in the degree of uniformity between molded cylinder and core compressive strengths. The possibility also exists that the strength of concrete from the flexure beams is inherently more erratic than that of molded cylinders due to differences caused by specimen molding techniques. The discussion here relates primarily to the uniformity and reliability of core compressive strength test results. The magnitudes of core compressive strengths compared to molded cylinder compressive strengths has been discussed elsewhere in this report; 60 and 90 day age results are available from both groups for direct comparison.

CHAPTER 6. DURABILITY AND SOUNDNESS

6.1 Freeze-Thaw Durability

6.1.1 General

Freeze-thaw testing was conducted on selected mixes in accordance with procedures outlined in ASTM: C666-73. An automatic freeze-thaw chamber monitored with a Marshalltown Model "1000" Recorder was used. Time-temperature data were recorded continuously on an electrically driven chart. The preparation and curing of test samples are described in Chapter 4 under Batching and Sample Molding. Fundamental transverse frequency of specimens was determined utilizing a Soiltest Model CT-366 Sonometer.

The complete freeze-thaw cabinet with refrigeration, control and recording components was manufactured by Logan Refrigeration Company, Logan, Utah. The freeze-thaw cabinet had a maximum capacity of 18 specimens. One of the 18 spaces was occupied by a control dummy in which the thermostatic control pickup units were embedded. Therefore, 5 sets of 3 specimens each, plus the control dummy and two space-occupying dummies filled the cabinet for each test run. Two test runs were completed over a period of about 6 months including time for batching, curing and the 300+ test cycles.

The ASTM: C666-73 method provides two options for the freeze-thaw specimen environment: 1) freezing and thawing in water, or 2) freezing in air and thawing in water. The first method was used in this series of tests.

6.1.1 Test Results

Nine of the concrete mix designs were selected for freeze-thaw testing. The mixes selected produced 28 day compressive strengths generally in the range of 3000 to 3500 psi (211 to 246 $\frac{Kg}{cm^2}$). Normal portland cement, IP cement and all four fly ash sources were represented. Laboratory data is tabulated in Table 6-1 in the order of decreasing durability factor (as defined in ASTM: C666-73). A few pertinent mix design parameters are included in the tabulation for comparison. Complete batch information is presented in Appendix B.

One set of test specimens molded with non-air entrained concrete was included for comparison. These specimens deteriorated too rapidly (less than 36 cycles) to permit even a first determination of fundamental transverse frequency; therefore, no data are included in the tabulation.

Each reported value represents an average for three test specimens. In most cases, the range of variation for the three specimens was within $\pm$ 7% of a midrange value. The single exception to this was mix C-3-2. One specimen in this series cracked significantly in a plane perpendicular to the long axis of the specimen. Results are reported both for the average of all three specimens and for the average of the two more competent specimens.

Testing was continued to at least 300 cycles or until the relative dynamic modulus declined to 60. Specimens in the cabinet at any given time were of varying cycle-ages due to the fact that all samples could not be physically batched and molded in a

TABLE 6-1. Freeze-Thaw Test Data

Mix Series	Cycles *	Relative Dynamic Modulus *	Dura-bility Factor	Wt. Loss %*	28 Day Compressive Strength (psi) ***	PC lb./CY ****	FA lb./CY ****	FA/PC % Wt.	Water to PC Ratio ****	Water to CM Ratio ****	Air % ****
0-3	300	93(90-95)	93	7	2710	401	0	0	0.55	0.55	4.8
IP 0-0	300	92(91-93)	92	5	3290	503	Unknown	Unknown	Unknown	0.50	4.7
C-1-2	300	91(88-93)	91	5	3190	449	77	17	0.55	0.47	4.8
M-2-2	300	91(89-94)	91	5	3710	479	109	23	0.58	0.47	4.5
0-2	300	90(89-92)	90	7	3455	461	0	0	0.49	0.49	4.4
N-1-3	300	89(87-91)	89	7	3755	402	115	29	0.70	0.55	4.5
F-1-3	300	86(79-90)	86	8	3370	404	105	26	0.60	0.48	4.6
C-3-2	300	83(77-88)	83**	8	3770	481	131	27	0.60	0.47	4.0
		69(60-88)	69**	8							
C-5-3	169 (145-183)	60	34	8	3180	396	259	65	0.74	0.45	4.1

* Testing was continued until the relative dynamic modulus diminished to 60, or the completed cycles exceeded 300. Results are an average of 3 specimens. Range of test values is indicated in parenthesis.

** One specimen cracked visibly. Upper value is the average of the 2 more competent specimens. Lower value is the average of all three specimens.

*** Obtained from compressive strength test series.

**** Indicated values are for the concrete specifically batched for durability specimens; weights vary slightly from compressive and flexural strength specimen batches for similar series.

single day. It was not practical, therefore, to stop each set at precisely 300 cycles. The cabinet was opened at intervals sufficient to obtain the necessary data about every 36 cycles. Testing of a particular series was discontinued at the first cabinet opening after the series had been subjected to 300 cycles. Durability factor and relative dynamic modulus were calculated on the basis of a linear correction to 300 cycles.

6.1.2 Relative Performance

Many variables occur in the mix designs utilized in the study, including portland cement content, fly ash source and content, and water-cement ratio. Each of these variables can reasonably be presumed to have some effect on the freeze-thaw durability of concrete. A definitive study of this particular aspect would require that the number of test series exceed the number of variables by a considerable and rationally determined number. The number of tests performed in this study was not sufficient to provide a foundation for broad statements on durability for all the fly ash types considered. Certain observations can be made, however, on the basis of the data obtained. The tabulation of Table 6-1 provides the background for the following observations.

Weight loss varied only through the range of 5% to 8% for the nine mixes tested. Durability factor ranged from a high of 93 down to 34; however, the durability factor for seven of the nine test mixes ranged between 93 and 86, a rather narrow range of variation. It may be significant to note that the weight loss criteria did not reflect the apparent marked deterioration of mix C-5-3. Weight loss did correlate well with durability factor, increasing as durability factor decreased.

Air content has been treated as a constant throughout the study, for practical reasons. During the batch-in procedure, air content was controlled at $4\frac{1}{2} \pm \frac{1}{2}$ percent. Any attempt at closer tolerance was judged to be impractical; in fact, there is considerable discussion in the general literature to the effect that air content probably cannot be reliably repeated with this degree of tolerance. Nevertheless, the most consistent relationship apparent in Table 6-1 is that of air content vs durability factor. Air content apparently varied only through the range of 4.0 percent to 4.8 percent, and appeared to relate directly to the durability factor. Further detailed study would be needed to determine if these relatively small variations in air content do indeed outweigh the effects of changes in the other variables. Comparison with the calculated air contents yields the same relative correlation.

Consideration of the test results of the control series 0-3 and 0-2 provides some interesting insights into the freeze-thaw test data. Compared to series 0-3, 0-2 has a higher cement factor, lower water-cement ratio and a higher compressive strength, all of which are consistent. Series 0-3 shows a higher durability factor which does not seem consistent. The most reasonable answer appears to be one of two possibilities, or possibly a combination of both. The difference between durability factors of 93 and 90 may have no significance. The other possibility is that the indicated difference in air content of 0.4 percent is more significant than than other variables. In either event, the compressive strength did not prove to be a reliable indicator of freeze-thaw durability.

Throughout the test series, compressive strength data demonstrates little or no correlation with freeze-thaw resistance. This may provide a proper setting for a consideration of the general effect that the addition of fly ash has on the concrete mix designs. The addition of the new variable, fly ash content, adds greatly to the complexity of the relationship between mix design variables (water-cement ratio, air content, consistency) and concrete response (strength, durability). Considering the large number of variables involved, it is easily seen that the addition of a single variable increases geometrically the complexity of the solution. While frequently overlooked, this is a major portion of the challenge involved in the evaluation of fly ash concretes. Fly ash is, in many respects, an admixture; however, it is an admixture which is used in sufficient quantity to upset the volumetric relationships (cement factor, water-cement ratio, consistency) which have long been established as direct indicators of concrete performance. It should be kept in mind that for a given consistency, an infinite number of fly ash cement combinations may be used to arrive at a given compressive strength. Performance with regard to other criteria (durability, flexural strength, permeability, volume stability) may be expected to vary through a much wider range (relative to compressive strength) than was the case for normal portland cement concrete.

The relationship between durability and water-cement ratio (considering portland cement only) is very roughly the type of correlation expected, although some outstanding anomalies are apparent. The N-1-3 series, for example, has a high water-cement ratio (0.70) but also a relatively high durability factor. The contribution of the fly ash to the relatively high compressive strength of the mix apparently maintained the durability at a level comparable to mixes with lower water-cement ratios and higher cement factors (mix series 0-2 for example). The contrast between the performances of N-1-3 and C-5-3 is also outstanding. The data do not suggest a reason for this other than possibly the very high fly ash content, the somewhat lower air content, or the difference in the fly ash source.

The relationship between durability and water-cementious material ratio (considering cement and fly ash) does not provide any clues to behavior. The relationship appears to be roughly the inverse of the water-cement ratio data.

The data suggest somewhat of an inverse relationship between durability and fly ash content. Any generalized conclusion appears unwarranted considering the anomalies that exist with regard to this single variable. A threshold may exist, beyond which the further addition of fly ash results in decreased freeze-thaw resistance. The one data point which tends to suggest this is certainly far from conclusive.

Series C-5-3 exhibited the lowest durability factor and was the only set that failed to reach 300 freeze-thaw cycles before the relative dynamic modulus declined to 60. This series contained a highly undesireable combination of variables from the standpoint of durability. The specimens had a low air content, the highest water-cement ratio, lowest cement factor, and highest fly ash content of all the mixes studied. The mix possibly represents the lower margin of durability for practical mix designs in the range under consideration.

The test data indicate that fly ash concrete, utilizing the constituents available to this study, can be designed with a laboratory freeze-thaw resistance comparable to normal portland cement concrete in the same strength range. This was the objective of this portion of the study.

6.2 Sulfate Resistance

6.2.1 General

Selected cement and cement-fly ash samples were subjected to a laboratory test procedure to evaluate resistance to sulfate attack. The sulfact soundness test procedures in fact performed the dual purpose of evaluating the relative behavior of the selected samples as well as evaluating a relatively new rapid test procedure for determination of soundness. The samples selected for testing included:

Type II portland cement
Type IP portland-pozzolan cement
Type V portland cement
Type II cement-Navajo fly ash, 75% - 25% by wt.
Type II cement-Navajo fly ash, 65% - 35% by wt.
Type II cement-Cholla fly ash, 75% - 25% by wt.

The test method used was the procedure for rapid determination of sulfate resistance of cements, described by Mehta (55, 56, 57). The Mehta procedure is directed toward the detection of two phenomena which are thought to occur when cements are exposed to a sulfate environment. It is theorized that expansion occurs due to the formation of colloidal calcium sulfoaluminate hydrate in hardened concrete. A relatively high proportion of reactive aluminate (greater than 3% tricalcium aluminate) is necessary for this reaction to occur. The second potentially destructive phenomenon involves the formation of gypsum and a resulting surface deterioration. The expansion can be detected by length measurements on bars exposed to sulfate attack. The surface deterioration can be detected by compressive strength determinations since the cross sectional area of the specimens effectively diminishes.

6.2.2 Summary of Test Procedures

Neat paste specimens were immersed in four environments during aging: 1) distilled water for a non-destructive control environment; 2) phosphoric acid solution for an acidic non-sulfate control environment; 3) sodium sulfate; and 4) magnesium sulfate.

Specimens were evaluated on the basis of visual appearance, compressive strength and expansion during and after immersion in the sulfate and control environments.

6.2.2.1 Mixing

Neat paste was formed with cement and distilled water proportioned for a water-cement ratio (by weight) of 0.53.

It should be pointed out that the ratio as expressed here is perhaps not a water-cement ratio in the strictest sense since total cementitious material (portland cement plus pozzolan) is included in the ratio.

The paste was mixed in a commercial blender for three minutes on low speed, then two minutes on high speed. After standing for one hour, the paste was again mixed for three minutes at high speed. The cubes (1 inch) and bars (1 x 1 x 11 inches) were formed in metal molds.

6.2.2.2 Curing

Specimens were cured in the molds for 24 hours in a moist room at 73°F (23°C) then stripped and moist cured at 122°F (50°C) for 6 days.

6.2.2.3 Storage

Specimens were immersed in each of the following solutions and maintained at moist room temperature:

1) Distilled water.
2) Distilled water plus a 1N solution of H_3PO_4 to maintain a pH near 6.0.
3) A 4% Na_2SO_4 solution developed and maintained using a 1N solution of H_2SO_4; pH maintained near 6.0.
4) A 3.3% $MgSO_4$ solution (6.8% $MgSO_4$) developed and maintained using a 1N solution of H_2SO_4; pH maintained near 6.0.

Solutions were continuously agitated to maintain a uniform concentration within the baths. During later stages of testing a 6N, rather than 1N, solution of H_2SO_4 was used for pH control to minimize the possibility of continually diluting the sulfate ion concentration.

6.2.2.4 Testing

Compressive strength of cubes was determined (5 specimens each) at 0, 28, 56 and 180 immersion days.

Length measurements were made (3 specimens each) at 0, 28, 56 and 180 immersion days.

Dynamic modulus testing was erratic, due to small sample dimensions, and was discontinued.

Expansion and compressive strength tests were performed in accordance with the applicable provisions of ASTM: D452-68 and C109-70, respectively.

6.2.3 Compressive Strength Test Results

Specimens were tested in unconfined compression at immersion ages 0, 28, 56 and 180 days. In each case, five test cubes were broken for each cement type, for each weathering environment.

At early ages the compressive strength was inconclusive with regard to differentiation of behavior between cement (or cement-fly ash) types. An earlier series of tests using two inch instead of one inch cubes was abandoned due to lack of definitive results within the desired time frame. The series reported here, however, did yield results at later ages which appear to effectively differentiate sulfate soundness behavior.

The relationship between compressive strength and immersion age is presented in Figure 6-1. Test results are inconclusive at early ages. The probable reason is that distinguishable difference in behavior did not develop until sufficient time had elapsed for the solutions to penetrate the sample prisms. Examination of all the curves indicates that by age 180 days the pattern of relative behavior has become quite evident. The pattern is uniform. In every case samples subjected to the sulfate environments exhibit a loss of strength compared to control environment samples. Perhaps surprisingly, the specimens generally exhibit a significant absolute strength gain throughout the immersion period in spite of the accelerated curing procedure used to develop high early strength. The continuing natural strength gain with age was apparently greater than the loss of strength through sulfate attack. The major exception to this is the 25% Navajo blend which shows a decline in absolute strength beginning at an immersion age of about 60 days.

An anomaly exists in the 35% Navajo fly ash series. The apparent drop in compressive strength at 28 days immersion age, even for the H_2O control environment specimens, is unexplained. It seems logical to suspect laboratory error in the sample breaking or reporting of compressive strengths. The samples at later ages perform in a manner consistent with

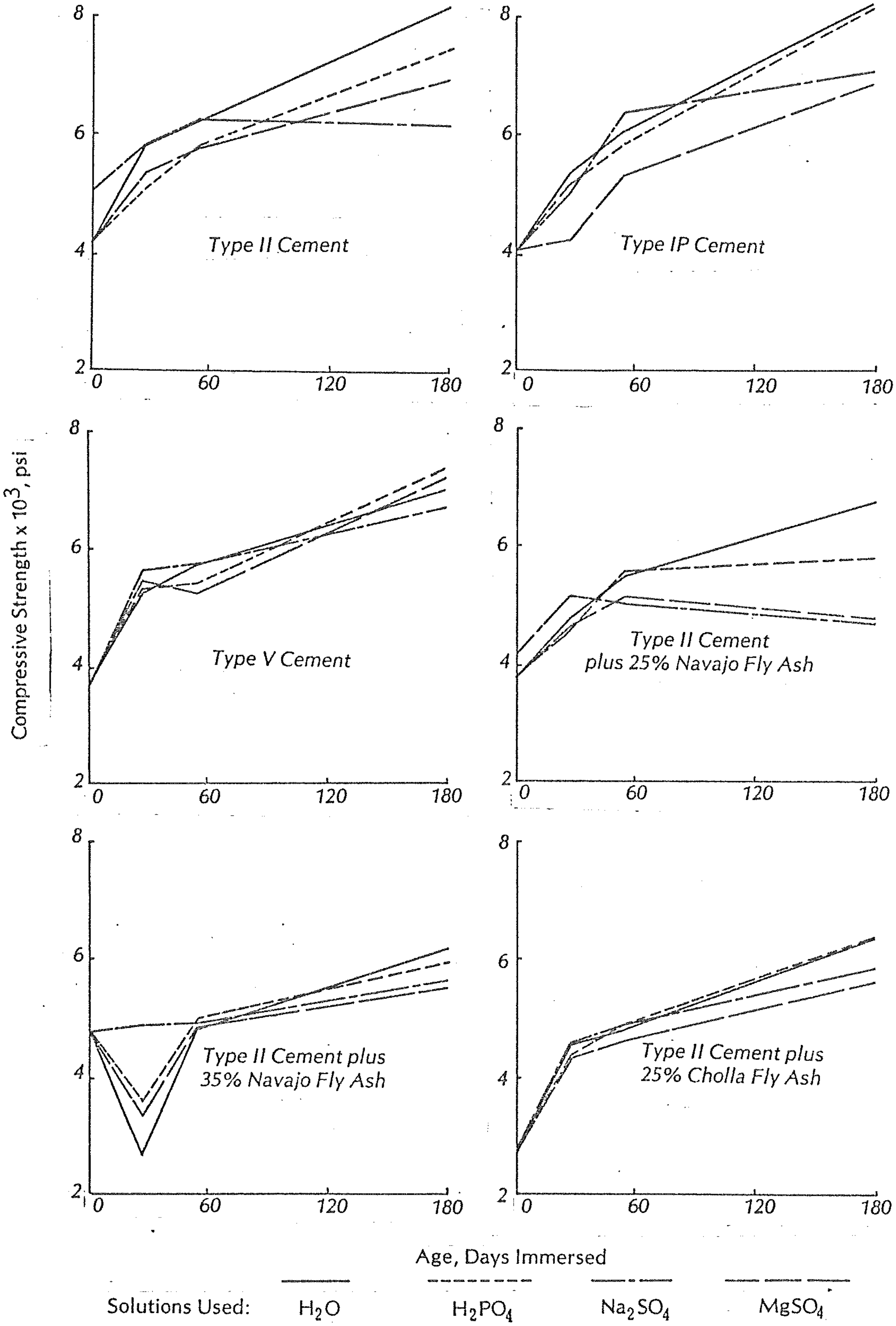


FIGURE 6-1. COMPRESSIVE STRENGTH OF SULFATE IMMERSION SPECIMENS

the other series.

The relative performance of the various cements and blends can most readily be determined by comparison of data at the final test age of 180 immersion days. The relative compressive strengths of the specimens are tabulated for comparison in Table 6-2. The basis for comparison in each series is the compressive strength of the control specimens immersed in distilled water, and tested at the same age.

The Type V cement specimens were clearly the outstanding performers. They exhibited essentially no change in compressive strength relative to the distilled water control specimens. The remainder of the sample series were difficult to clearly differentiate. Overall, the IP cement and the fly ash-cement blends appeared to slightly outperform the straight Type II cement specimens.

6.2.3 Visual Appearance

Throughout the immersion period, cube and bar specimens were periodically examined for visual evidence of cracking. Cracking was not visually apparent in any specimens until 105 immersion days had elapsed. All sets of specimens immersed in the sodium sulfate solution finally exhibited visual cracks. Only one set of samples in the magnesium sulfate cracked, and none in the distilled water and acidic control environments. Table 6-3 provides a summary of the ages at which cracking was first visually apparent. On the basis of visual evidence of cracking, the Type V cement specimens, as should be expected, exhibited superior performance. The

TABLE 6-2. Compressive Strengths at Immersion Age 180 Days.

Cementitious Material Type*	Fluid Environment	Compressive Strength (psi)	Relative Compressive Strength
IP Cement	Distilled water	8250	100
	Phosphoric acid	8140	99
	Sodium sulfate	7070	86
	Magnesium sulfate	6830	83
II Cement	Distilled water	8190	100
	Phosphoric acid	7480	91
	Sodium sulfate	6160	75
	Magnesium sulfate	6960	85
V Cement	Distilled water	6990	100
	Phosphoric acid	7320	105
	Sodium sulfate	6680	96
	Magnesium sulfate	7190	103
II with 35% Navajo Fly Ash	Distilled water	6160	100
	Phosphoric acid	5920	96
	Sodium sulfate	5610	91
	Magnesium sulfate	5500	89
II with 25% Navajo Fly Ash	Distilled water	6720	100
	Phosphoric acid	5800	86
	Sodium sulfate	4700	70
	Magnesium sulfate	4800	71
II with 25% Cholla Fly Ash	Distilled water	6340	100
	Phosphoric acid	6360	100
	Sodium sulfate	5840	92
	Magnesium sulfate	5600	88

* Fly ash content is expressed as percent total cementitious material, by weight.

TABLE 6-3. Age at Which Visible Cracking of Specimens was First Observed.

Fluid Environment *	Cementitious Material Type **					
	IP	II	V	II with 35% Navajo	II with 25% Navajo	II with 25% Cholla
Distilled Water	None	None	None	None	None	None
Phosphoric Acid	None	None	None	None	None	None
Sodium Sulfate	105	105	140	105	105	105
Magnesium Sulfate	None	140	None	None	None	None

* Samples visually examined at 28, 56, 90, 105, 120, 140 and 180 days immersion.

** Fly ash contents are expressed as percent total cementitious material, by weight

Type II cement specimens appeared to exhibit the least desirable performance. The Type IP and blended fly ash-cement specimens could not be visually differentiated, and as a group were intermediate between the Type V and Type II specimens.

All specimens were visually examined at the final test age of 180 immersion days for evidence of relative deterioration including edge and corner spalling as well as cracking. No significant visual evidence of deterioration was noted in any specimens in the distilled water or phosphoric acid control environments. In the sodium sulfate solution all specimens of all sets except the Type V exhibited cracking parallel to and close to the edges as well as deterioration of edges and corners. The Type V specimens exhibited cracks in a few specimens, but no significant edge or corner deterioration. In the magnesium sulfate solution the Type V specimens did not show any visible cracking or deterioration. All IP and cement-fly ash blend specimens evidenced edge and corner deterioration. The Type II specimens exhibited cracks close to and parallel to the edges as well as general edge and corner deterioration. Specimen appearances at immersion age 180 days are summarized in Table 6-4.

The cracks discussed here were typically about 0.05 inches (0.13 cm) from the edge of the specimen, parallel to the edge, and generally appeared on several faces of the specimen. Cracks began as barely visible hairline features, widening with time and eventually resulting in visible distortion of the adjacent surface. The edge and corner deter-

TABLE 6-4. Appearance of Specimens at Immersion Age 180 Days

Fluid Environment	Cement Type		
	IP	II	V
Distilled Water	No evidence of deterioration.	No evidence of deterioration.	No evidence of deterioration.
Phosphoric Acid	No evidence of deterioration.	No evidence of deterioration.	No evidence of deterioration.
Sodium Sulfate	Edges and corners deteriorated. Cracks parallel to edges.	Edges and corners deteriorated. Cracks parallel to edges.	Some samples cracking parallel to edges.
Magnesium Sulfate	Edges and corners deteriorated.	Edges and corners deteriorated. Cracks parallel to edges.	No evidence of deterioration.

Fluid Environment	Type II Cement with Fly Ash *		
	35% Navajo	25% Navajo	25% Cholla
Distilled Water	No evidence of deterioration.	No evidence of deterioration.	No evidence of deterioration.
Phosphoric Acid	No evidence of deterioration.	No evidence of deterioration.	No evidence of deterioration.
Sodium Sulfate	Edges and corners deteriorated. Cracks parallel to edges.	Edges and corners deteriorated. Cracks parallel to edges.	Edges and corners deteriorated. Cracks parallel to edges.
Magnesium Sulfate	Edges and corners deteriorated.	Edges and corners deteriorated.	Edges and corners deteriorated.

*Fly ash content expressed as percent total cementitious material, by weight.

ioration described here consisted of a general spalling and rounding of sharp corners and edges. Such rounding occurred spontaneously, with no brushing, handling or abrasion.

On the basis of overall visual evaluation, the cements and blends tested can be differentiated and rated. The data indicate that Type V cement was least affected by the sulfate environment. The Type IP and the Type II fly ash blends were somewhat less resistance to sulfate attack but with no clear distinction within the four sets. The Type II cement appeared to rate least resistant to sulfate attack, although by a very small margin, if at all. This evaluation, while somewhat subjective, is nevertheless considered of value. The cracking and edge deterioration were readily visible and no particular difficulty was encountered in differentiation between specimens to the extent outlined in Tables 6-3 and 6-4.

6.2.4 Expansion

Specimens of the six cement and blended cement types were subjected to laboratory determination of expansion using applicable portions of ASTM: C157-75, modified as described in the Mehta procedure previously referenced. Specimens were measured at ages 0, 28, 56 and 180 immersion days. Three bars were averaged for each reported test value.

At early ages the expansion test data were more conclusive than compressive strength data. In four of the six sets of specimens the relative pattern of comparison which emerged at 180 days age was clearly established at 28 days immersion age; however, magnitudes of expansion were, at the early ages, too small to be reliable indicators for comparison. The relationship between length change and immersion age is presented in Figure 6-2.

The test results indicate that Type V cement is clearly in a class by itself relative to the other five cements and blends tested. The relative volumetric stability of Type V is evident even in the case of the control specimens aged in distilled water. The volume change in distilled water for Type V specimens was approximately 60% of that of the remaining specimens.

The relative volume changes at the final test age of 180 days are presented in Table 6-5. From these results it appears that no clear distinction can be found between the Type IP, II and fly ash-cement blends. These specimens were all distinctly more susceptible to volume change (expansion) than the Type V. Excluding the Type V the volume changes in the control environments were essentially the same. The relative expansion results, therefore, can be used as the basis for comparison. There appears to be no significant difference between the overall behavior of the Type IP, Type II and the fly ash-cement blends.

6.2.5 Relative Performance Overall

Considering the results of visual observations, compressive strength testing and expansion testing, some limited conclusions can be drawn.

6.2.5.1 Test Procedure

The test procedure appears to offer the

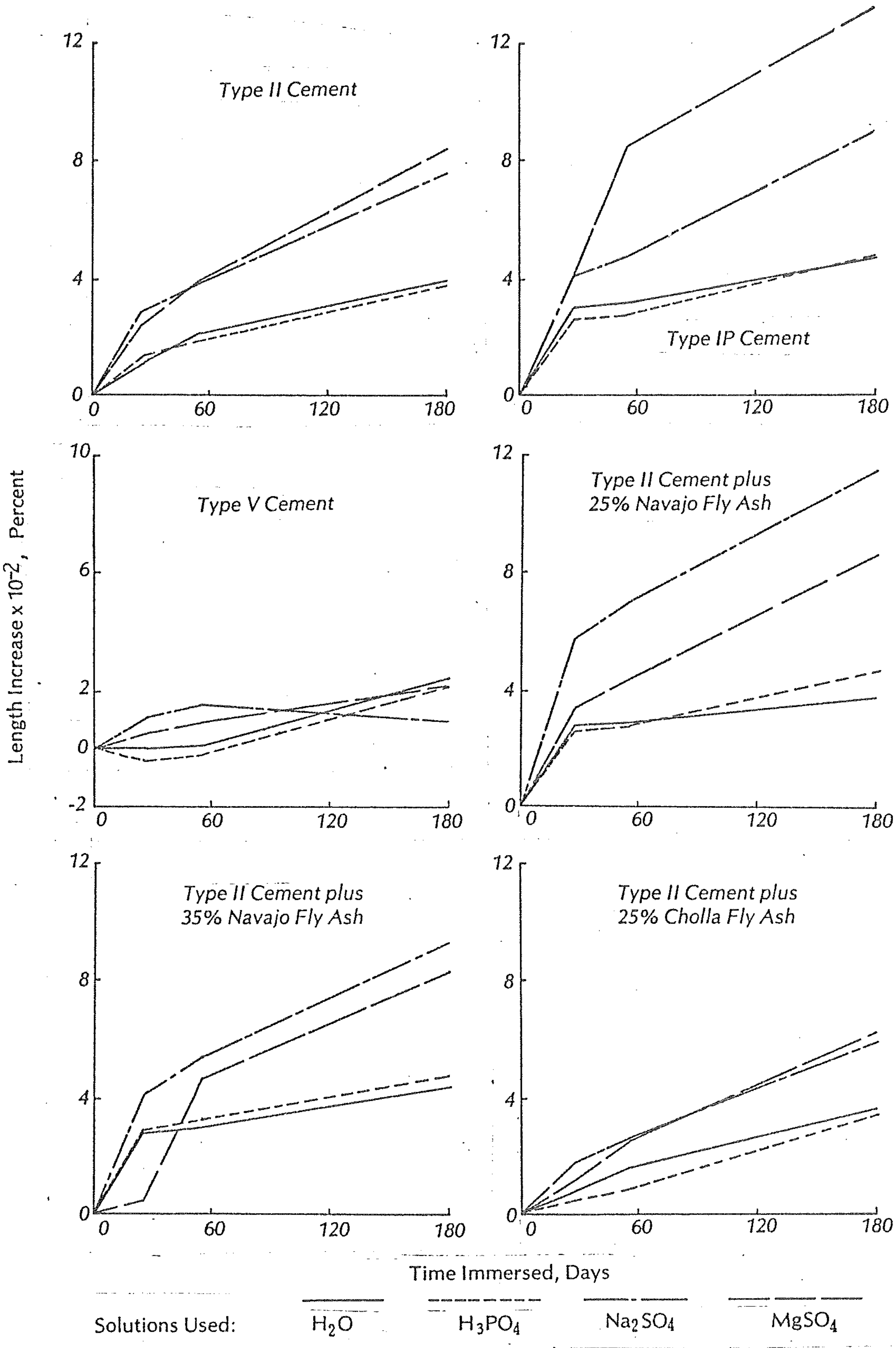


FIGURE 6-2. EXPANSION OF SULFATE IMMERSION SPECIMENS

TABLE 6-5. Expansion Test Results at Immersion Age 180 Days.

Cementitious Material Type*	Fluid Environment	Expansion %	Relative Expansion
IP Cement	Distilled water	0.047	100
	Phosphoric acid	0.048	102
	Sodium sulfate	0.090	191
	Magnesium sulfate	0.131	279
II Cement	Distilled water	0.040	100
	Phosphoric acid	0.038	95
	Sodium sulfate	0.076	190
	Magnesium sulfate	0.084	210
V Cement	Distilled water	0.024	100
	Phosphoric acid	0.021	88
	Sodium sulfate	0.006	25
	Magnesium sulfate	0.021	88
II with 35% Navajo Fly Ash	Distilled water	0.044	100
	Phosphoric acid	0.048	109
	Sodium sulfate	0.093	211
	Magnesium sulfate	0.083	189
II with 25% Navajo Fly Ash	Distilled water	0.038	100
	Phosphoric acid	0.047	124
	Sodium sulfate	0.114	300
	Magnesium sulfate	0.086	226
II with 25% Cholla Fly Ash	Distilled water	0.036	100
	Phosphoric acid	0.034	94
	Sodium sulfate	0.059	164
	Magnesium sulfate	0.062	172

* Fly ash content expressed as percent total cementitious material, by weight.

possibility of comparatively short term evaluation of cements relative to sulfate resistance. The usefulness of the test procedure would be enhanced if two improvements could be made. It would seem desirable to reduce further the period of time required for significant results to be achieved and to increase the magnitude of the results.

The author of the test procedure described the use of test specimens considerably smaller than those used in the laboratory testing for this study. The choice of the larger specimen size was based on the probability that specimens as small as 0.49 in. (1.25 cm) in dimension would result in erratic data, thereby necessitating a very large number of samples as well as a detailed rational determination of the test reliability. This reasoning still appears valid, although it may be desirable to investigate the use of smaller specimens if the test procedure is to be frequently used. It seems reasonable to assume that the higher relative surface area afforded by the smaller specimens would allow more rapid penetration of the sulfate solution and a greater degree of deterioration within any given time. Certainly greater than normal care would be necessary in the preparation of very small specimens, since minor cracks, chips or voids would have a significant effect on the effective cross sectional area and on the test results.

The effect of higher sulfate ion concentrations might also be worthy of further study relative to the rate of deterioration.

6.2.5.2 Cement Type

The relative performance of the six cement and fly ash-cement blends tested remained nearly uniform for the three evaluation procedures used (compressive strength, visual appearance and expansion). In all cases the Type V cement specimens exhibited an unquestionably greater resistance to sulfate attack than the other cement types and blends. The IP cement and the fly ash-cement blends slightly outperformed the straight Type II cement specimens except in the case of the expansion testing where no significant difference could be detected. Overall, the data appeared to indicate that the addition of fly ash in the range of proportions considered in the test series increased the resistance of the paste to sulfate attack. While some difference may exist between the sulfate resistance of the IP and the various fly ash-cement blends, a large amount of repetitive test data would be required to detect the probably slight difference in performance. It seems reasonable to assume that, if the addition of fly ash affects the resistance to sulfate attack, the test result cannot be indifferent to the proportions of fly ash in the paste.

CHAPTER 7. CONCLUSIONS

7.1 General

One objective of this study was to develop effective and practical guidelines for the use of fly ash in portland cement concrete in Arizona highway construction. The data derived from the preceding chapters was utilized in the development of a fly ash mix design procedure, presented in the following chapter. In general, the available fly ash sources were found to be beneficial admixtures in concrete. The fly ashes were found each to have unique characteristics which should be considered in the development of mix designs. The fly ash admixture modifies concrete performance and should, therefore, not be considered simply as a cement replacement. Fly ash concretes should be designed to take advantage of the changes that are effected by the admixture (cost, strength or durability). Comparisons between fly ash and normal portland cement concretes can then be made on the basis of their respective abilities to meet predetermined design criteria.

Conclusions presented herein are based primarily on test data developed in the course of the study. Comments and conclusions from reference literature are summarized in Chapter 2.

7.2 Compressive Strength

The data developed in the study indicate that fly ash concrete mixes can be reliably designed to produce a wide range of compressive strengths. Optimum mix proportions are dependent on the relative costs of fly ash and cement, efficiency of the fly ash as a pozzolan, age for which design strength is selected and the strength range itself. Strength is predictable to the degree expected of normal portland cement concrete, and the uniformity of performance is equal to or better than normal concrete in most cases.

The relative costs of fly ash and portland cement influence the optimum proportions for any desired strength level (at a given age). As the cost of fly ash increases, approaching the cost of cement, the quantity of fly ash which can be economically utilized to achieve the strength diminishes.

Efficiency of a particular fly ash as a pozzolan is discussed and defined in Chapter 8. In general, efficiency may be considered as the ratio of the weight of cement which would produce a given increase in compressive strength to the weight of fly ash which would produce a similar increase in strength. High efficiency increases the quantity of fly ash which can be effectively utilized for a given strength level.

The age at which the design strength is to be met influences mix proportions since each fly ash affects the slope of the aging curve in a difference way. Determination of the optimum ratio of fly ash to portland cement should include consideration of the change in fly ash cementing efficiency with age.

The design strength level also affects optimum mix proportions. The quantity of fly ash which can be efficiently utilized decreases with increasing strength level.

7.3 Flexural Strength

Improvements in flexural strength performance are possible, even on a one-to-one volume replacement basis, with the addition of fly ash. This advantage can be increased by the further addition of fly ash as well as by extending the design age beyond 28 days. The predictability of fly ash concrete flexural strength is at least equal to that of normal portland cement concrete.

The mix designs utilized in the study were not particularly designed to meet flexural strength objectives. Full realization of fly ash concrete flexural strength potential may require examination of mix designs which take into account the proportioning and selection of aggregates which are known to optimize flexural strength.

7.4 Freeze-Thaw Resistance

The data developed in this study indicate that the tested fly ash concretes are at least comparable to normal portland cement concretes with respect to standard laboratory freeze-thaw resistance. The relationship between laboratory freeze-thaw performance and field performance is unresolved. Historical data on field performance therefore, must eventually play an important role in evaluating the freeze-thaw durability of fly ash concrete batched with locally available fly ash, aggregate and cement.

Standard ASTM: C666-73 freeze-thaw testing may provide an unrealistic evaluation of fly ash concrete for two reasons. First, the relatively early test age of 14 days probably places fly ash concrete at a distinct disadvantage due to somewhat slower strength development. The early test age would be particularly misleading in the case of field concrete which cured for a long period before being exposed to freezing and thawing. Secondly, the optimum air content for fly ash concrete may be different than for normal concrete. Both the quantity and character of the paste are significantly affected by the addition of fly ash. The character of the void system, including but not limited to the entrained air voids, is acknowledged to control to a great extent the development of potentially disruptive pore pressures during freezing. It should not be assumed that entrained air contents historically determined as optimum for normal concrete remain the same for fly ash concrete.

In light of the above general considerations, the test data of this study appear to have established the freeze-thaw acceptability of the fly ash mixes under what might have been extremely unfavorable circumstances for comparison.

7.5 Sulfate Soundness

Relative resistance to sulfate attack appears to have been effectively differentiated by the rapid test method used in the study. The general discussion of test results, presented in Chapter 6, leads firmly to the conclusion that fly ash increases the resistance of paste to sulfate attack. The fly ash-cement blends, including Type IP blended cement are less vulnerable to attack than straight Type II cement paste. The blends, however, are significantly less resistant to sulfate attack than Type V sulfate resistant cement.

Refinement of the rapid test procedure and long term correlation with field performance (or simulated field performance) will be required if subtle differentiation of sulfate resistance is to be a serious objective of fly ash concrete evaluation.

7.6 Air Entrainment

The quantity of air entraining agent necessary to maintain a given air content is influenced not only by the presence of fly ash, but by the characteristics of the particular fly ash used. In order of AEA demand, from high to low, the ashes rank Navajo, Mohave, Four Corners and Cholla. In the test series, Navajo fly ash mixes required from 1.3

to 2.8 times more AEA than comparable Cholla mixes. The lower ratios correspond to lower total volumes of cementitious material. Fly ash generally increases the AEA demand for a given air content, compared to normal portland cement concrete.

Companion batches (A & B batches of each mix) required nearly identical AEA quantities for all the test series. Concrete for durability specimens, batched separately from that for strength specimens, differed significantly in AEA demand for comparable mixes. Indications are, from the test data, that air content can be routinely established and controlled in fly ash concrete. However, the precision with which air content can be predicted for a given proportion of AEA is unresolved and invites further study.

7.7 Economics

The relative economics of fly ash and normal portland cement concretes have been discussed throughout this report. It has been assumed throughout the study that the feasibility of fly ash concrete depended on its ability to meet a given set of design criteria while presenting a cost advantage.

Cost savings are indicated from both direct and indirect sources. Direct cost savings accrue from decreases in the absolute cost of cementitious material when a mix is designed utilizing an optimizing procedure. In general direct savings (materials cost savings) are possible so long as the fly ash efficiency factor exceeds the fly ash to cement cost ratio. Savings in quantity of fine aggregate further contribute to direct cost savings. It is expected that indirect savings will normally accrue due to the improved workability of fly ash mixes. This would result from reduced labor costs in the placing and finishing operations. Direct and indirect savings would be offset somewhat by the capital and operating costs of fly ash handling equipment at the batch plant.

The data of this study tend to indicate that overall savings equivalent to the cost of approximately one-third to one-half sack of cement per cubic yard can reasonably be expected. This is based on the condition that design criteria would be limited to compressive strength, flexural strength, freeze-thaw durability and sulfate resistance.

7.8 Fly Ash

It was pointed out in Chapter 3 that each of the fly ash samples representing ash used in the test series failed in some way to meet the ASTM: C618, Class F pozzolan specification. Nevertheless concrete batched utilizing each fly ash demonstrated that benefit could be achieved.

Four samples of fly ash, representing four sources, were used in the concrete batched for the test series. This is insufficient data for any meaningful evaluation of the correlation between specific fly ash characteristics and concrete performance. It remains to be determined, therefore, which specific fly ash characteristics are directly related to concrete performance and which, if any, are redundant.

The ASTM: C618 specification is presently under review, as was discussed in Chapter 2. Proposed changes include fineness criteria and Pozzolanic Activity Index, the areas in which the subject fly ashes generally failed to meet the specification.

It is suggested that for long term usage of locally available fly ash, the character and variability of available materials be considered in the preparation of specifications.

The purpose in this is of course to avoid eliminating materials which, if properly utilized, can be of benefit.

The requirements for Blaine fineness and Pozzolanic Activity Index with lime could probably be eliminated with no significant loss of control over fly ash quality. The Pozzolanic Activity Index with portland cement could be reduced to 75% minimum, as has been suggested by various authorities, or possibly lower since the data of this study indicates that ash can be effectively utilized even though the Index is as low as 56%.

It is believed that the concept of fly ash cementing efficiency, as described in Chapter 8, may prove valuable in determining the degree of importance of specific fly ash characteristics. Long term correlation of fly ash efficiency with fly ash test data could be used to establish the significance of specific fly ash characteristics relative to strength development (or other measures of performance).

Pending the probable future changes in the ASTM specification, and subject to the modifications suggested above, the ASTM: C618 specification provides a reasonable guideline for a highway construction fly ash specification.

CHAPTER 8. MIX DESIGN

8.1 Introduction

8.1.1 General

Mix design procedures for normal portland cement concrete have been developed and published by a number of authorities. The mix design outlines which are most widely used are probably those published by the Portland Cement Association (PCA) and the American Concrete Institute (ACI). These procedures are based on general knowledge of the relationship between the mix proportions and the expected characteristics of both the plastic and hardened concrete. Laboratory testing is usually required to verify the expected performance. Knowledge of the specific characteristics of available aggregates, cements and admixtures is always necessary if extensive trial and error is to be eliminated from the mix design procedure. Without belaboring the obvious, it can be stated that the state-of-the-art in design of concrete mixes is such that performance cannot ba calculated; it can be estimated and then must be verified by physical testing. The extent of physical testing necessary depends on the information available on the past performance of each of the particular constituents used in the mix.

The above considerations apply to the use of admixtures as well as the bulk ingredients of the mix. Fly ash has generally been considered as an admixture in this study and the tendency to consider it as a cement replacement has been avoided. This is consistent, for example, with the treatment of water reducing agents, which reduce the cement required for a target compressive strength, but are not considered as cement replacements. Fly ash differs from most admixtures in one respect which considerably complicates the mix design procedure. The fly ash is added in such quantity that the usual volume relationships which have gained general acceptance are disrupted. It is necessary to consider how these changes affect the water-cement ratio, coarse to fine aggregate ratio and other volumetric relationships which have come to be a part of concrete mix design experience.

Standardized and widely accepted procedures for fly ash concrete mix design are as yet not available within the industry. Several mix design procedures were evaluated and considered for use. For the purposes of this study, the rationale for the development of a mix design procedure consisted of several important considerations:

1) The fly ash or blended cement mix design procedure has as its objective a particular compressive strength (28 day) at a chosen consistency (slump).

2) The cost of fly ash is an important factor. To the producer fly ash concrete is economically feasible when the total cost of materials in the fly ash mix is less than the cost of materials in a comparable conventional mix. The mix design procedure should provide some rational way of selecting the optimum (minimum cost) cement-fly ash combination.

3) Fly ash is considered as an admixture in concrete, rather than as a cement replacement, and

has unique characteristics.

4) Strength and durability must be verified by laboratory testing. The fly ash mix design procedure can be no more precise than conventional portland cement mix design procedures. The complexity of the mix design procedure should be consistent with the results which can reasonably be expected.

The various mix design procedures were reviewed with these considerations in mind. Each of the procedures reviewed was found lacking in some respect relative to these criterion. A modified procedure was therefore developed to meet the particular needs of this study.

8.1.2 TVA Procedure

A mix design procedure has been developed by the Tennessee Valley Authority (TVA) based on data developed over a large number of years (12). The organization and logic of the TVA procedure appeared to be applicable to the purpose of the present study. The design charts and curves, however, are apparently unique to local conditions, costs and materials. The data developed in this study is not consistent with the predictions of the TVA procedure and the data is much too limited to attempt revision of the comprehensive TVA method. Applicable portions of the TVA procedure have been recommended for inclusion in the method developed for the present study.

8.1.3 Smith Procedure

The fly ash mix design procedure reported by Smith (88, 89) was developed for use in the United Kingdom.

This procedure is considered to be more complex than warranted, particularly considering the state-of-the-art of normal portland cement concrete mix designs. Optimization of costs is omitted completely from the method, which appears to pursue the objective of minimum cement content for a selected workability and strength. While not a technical objection, the Smith procedure suffers the practical objection of not being generally compatible with the normal mix design methods in use in the United States. One aspect of the Smith approach was considered to be particularly relevant to the objectives of this study. An efficiency factor was introduced into the mix design procedure relating fly ash to portland cement. This concept is used in the mix design method suggested herein, and is particularly applicable since the four fly ash sources studied appeared to differ markedly in cementing efficiency (at a given age).

8.1.4 Lovewell-Hyland Procedure

The proportioning technique presented by Lovewell and Hyland (46) is straightforward and apparently well founded. The authors are careful to point out that considerable background information on the specific materials under consideration is necessary before reliable design curves can be developed. The procedure does not include cost optimization as a design criterion and was therefore considered limited in application. Optimum fly ash content is presented as a linear function of cement content, presumably based on absolute values of compressive strength.

8.2 Proposed Mix Design Method

8.2.1 General

In general, the mix design procedure is based on a "control" conventional portland cement mix which would be expected to produce the desired strength and consistency (slump). The mix is adjusted by adding fly ash, decreasing cement, water and fine aggregate, all dependent on the cost and relative cementing efficiency of the fly ash. The compressive strength predicted by usual portland cement concrete mix design procedures is, of course, subject to some range of variation. The addition of fly ash (a new variable) adds one more degree of uncertainty to the design procedure. While the fly ash does add an additional variable to the mix design procedure, there is evidence that concrete properly designed with fly ash is more uniform, with regard to compressive strength, than a comparable normal mix.

The mix design procedure is primarily concerned with the problem of rationally proportioning the portland cement and fly ash. Considerations involving fine to coarse aggregate ratio, shape of coarse aggregate particles and the numerous other variables involved in mix designs are not considered within the scope of this discussion. Such considerations are subject to the same rules of experience which apply for normal portland cement concrete mix designs with one additional consideration. The addition of fly ash apparently tends to increase workability and finishability to the extent that coarser fine aggregates can sometimes be used than would otherwise be acceptable.

Lightweight or heavyweight concretes have not been considered in any phase of this study. The mix design procedures should be construed as applicable to normal weight concrete only.

8.2.2 Water-Cement Ratio

The initial step in the mix design procedure is the selection of the control normal concrete water-cement ratio for the desired design strength. The familiar curves presented in Figure 8-1 may be used as a guide, supplemented by local experience.

The control mixes (Type II cement, no fly ash) which were batched and tested as a part of this study are plotted on the water-cement ratio curves for general information.

8.2.3 Fly Ash to Cement Ratio

A fly ash to portland cement ratio is selected on the basis of experience or from Figure 8-2. The relationship of Figure 8-2 is based on the lowest total cost of cementitious material per unit volume of concrete. Offsetting costs which may be incurred, such as the cost of handling the additional admixture (fly ash) have not been considered; however, these factors could be easily incorporated. The cost ratio of Figure 8-2 is the ratio of unit weight costs, fly ash to portland cement.

8.2.4 Fly Ash Efficiency

An appropriate value for the cementing efficiency of the fly ash (k) must be determined. Table 8-1 is a tabulation of the values obtained from the laboratory testing in the course of this study. The cementing efficiency (k) may be considered as the

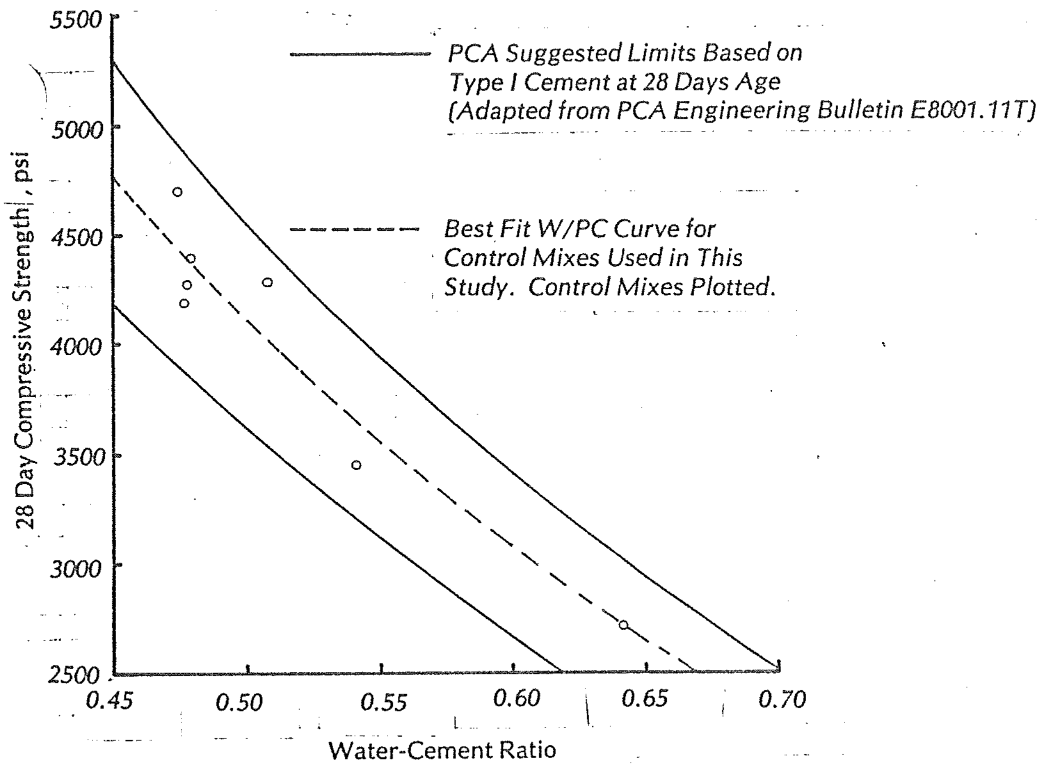


FIGURE 8-1. WATER-CEMENT RATIO CURVES FOR NORMAL PORTLAND CEMENT CONCRETE

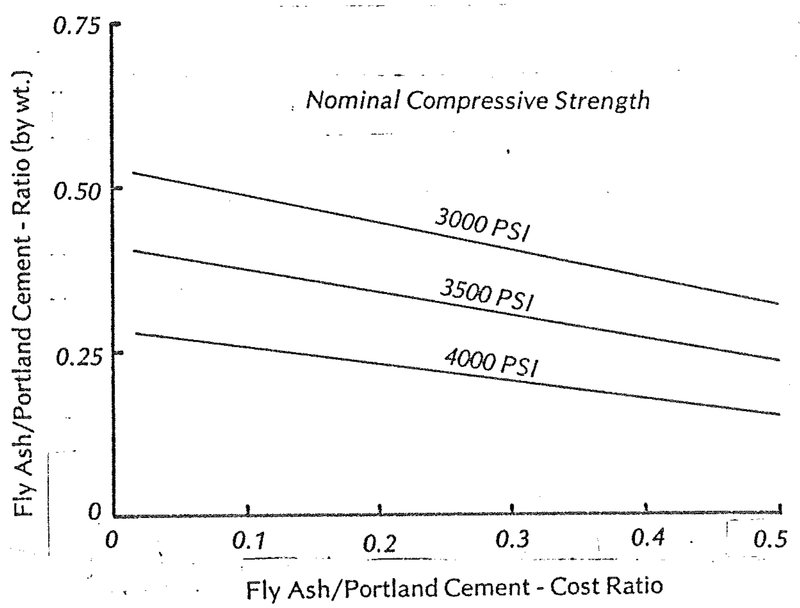


FIGURE 8-2. ECONOMIC PROPORTIONS FOR 28 DAY COMPRESSIVE STRENGTH (FROM ETL TEST DATA)

ratio of the weight of cement which would produce a given increase in compressive strength to the weight of fly ash which would produce a similar increase in strength.

8.2.5 Adjusted Water-Cement Ratio

An adjusted water-cement ratio is calculated from the relationship

$$W = W_s\ (1+kF)$$

in which:

W = water-cement ratio of fly ash concrete, by weight

W_s = water-cement ratio of the control normal mix for the desired strength

k = cementing efficiency of fly ash with respect to cement

F = fly ash-cement ratio, by weight

The adjusted water-cement ratio is based on portland cement; fly ash is not considered part of the cement.

8.2.6 Mixing Water

Using standard tables, supplemented by local experience, the total water necessary for the desired consistency is estimated for a normal control portland cement mix. Table 8-2 is presented as a guide in the event that local information is not available.

8.2.7 Cement Factor

The required weight of portland cement is determined from the adjusted water-cement ratio (W) and the

TABLE 8-1. Relative Fly Ash Cementing Efficiency, k.
(From ETL Test Data)

Source / Age	Cholla	Four Corners	Mohave	Navajo
28 day	0.25	0.55	0.55	0.80

TABLE 8-2. Estimated Water Requirement

Maximum size of aggregate, in.	Air-entrained concrete		
	Slump, in.		
	1 to 2	3 to 4	5 to 6
	Water, lb./cy		
3/8	310	340	360
1/2	300	325	340
3/4	275	300	315
1	260	285	300
1 1/2	240	265	285
2	225	250	265
3	210	235	-
6	185	200	-

Adapted from Recommended Practice for Selecting Proportions for Concrete (ACI 613-54).

volume of water estimated from the preceding step:

$$\text{Cement weight} = \frac{\text{water weight}}{W}$$

8.2.8 Fly Ash Factor

The weight of fly ash is calculated from the previously selected fly ash to cement ratio, F:

$$\text{Fly ash weight} = F\ (\text{cement weight})$$

8.2.9 Water Reduction

The actual water to be used in the fly ash mix is estimated by using a water reduction factor obtained from Figure 8-3, interpolating as necessary.

8.2.10 Final Proportions

The remaining constituents are proportioned using absolute volume calculations and the weights of water, fly ash and cement already determined. In general, the volume of coarse aggregate can be held constant (as compared to a normal portland cement mix) and volume adjustments can be made by adjusting fine aggregate content.

8.3 Mix Design Examples

8.3.1 Mix Number One

Target Strength - 3500 psi (246 $\frac{Kg}{cm^2}$) at 28 days

Slump - 3 ± 1 inch (7.6 ± 2.5 cm)

Air - 5½ ± 1½%

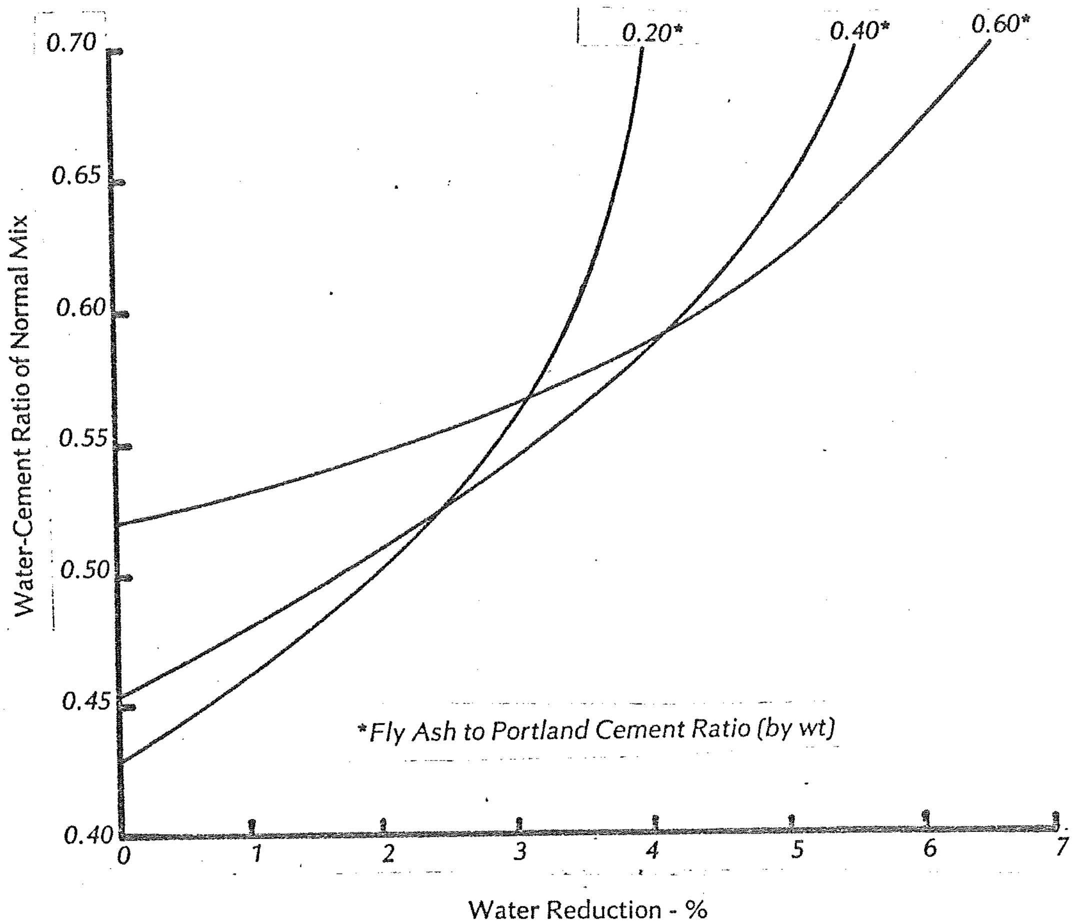
Cement - Type II (Sp. Gr. 3.13)

FA/PC Ratio - Cost ratio is 0.3

Fly Ash - Navajo (Sp. Gr. 2.25)

Coarse Aggregate - Size 57, 1 in. to #4 (2.5 to - 0.48 cm) (Sp. Gr. 2.68)

Fine Aggregate - AASHO or ASTM (Sp. Gr. 2.65)



(Adapted from Cannon, Proportioning Fly Ash Concrete Mixes for Strength and Economy)

FIGURE 8-3. WATER REDUCTION FACTOR

1) Water-cement ratio:

From Figure 8-1 select mid-range value of 0.56 unless knowledge of specific materials indicates a different value would be more appropriate.

2) Fly ash to cement ratio:

In the absence of other criteria select the ratio on the basis of optimum cost from Figure 8.2. For the given cost ratio of 0.30, the fly ash cement ratio is estimated at 0.30.

3) Fly ash efficiency:

Table 8-1 indicates a value of 0.80 for the Navajo fly ash source.

4) Adjusted water-cement ratio:

$$W = W_s \ (1+kF)$$
$$= 0.56 \ [1+(0.80)(0.30)]$$
$$= 0.69$$

5) Control mixing water:

Estimate by interpolation from Table 8-2, for 1 in. aggregate size, 279 lb. (165 $\frac{Kg}{m3}$).

6) Cement factor:

Using the estimated control mixing water and the previously determined control water-cement ratio, the required cement weight = $\frac{279 \text{ lb.}}{0.69}$ = 404 lb. (240 $\frac{Kg}{m3}$).

7) Fly ash content:

Using the previously established fly ash to cement ratio and the cement weight, fly ash content = 0.30 (404 lb.) = 121 lb. (72 $\frac{Kg}{m3}$).

8) Water reduction:

A water reduction factor of 4.6% is estimated from Table 8-3, by interpolation. Adjusted mixing water is calculated as 279 lb. - 0.046 (279 lb.) = 266 lb. (158 $\frac{Kg}{m^3}$).

9) Final proportions:

The proportions and weights of the aggregates are determined from experience with local materials and specific use, or estimated from ACI, PCA or other mix design tables. In this example a coarse aggregate weight of 1850 lb. (1097 $\frac{Kg}{m^3}$) was selected. Volumes of constituents can be calculated from the previously determined weight and the known specific gravities. The one cubic yard batch is completed by filling out the remaining volume with fine aggregate.

	Weight lb. (Kg)		Volume ft^3 (m^3)	
Cement (4.3 sk.)	404	(183)	2.07	(.0586)
Fly ash	121	(55)	0.86	(.0243)
Water (31.9 gal.)	266	(121)	4.26	(.1206)
Coarse Agg.	1850	(839)	11.06	(.3131)
Fine Agg.	1200	(544)	7.26	(.2055)
Air (5½%)	0		1.49	(.0422)
	3841	(1742)	27.00	(.7644)

Plastic Unit Wt. 142.3 $\frac{lb.}{ft^3}$ (2280 $\frac{Kg}{m^3}$)

8.3.2 Mix Number Two

Target Strength - 3000 psi (211 $\frac{Kg}{cm^2}$) at 28 days

Slump - 3 ± 1 inch (7.6 ± 2.5 cm)

Air - 5½ ± 1 1½%

Cement - Type II (Sp. Gr. 3.13)
FA/PC Ratio - Use 25% by volume (arbitrarily selected)
Fly Ash - Cholla (Sp. Gr. 2.17)
Coarse Aggregate - Size 57, 1 in. to #4 (2.5 to 0.48 cm) (Sp. Gr. 2.68)
Fine Aggregate - AASHO or ASTM (Sp. Gr. 2.65)

1) Water-cement ratio:
   From Figure 8-1 select the mid-range value of 0.61 unless knowledge of local materials would suggest a higher or lower value.

2) Fly ash to cement ratio:
   The given value of 25% by volume must be converted to a weight ratio. Using the specific gravities of the cement and fly ash,

$$F = 0.25 \text{ by vol. or } \frac{0.25\ (2.17)}{1.00\ (3.13)} = 0.17 \text{ by wt.}$$

3) Fly ash efficiency:
   From Table 8-1 the value of k is 0.25.

4) Adjusted water-cement ratio:

$$\begin{aligned} W &= W_s\ (1+kF) \\ &= 0.61\ (1+(0.25)(0.17)) \\ &= 0.64 \end{aligned}$$

5) Control mixing water:
   Estimate by interpolation from Table 8-2, for 1 in. (2.5 cm) aggregate size, 279 lb. (165 $\frac{Kg}{m^3}$).

6) Cement factor:
   Using the estimated control mixing water and the previously determined control water-cement ratio,

the required cement weight = $\frac{279 \text{ lb.}}{0.64}$ = 436 lb. (259 $\frac{Kg}{m^3}$).

7) Fly ash content:

Using the previously established fly ash to cement ratio and the cement weight, fly ash content = 0.17 (436 lb.) = 74 lb. (44 $\frac{Kg}{m^3}$).

8) Water reduction:

A water reduction factor of 3% is estimated from Figure 8-3. Adjusted mixing water is calculated as 279 lb. - .03 (279 lb.) = 271 lb. (161 $\frac{Kg}{m^3}$).

9) Final proportions:

The proportions and weights of the aggregates are determined from experience with local materials and specific use, or estimated from ACI, PCA or other mix design tables. In this case a coarse aggregate weight of 1840 lb. (1091 $\frac{Kg}{m^3}$) was selected Volumes of constituents can be calculated from the previously determined weights and the known specific gravities. The one cubic yard (0.76 m^3) batch is completed by filling out the remaining volume with fine aggregate.

	Weight lb.	(Kg)	Volume ft^3	(m^3)
Cement (4.64 sk.)	436	(198)	2.23	(.0631)
Fly Ash	74	(34)	0.55	(0.156)
Water (32.5 gal.)	271	(123)	4.34	(.1229)
Coarse Agg.	1840	(835)	11.00	(.3114)
Fine Agg.	1224	(555)	7.40	(.2095)
Air (5½%)	0		1.49	(.0422)
	3845	(1744)	27.00	(.7647)

Plastic Unit Wt. 142.4 $\frac{lb.}{ft^3}$ (2280 $\frac{Kg}{m^3}$)

8.4 Evaluation of Mix Design Procedure

8.4.1 General

The proposed mix design procedure is based on the concept that the water-cement ratio, revised to account for fly ash, is alone sufficient to predict compressive strength within reasonable practical limits. The adjusted water-cement ratio for a fly ash mix is dependent on certain characteristics of the fly ash, expressed in terms of the fly ash efficiency factor, k. A value for the efficiency factor must be determined, by laboratory testing, in order to utilize the mix design procedure with various combinations of cements, aggregates and admixtures. The purpose of this section will be to evaluate the mix design procedure relative to the available laboratory data and to attempt to define the efficiency factor more clearly. Particularly, the limits within which a given efficiency factor can be expected to be valid will be discussed.

8.4.2 Fly Ash Efficiency

The concept of a fly ash efficiency factor (k) is utilized in the mix design procedure for the purpose of making the most efficient (economical) use of a given fly ash. In the proposed procedure, values for the k factor are listed (Table 8-1) for the four fly ash sources used in the study. The data of this study suggests that the fly ash efficiency is dependent on age as well as source. It should be emphasized, therefore, that the values of Table 8-1 are applicable to 28 day compressive strength only.

A comparison of the data in Tables 5-1 and 8-1 indicates that the fly ash 28 day compressive strength efficiency is inversely proportional to the rate of strength gain at a later age (60 to 360 days). The Cholla fly ash source shows the highest rate of strength gain after 60 days, but the lowest efficiency at 28 days. The Navajo source shows the opposite extreme comparison and the Mohave and Four Corners sources are intermediate. This relationship indicates that the reactions which are necessary for strength gain proceed at different rates for the various fly ashes, and that the efficiency at 28 days is not directly indicative of the efficiency at any later age.

The values of fly ash efficiency (k) are tabulated in Table 8-3 for the four sources and for ages 28, 60 and 90 days. The individual k values for each mix design series were obtained by working backwards through the mix design procedure, using the actual batch weights and compressive strength results. Overall values for each source and age (representing the several combined series for each source) were then determined in two ways. Arithmetic averaging was used to obtain the values in the right-hand columns of Table 8-3. The values in the left-hand columns were obtained by an iterative process minimizing the error of the predicted versus actual portland cement content obtained by the mix design method, using an assumed value of k. The errors in predicted versus actual portland cement content were summed algebraically for each source and the process was repeated until the k value corresponding to a minimum algebraic sum of error was located.

It will be immediately noted that the k values in Table 8-3 differ slightly from the values suggested

TABLE 8-3. Fly Ash Efficiency

Fly Ash Source	k, computed by minimization of error in cement prediction			k, computed by averaging		
Cholla	0.25	0.31	0.39	0.31	0.41	0.48
Four Corners	0.61	0.51	0.53	0.66	0.47	0.44
Mohave	0.57	0.23	0.16	0.63	0.22	0.12
Navajo	0.88	0.80	0.53	0.90	0.78	0.47
All Sources	0.52	0.45	0.41	0.58	0.48	0.43
	28	60	90	28	60	90
	Age, Days					

in Table 8-1. The data of Table 8-1 represents suggested nominal values for use in mix design development. Some subjective judgment was involved in the selection of the suggested values. The numbers were rounded downward somewhat to provide a conservative estimate and to temper the influence of unusually high k values noted at very low fly ash to portland cement ratios. Any continued use of the proposed fly ash mix design method should be accompanied by a continuous refinement of the value of k, as more data is accumulated.

The change in apparent fly ash efficiency with time is illustrated in Figure 8-4. The Cholla, Navajo and Four Corners fly ashes exhibit a well-defined trend. The efficiencies are widely separated at age 28 days but tend to converge at age 90 days. The Mohave fly ash apparently performs in a manner significantly different than the remaining three. The Mohave efficiency decreased with time exhibiting a considerably lower value of efficiency at 90 days age.

Viewed another way the Cholla fly ash differs from the other three. The Cholla efficiency increases with age while the others decrease.

No obvious explanation is found for these differences in behavior between the sources. Mix designs based on ages later than 28 days should take into account the adjusted value of k for the particular design age.

8.4.3 Mix Design Reliability

To properly assess the validity of the proposed design procedure, the economic relationship,

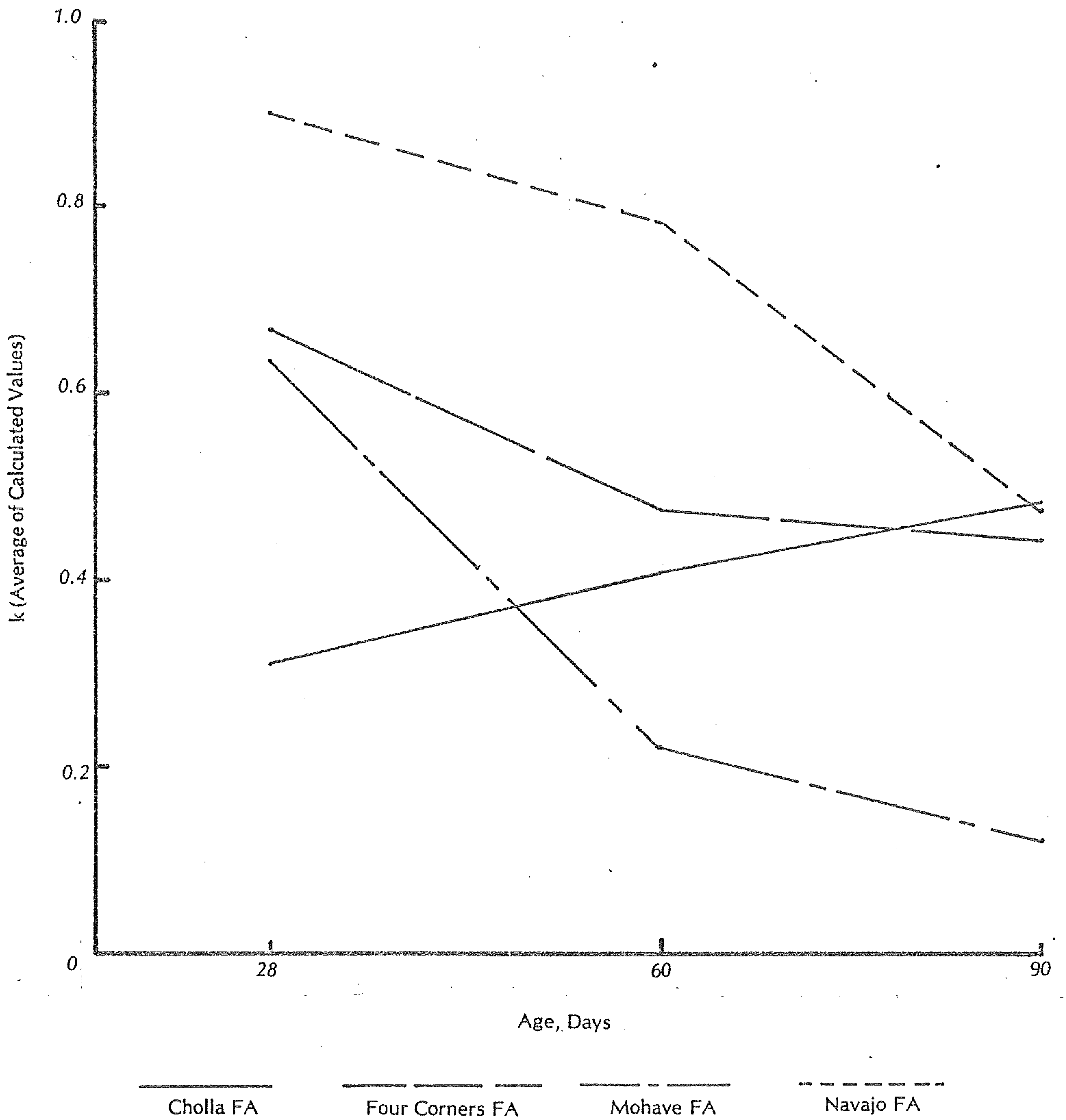


FIGURE 8-4. FLY ASH EFFICIENCY AS A FUNCTION OF AGE

typically Figure 8-2, should be developed for the specific fly ash source. Technically this relationship is a function of the cementing efficiency of the fly ash. The wide range of cementing efficiencies observed in this study resulted in different economic relationships for the fly ashes, particularly for the high and low efficiency values. Figure 8-5 contains the resulting relationships. A band has been shown encompassing all cementing efficiency factors within the range of 0.25 and 0.80 for each 500 psi (35 $\frac{Kg}{cm^2}$) compressive strength range. It is noted that the relationship for a k = 0.80 typically results in a fly ash to portland cement ratio about 0.04 higher than for a fly ash with a cementing efficiency of 0.25.

Using the actual test cylinder compressive strengths of each mix as the target design strength for initiating the proposed design procedure, the predicted portland cement content was determined for each fly ash mix. Interpolation was employed when using Figure 8-5. Comparison of the actual and predicted cement contents can be gained from Figure 8-6; the data is based upon an assumed fly ash to portland cement cost ratio of 0.3. The tabulated data on which Figure 8-6 is based is presented in Table 8-4.

8.4.4 Adjusted Water-Cement Ratio Curves

A general relationship can be shown to exist between compressive strength and an adjusted water-cement ratio for the fly ash mixes. The relationship is based on what might be termed "equivalent cement". Equivalent cement content is the sum of the portland cement weight in the mix plus the product of the fly

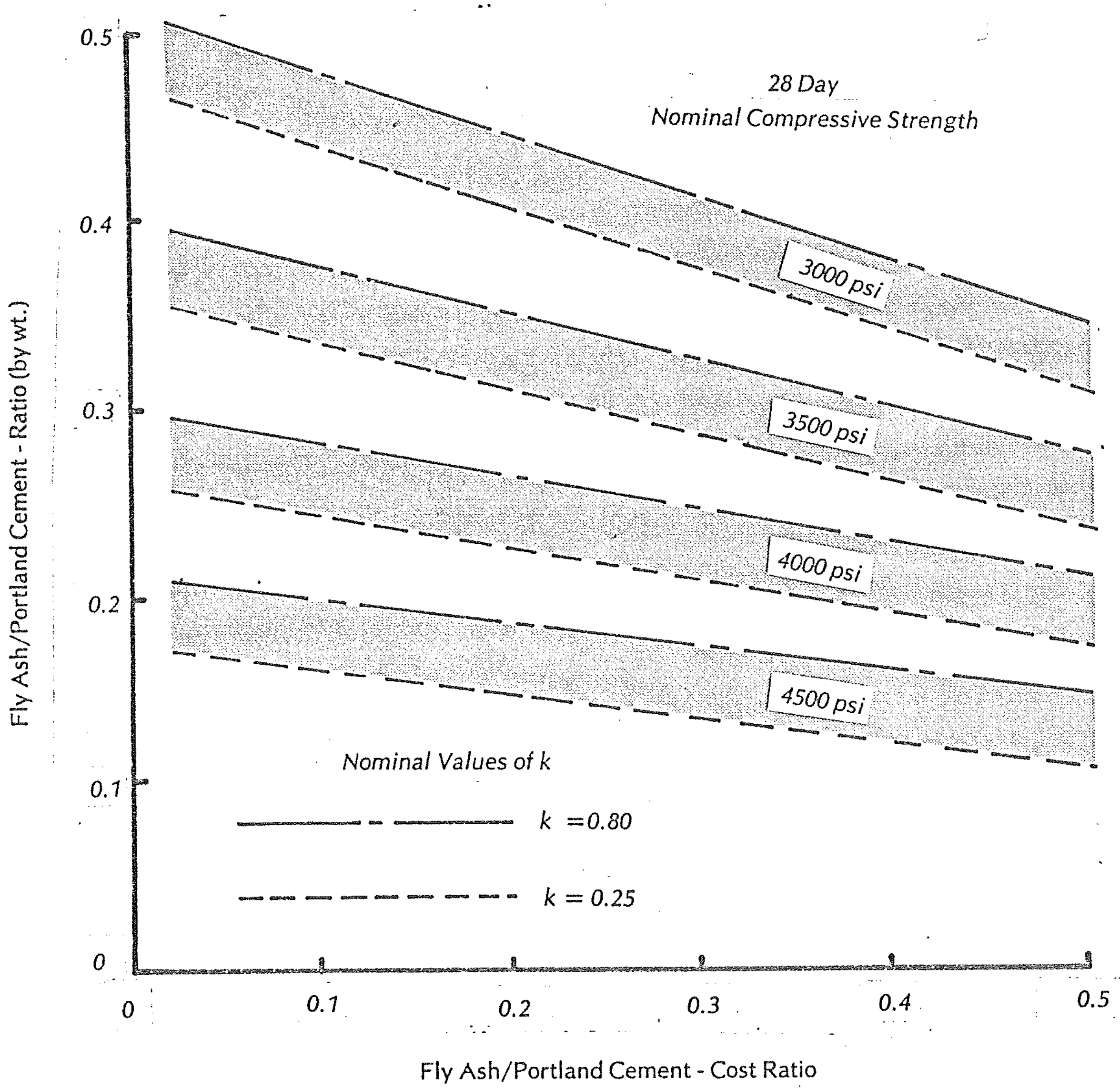


FIGURE 8-5. ECONOMIC RELATIONSHIPS BASED ON TEST DATA

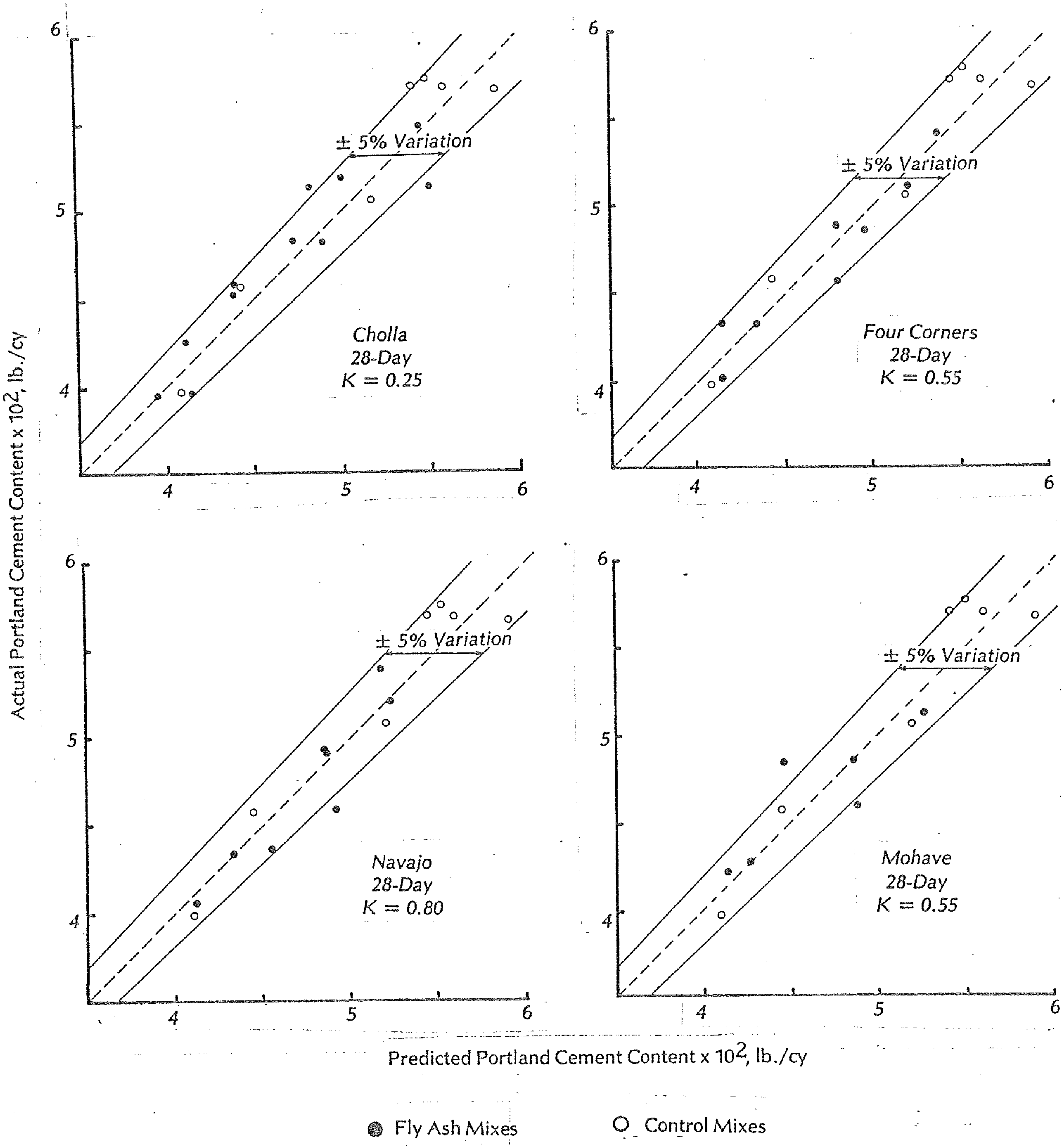


FIGURE 8-6. CEMENTING EFFICIENCY FACTOR CORRELATION

TABLE 8-4. Comparison of Portland Cement Contents

Mix	Actual Compressive Strength (psi)	Actual PC (lb./cy)	Predicted PC (lb./cy)	$\frac{\text{Predicted PC}}{\text{Actual PC}} - 1$
C-1-1	4400	513	541	.055
C-1-1A	3820	518	481	-.071
C-1-2	3190	458	424	-.074
C-1-3	3010	397	408	.028
C-2-2	3870	483	486	.006
C-2-3	3130	422	417	-.012
C-3-1	4530	544	554	.018
C-3-2	3770	483	477	-.012
C-3-3	3100	425	416	-.021
C-5-1	4020	513	501	-.023
C-5-2	3630	452	463	.024
C-5-3	3180	396	422	.066
F-1-1	4160	512	483	-.057
F-1-2	3930	457	457	.000
F-1-3	3370	402	401	-.002
F-2-2	4010	489	468	-.043
F-2-3	3700	432	434	.004
F-3-1	4610	540	537	-.006
F-3-2	4420	486	513	.056
F-3-3	3660	432	429	-.007
M-1-1	4290	512	500	-.023
M-1-2	4140	460	482	-.048
M-2-2	3710	485	436	-.101
M-2-3	3640	421	428	.017
M-3-2	4500	484	524	.083
M-3-3	4110	427	478	.119
N-1-1	4330	520	476	-.085
N-1-2	4340	458	477	.041
N-1-3	3750	406	437	.076
N-2-2	4410	489	486	-.006
N-2-3	4440	434	459	.058
N-3-1	4700	540	529	-.020
N-3-2	4720	491	530	.079
N-3-3	4520	432	501	.160

ash weight and the fly ash efficiency factor (k). Using the actual test compressive strengths and the actual adjusted water-cement ratios, based on batch weights for each mix, the curves of Figures 8-7a, b and c were developed. The curves represent a least squares best fit of the data to exponential curves of the general form $Y = Ae^{BX}$ in which:

Y = compressive strength
A, B = constants
e = natural logarithm base
X = equivalent (adjusted) water-cement ratio

The curves are based on the test data developed in the course of this study only. Control mix data points are included for which the equivalent water-ratio simply reduces to an ordinary water-cement ratio. The curves should not be considered as universal, due to the limited data involved. The control mixes have also been fitted by separate curves on Figures 8-7a, b and c for comparison. The control mix curve of Figure 8-7a was shown previously on Figure 8-1 indicating the position of the test data relative to the PCA Type I cement 28 day design curves.

The purpose of the curves in Figures 8-7a, b and c is to provide some guidance in the evaluation of probably compressive strengths for proposed fly ash concrete mix designs.

The curves for 28, 60 and 90 day ages are remarkably consistent in trend. The curves are dependent on the fly ash efficiency (k) values selected for each source. Independent values of k have been determined

Data Included	Constant A*	Constant B*	Coefficient of Determination	Symbol
Fly Ash and Control	14,425	-2.544	0.760	— — — —
Fly Ash Only	13,484	-2.416	0.699	——— - ———
Control Only	17,716	-2.919	0.943	————

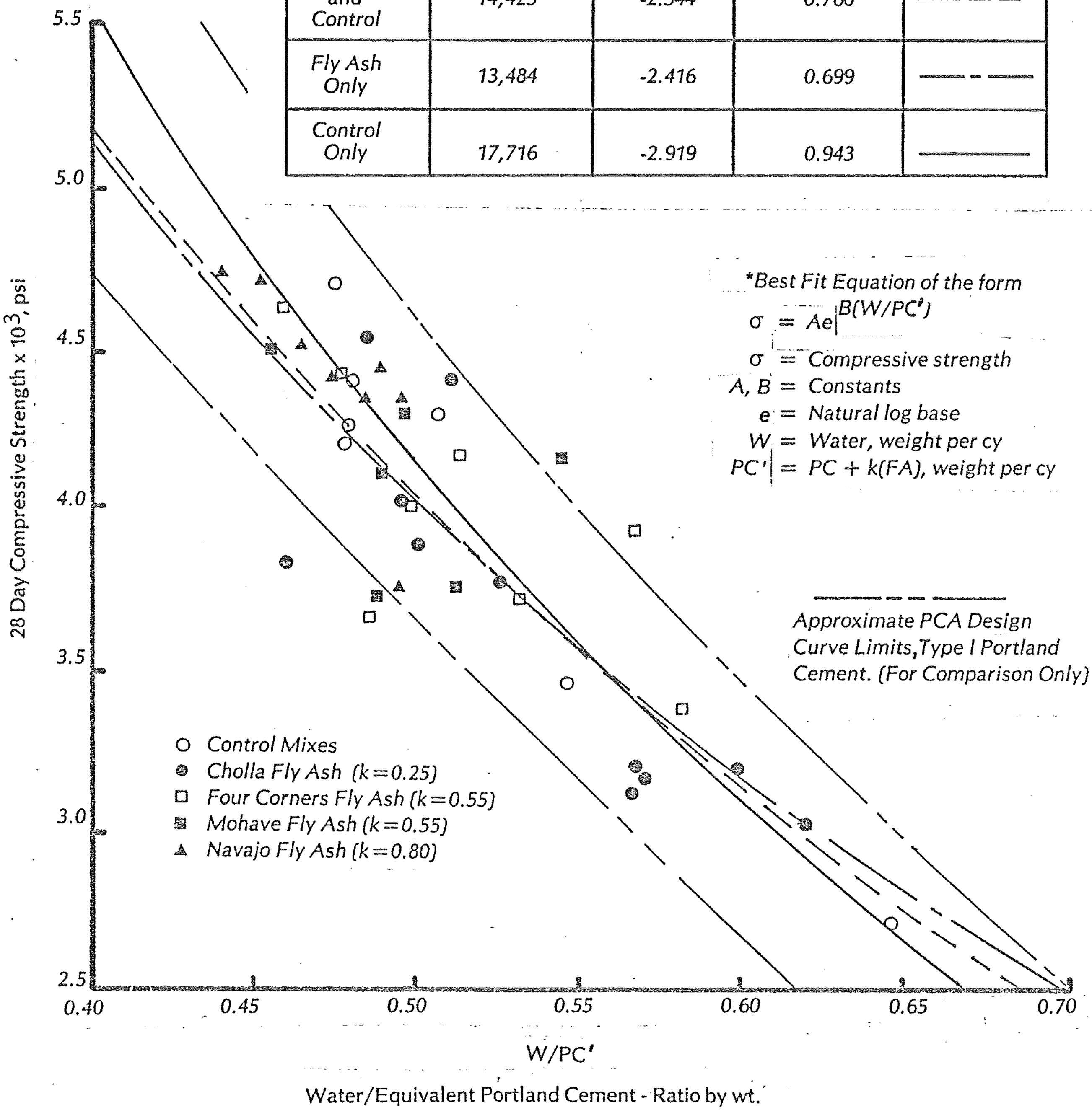
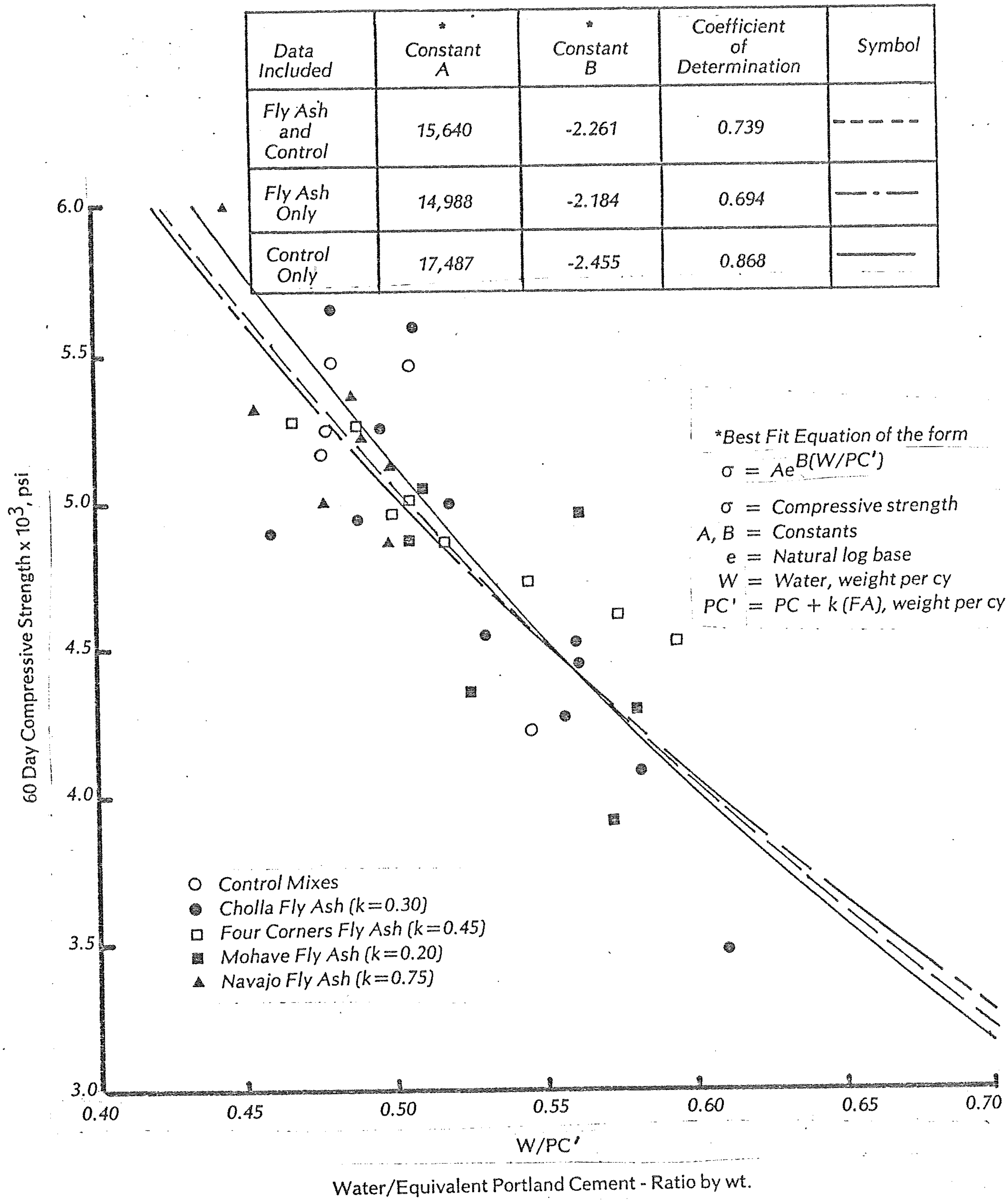
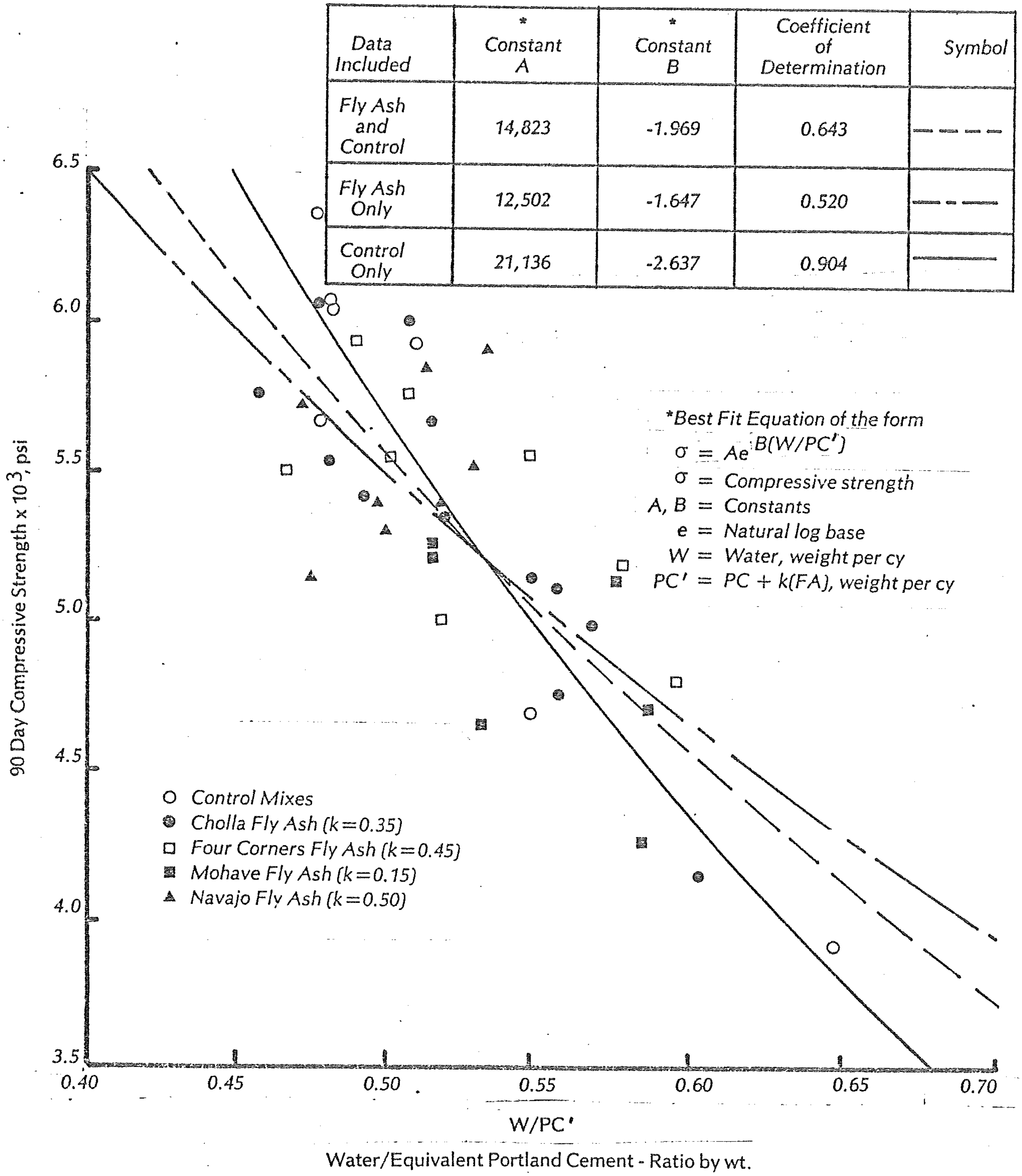


FIGURE 8-7A. ADJUSTED WATER-CEMENT RATIO CURVES FOR 28 DAY AGE



Data Included	Constant A*	Constant B*	Coefficient of Determination	Symbol
Fly Ash and Control	15,640	-2.261	0.739	– – – – –
Fly Ash Only	14,988	-2.184	0.694	—— - ——
Control Only	17,487	-2.455	0.868	———

FIGURE 8-7B. ADJUSTED WATER-CEMENT RATIO CURVES FOR 60 DAY AGE



Data Included	* Constant A	* Constant B	Coefficient of Determination	Symbol
Fly Ash and Control	14,823	-1.969	0.643	— — — —
Fly Ash Only	12,502	-1.647	0.520	—— - ——
Control Only	21,136	-2.637	0.904	————

FIGURE 8-7C. ADJUSTED WATER-CEMENT RATIO CURVES FOR 90 DAY AGE

for each age (the values indicated in Figures 8-7a, b and c are suggested nominal values, slightly lower than the computed values of Table 8-3). Nevertheless, for each age, the curves indicate, ideally, that for the lower adjusted water-cement ratios, straight portland cement mixes can be expected to yield a higher compressive strength than fly ash mixes. The reverse is indicated for high adjusted water-cement ratios. These considerations do not evaluate the cost efficiency of the mixes. Coupled with the knowledge that the addition of fly ash improves mix workability (or lowers water demand for a given workability) the design curves suggest a preference for fly ash mixes, where workability and compressive strength are the controlling design criteria, in the lower strength ranges.

The coefficients of determination for the fly ash curves are somewhat lower than for the normal control mixes. This would tend to indicate that the water-cement ratio alone may be a more reliable strength predicter for normal portland cement mixes than for fly ash mixes. (In considering this, the relatively few data points available for control mixes should be noted). Normally a "perfect" data fit is indicated as the coefficient of determination approaches a value of one. It may be more reasonable in this case to consider the fit of the control data as the attainable goal since the portland cement is unquestionably the primary contributor to strength. In any event the curves appear to suggest a reasonably good approach for estimating the probable strength of a given mix design within a range of about plus or minus ten percent.

8.4.5 Evaluation of Given Mix Design

A proposed mix design can be evaluated with reqard to expected compressive strength by using curves similar to Figures 8-7 a, b and c. The procedure is illustrated in the example which follows.

Given the following mix design data, estimate the probable 28 day compressive strength:

Type II cement, 425 lb./cy (252 $^{Kg}/_{m^3}$)
Navajo fly ash, 135 lb./cy (80 $^{Kg}/_{m^3}$)
Water, 31.8 gal/cy (0.16 $\frac{m^3}{m^3}$)

The first step is to determine the equivalent water-cement ratio for the fly ash mix.

Water weight = W = 31.8 x 8.33 = 265 lb./cy (157 $^{Kg}/_{m^3}$).

A value of 0.80 is selected for fly ash efficiency, k, from Figure 8-7a.

Equivalent portland cement weight is calculated, using the equation given in Figure 8-7a.

$$\begin{aligned} PC' &= PC + k\ (FA) \\ &= 425 + 0.80\ (135) \\ &= 533 \text{ lb. } (242 \text{ Kg}) \end{aligned}$$

The equivalent water cement ratio is then computed as

$$W/PC' = \frac{265}{533} = 0.50$$

Compressive strength can now be estimated from Figure 8-7a. A 28 day strength of 4000 psi (281 $\frac{Kg}{cm^2}$) is indicated.

No safety factor is included in the curves of Figure 8-7a; it is assumed the reviewer will select a suitable margin, consistent with reliability of the design curves and the degree of control expected in the field. The proportions of aggregates would be evaluated in the normal way.

8.5 Economy of Mix Designs

8.5.1 Materials Costs

The relative economics of fly ash and normal concretes, as produced, can be evaluated by comparing the costs of constituent materials for two comparable mixes. The mix design example Number One from Section 8.3.1 provides a basis for such a comparison. A normal mix to meet the given design criteria would require 498 pounds of cement per cubic yard (295 $\frac{Kg}{m^3}$), based on the water-cement ratio of 0.56 and the water demand of 279 pounds (165 $\frac{Kg}{m^3}$) from Figure 8-1 and Table 8-2. The fly ash mix included 404 pounds (239 $\frac{Kg}{m^3}$) of cement and 121 pounds (72 $\frac{Kg}{m^3}$) of fly ash. Using the given cost ratio of 0.3 (fly ash to cement), the cement and fly ash would be equivalent in cost to 404 + 0.3 (121) = 440 pounds (261 $\frac{Kg}{m^3}$) of cement. A cost savings equivalent to 58 pounds of cement per cubic yard (20 $\frac{Kg}{m^3}$) is thus indicated. This example considers only the costs of cementitious materials. A slight savings from reduced fine aggregate volume would also normally accrue.

8.5.2 Placing Costs

Although no data are available on which to evaluate specific cost benefits, improved workability of fly ash concrete would be expected to produce savings compared to normal concrete. This would be due to reduction in labor for the placement and finishing operations.

8.5.3 Fly Ash Handling

The addition of fly ash during the batching operation necessitates the handling of one additional constituent. The cost of storing and handling of fly ash within the batch plant must be considered in any overall economic analysis of fly ash concrete. In general storage and handling systems are similar to those used for portland cement.

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SUBJECT INDEX TO REFERENCES

Numerous references relative to the use of fly ash in portland cement concrete have been presented in the previous section, many of which have not been directly noted in the report text. This guide is included as an aid to the identification of those references pertinent to a specific characteristic or property of fly ash and/or fly ash-portland cement mixtures which may be of particular interest to the reader. No special significance has been accorded to selected topic areas or to the ordering thereof. Several references contain material relevant to more than one selected topic area. In such cases, multiple citing of the reference has been made herein; thus, no special significance should be attached to the numerical ordering of the cited references.

Water Reduction:

12, 14, 54, 67, 73, 100 and 102.

Time of Set:

54, 69 and 104.

Curing Conditions:

9, 10 and 100.

Air Content:

40, 41, 51, 54, 66, 67, 94, 97, 98 and 100.

Volume Change:

8, 9, 13, 17, 18, 20, 28, 51, 52, 76, 95 and 97.

Creep:

44.

Permeability:

6, 8, 20, 36, 52 and 54.

Freeze-Thaw:

8, 9, 13, 17, 20, 25, 28, 29, 36, 40, 41, 42, 52, 67, 71, 95, 97, 100 and 104.

Sulfate Resistance:

13, 18, 19, 20, 26, 28, 39, 69, 73, 76, 83 and 100.

Surface Scaling:

25, 28, 41, 97 and 104.

Alkali-Aggregate Reaction:

8, 20, 43, 66, 79 and 86.

Corrosion Effects:

26, 38, 74, 83 and 85.

Proportioning Techniques:

12, 28, 31, 46, 47, 83, 84, 88 and 89.

Structural Uses:

33, 35, 39, 46, 48, 66, 82 and 83.

Highway Test Sections:

22, 28, 30, 32, 35, 39, 41, 49, 50, 59, 80, 94 and 95.

Specifications:

28, 34, 36, 37, 60, 61, 62, 68, 72, 75, 78, 90, 91, 92, 93, 103 and 105.

APPENDIX A. FLY ASH CHARACTERISTICS

A.1 Fly Ash Source Facilities

A.1.1 General

Fly ash is the finely divided residue that results from combustion of ground or powdered coal. The ash is transported from the boilers by flue gases, and can be discharged into the atmosphere or collected by mechanical or electrostatic precipitation devices. Fly ash is a pozzolan and is usually formally described as a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Particles are primarily composed of silica and alumina, with carbon, oxides of iron, calcium, magnesium and sulphur, and other minor constituents. The quality and uniformity of the ash are influenced by coal quality, plant combustion characteristics and the method of collection.

A.1.2 Coal Sources and Descriptions

The present sources of fly ash within practical hauling distance of Arizona construction sites include the Cholla, Four Corners, Mojave and Navajo power plants. Power plant locations, coal sources and typical data on coal characteristics are presented in Table A-1 and further illustrated on Figure A-1.

Coal from the Navajo Mine supplying the Four Corners Power Plant has approximately twice the ash content

TABLE A-1. Coal Sources and Characteristics

Plant	Cholla	Four Corners	Mohave	Navajo
Plant Location	Joseph City, Ariz.	Fruitland, N.M.	Laughlin, Nev.	Page, Ariz.
Coal Source	McKinley Mine Gallup, N.M.	Navajo Mine Fruitland, N.M.	Black Mesa Mine Kayenta, Ariz.	Kayenta Mine Kayenta, Ariz.
Typical Coal Data				
Heat of Combustion, BTU/lb.	10,356	8,793	12,300	11,824
Ash, %	10.58	23.41	9.8	11.3
Sulfur, %	0.52	0.63	0.4	0.55
Moisture, %	15.35	11.24	(47% Slurry)	15.4
Coal Haulage, miles	Rail 109	Rail 7 Truck 3½	Slurry Pipeline 273	Conveyor 10 Rail 80
Coal Preparation	Pulverized	Pulverized	Wet ground to 8 mesh to establish 47% slurry; dewatered, dried & pulverized at plant.	Pulverized

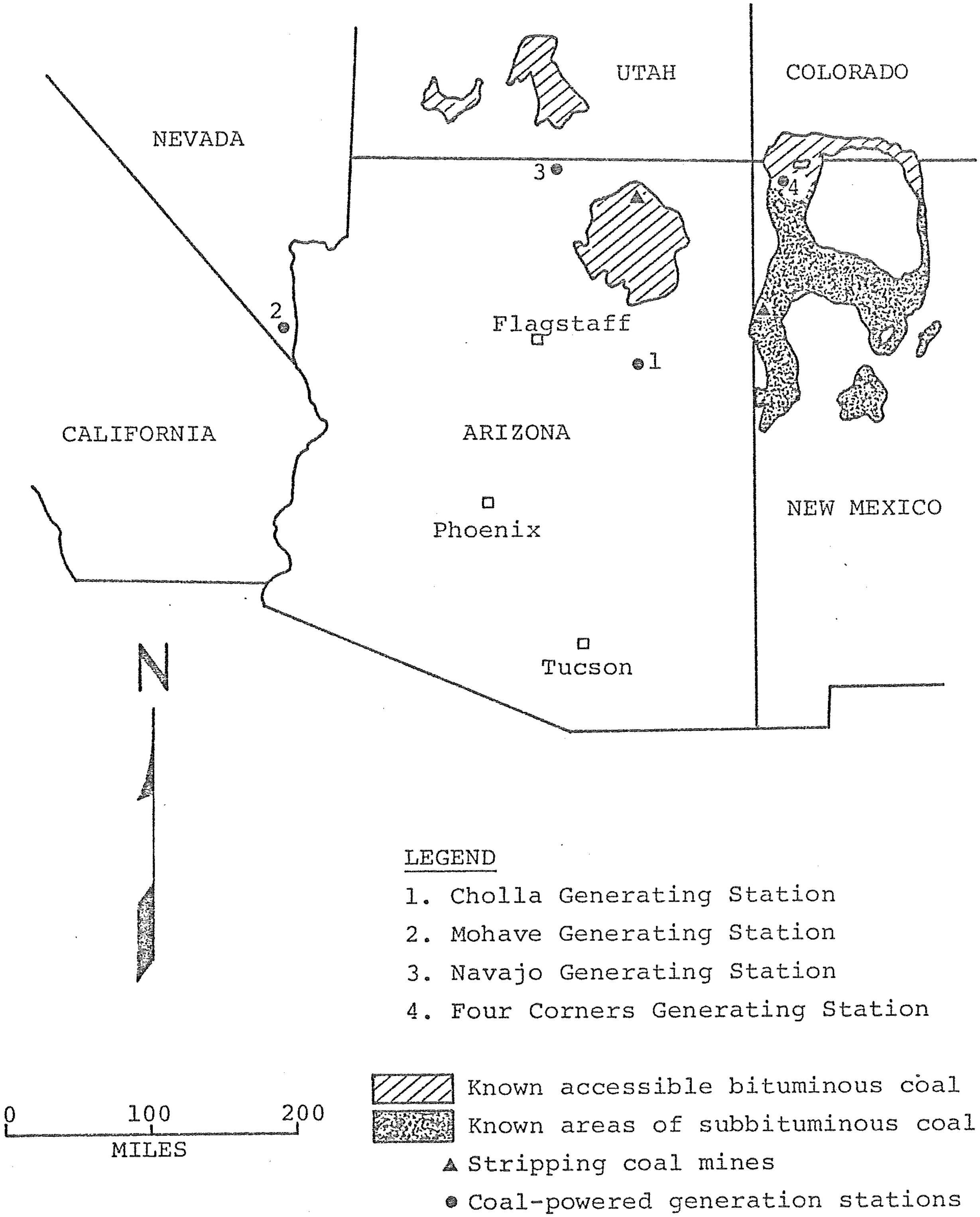

FIGURE A-1. COAL AND FLY ASH SOURCES

of the other three sources which yield typically about 10% or 11% ash.

The Mohave plant is unique in that the coal is transported as a water slurry. Preparation of slurry is accomplished by dry crushing and wet grinding to about number eight mesh size. Water introduced during the wet grinding process brings the slurry to suitable consistency for pumping 273 miles to the power plant site. Coal is delivered through an 18 inch pipeline at the rate of approximately 600 tons per hour (dewatered coal at approximately 11% moisture). The slurry is stored in tanks and agitated to maintain suspension of solids. Centrifugal dewatering, pulverizing and drying are accomplished prior to pneumatic transfer to the furnaces. Fines are also collected from the centrifuge effluent for use in the furnaces.

The Cholla, Four Corners and Navajo plants utilize pulverized coal dry transported by truck, rail and conveyor.

A.1.3 Ash Production and Collection

Information relative to the production of fly ash at the four sources is presented in Table A-2. This type of data can be used to estimate the annual production of fly ash for a plant. The following example, for the Cholla Plant, illustrates a method which can be used to estimate annual production.

$$\text{Output} = \text{Gross Load} \times \frac{\text{Boiler Heat Rate}}{\text{Coal Heating Value}} \times \text{Coal Ash Ratio} \times \frac{\text{Fly Ash Collected}}{\text{Total Ash}} \times \text{Capacity Factor}$$

TABLE A-2. Fly Ash Source Plant Characteristics

Plant	Cholla Unit 1	Four Corners Units 1 or 2	Four Corners Unit 3	Four Corners Units 4 or 5	Mohave Units 1 or 2	Navajo Units 1, 2 or 3
Gross Load, MW	116	175	220	800	790	760
Boiler Heat Rate, BTU/KWH	10,453(1)	11,308(1)	11,308(1)	10,122(1)	-	9,500
Boiler Design Pressure, psig	1,925	1,925	2,125	3,600	3,610	4,000
Superheat/Reheat Temperature °F	1,005	1,000	1,005	1,000	1008/1003	1,000
Boiler Mfgr.	Combustion Engineering	Riley Stoker Reheat Type YPR	Foster Wheeler	Babcock & Wilcox	Combustion Engineering	Combustion Engineering
Combustion Method	Corner Fired	Front Fired	Front Fired	Corner Fired	Tangential Fired	Tangential Fired
Coal Consumption, Tons/Hr.	54.30(1)	90(2)	115(2)	552(1)	330(2,3)	333
Capacity Factor	0.94(1)	0.66(1)	0.66(1)	0.60(1)	0.57(4)	0.8(4)

Notes: (1) 1974 Yearly Average
(2) Full Load
(3) Dry Coal
(4) 1975 Average

TABLE A-3. Fly Ash Collection Systems

Plant	Cholla Unit 1	Four Corners Units 1 or 2	Four Corners Unit 3	Four Corners Units 4 or 5	Mohave Units 1 or 2	Navajo Units 1, 2 or 3
Fly Ash Collection Equipment	Mechanical Collector & Wet Scrubber	Wet Scrubber	Wet Scrubber	Electro-static Precipita-tors	Electro-static Precipitators	Hot Electrostatic Precipitators
Fly Ash Recovery Method	Water Ejector	Wet	Wet	Pneumatic	-	Pneumatic
Ratio of Fly Ash / Total Ash	0.8	0.8	0.8	0.8 nominal	0.7	0.8
Estimated Dry Fly Ash Recovery:						
% of Fly Ash	65	0	0	100	100	100
Tons/year, each unit	27,000	0	0	480,000	110,000	190,000
Tons/year, Plant total	27,000	0	0	1,000,000	220,000	600,000

For the Cholla Plant:

$$\text{Output} = 116000\text{KW} \times 10453 \frac{\text{Btu}}{\text{KWH}} \times \frac{1}{10356} \frac{\text{lb.}}{\text{Btu}} \times$$

$$0.106 \frac{\text{lb.}}{\text{lb.}} \times 0.94 \times 0.65(0.8) \times$$

$$8760 \frac{\text{Hr.}}{\text{Year}} \times \frac{1}{2000} \frac{\text{Ton}}{\text{lb.}} = 27000 \frac{\text{Ton}}{\text{Year}} \text{ Fly Ash}$$

The methods of fly ash collection for the four plants are summarized in Table A-3. Fly ash recovery rates are approximations and should be expected to vary at each plant due to variations in plant operation and coal quality. Fly ash dry recovery rates given are based on nominal coal burn rates rather than unit load and heat rates.

A.2 Fly Ash Quality and Uniformity

A.2.1 Fly Ash Uniformity

During the course of the study samples were obtained from the various sources on a periodic but irregular basis. Many of the samples were obtained in connection with work unrelated to this study. Samples were generally subjected to all or a portion of the test series outlined in ASTM Designation: C618, Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolans for Use in Portland Cement Concrete. A summary of test results is presented in Tables A-4a and A-4b, including Chicago fly ash for comparison. In each case, the number of test results, the average result and the range of variation are given. Where ten or more test results are available the standard deviation and coefficient of variation are computed and listed. The averages in Table A-4a and A-4b are the arithmetic means of the test results available in each case. (The number of test results for each

TABLE A-4a. Fly Ash Uniformity

PROPERTY*	NAVAJO					MOHAVE				
	Average	Number of Samples	Standard Deviation	Coefficient of Variation, %	Range	Average	Number of Samples	Standard Deviation	Coefficient of Variation, %	Range
SiO_2 %	53.06	29	4.86	9	39.11-60.90	51.58	31	3.77	7	41.72-59.96
Al_2O_3 %	17.93	29	3.34	19	10.16-21.43	17.51	31	2.48	14	10.13-21.71
Fe_2O_3 %	4.80	29	0.85	18	2.63-6.44	4.89	31	0.65	13	3.45-6.06
Sum of oxides %	76.00	30	7.48	10	51.90-84.78	73.87	32	4.26	6	66.20-84.01
MgO %	2.18	30	0.66	30	0.63-3.44	1.87	32	0.59	32	0.74-3.28
SO_3 %	0.54	27	0.56	103	0.06-2.28	0.80	29	0.15	19	0.55-1.18
Moisture %	0.035	28	0.031	90	0-0.13	0.036	29	0.023	64	0.001-0.070
Loss on Ignition %	0.97	27	0.48	49	0.42-2.77	1.40	32	0.68	48	0.50-3.68
Available Alkalies As Na_2O %	0.99	22	0.26	26	0.48-1.57	1.10	32	0.21	19	0.44-1.46
Fineness										
Surface Area cm^2/cm^3	7500	8	-	-	6450-8236	10139	31	1275	13	5475-13561
Retained #325 %	25.3	50	4.7	19	14.9-36.8	30.7	61	8.6	28	15.3 -75.5
Multiple Factor %	24.4	27	15.9	65	9.8-95.3	36.8	29	18.6	50	9.9 -70.0
Pozzolanic Activity Index:										
Cement, % control	87.2	30	8.0	9	63.2-98.2	90.2	28	8.9	10	60.8-102.9
Lime, psi	714	16	172	24	579-1340	695	30	124	18	368-995
Water requirement % of control	96.7	27	1.5	2	94.8-100.5	97.0	28	1.7	2	93.0-99.3
Shrinkage, Increase %	0.011	16	0.005	51	-0.002-0.019	0.007	25	0.008	114	-0.015-0.020
Soundness, Autoclave %	0.044	19	0.010	23	0.030-0.070	0.065	12	0.025	37	0.043-0.130
Expansion-14 day %	0.017	6	-	-	0.005-0.027	0.024	23	0.010	43	0.012-0.054
Air-Entraining Admixture ml.	0.92	16	0.27	29	0.60-1.40	1.02	24	0.27	27	0.60-1.80
Specific gravity	2.25	56	0.11	5	2.10-2.70	2.37	60	0.06	2	2.26-2.50

*ASTM: C618 Test Series for Class F Pozzolan

TABLE A-4b. Fly Ash Uniformity

PROPERTY*	CHOLLA			FOUR CORNERS			CHICAGO
	Average	Number of Samples	Range	Average	Number of Samples	Range	Sample**
SiO_2 %	59.6	5	58.4-60.7	58.3	6	57.0-59.7	50.2
Al_2O_3 %	21.1	5	14.2-31.4	24.2	6	18.2-31.4	21.1
Fe_2O_3 %	3.64	5	1.3-5.7	3.18	6	0.8-3.9	12.4
Sum of oxides %	84.3	5	78.3-91.1	85.7	6	80.3-90.6	83.7
MgO %	1.28	4	0.8-1.7	1.33	5	0.81-2.55	2.2
SO_3 %	0.138	5	0.02-0.30	0.168	5	0.02-0.66	1.02
Moisture %	0.020	5	0.01-0.05	0.0283	6	0.01-0.05	0.06
Loss on Ignition %	0.64	5	0.6-2.85	0.623	6	0.21-1.35	1.53
Available Alkalies As Na_2O %	0.51	5	0.28-0.70	0.62	6	0.23-0.95	0.91
CaO %	4.46	5	3.7-5.4	3.53	6	3.10-3.84	5.9
Fineness							
Surface Area cm^2/cm^3	5096	4	4560-5461	4100	5	3350-5000	8569
Retained #325 %	36.2	1	-	45.9	5	29.8-62.3	22.7
Multiple Factor %	22.3	5	0.97-95.9	30.0	5	11.4-84.1	34.7
Pozzolanic Activity Index:							
Cement, % control	60.0	1	-	56.0	1	-	93.5
Lime, psi	-	0	-	-	0	-	895
Water requirement % of control	102	1	-	98.5	1	-	-
Shrinkage, Increase %	0.077	1	-	-	0	-	0.007
Soundness, Autoclave %	0.048	1	-	0.048	1	-	0.04
Expansion - 14 day %	-	0	-	-	0	-	-
Air-Entraining Admixture ml.	1.68	1	-	1.44	1	-	-
Specific gravity	2.17	4	2.07-2.26	1.90	5	1.85-1.93	2.53

*ASTM: C618 Test Series for Class F Pozzolan

**Single Sample for Comparison Only

source and test procedure varies through a wide range for the reasons discussed above). The range indicated in the table is simply a presentation of the highest and lowest test value encountered. The standard deviation was obtained in accordance with the usual statistical procedure, using the number of observations less one to calculate the variance (n-1). The coefficient of variation is the ratio of the standard deviation to the average, expressed as a percent. The standard deviation bears the dimensional units of the variable; the coefficient of variation is dimensionless.

The data of Tables A-4a and A-4b can be used to some extent to compare the characteristics of the four fly ashes. Certainly the data cannot be utilized in accordance with the strictest mathematical interpretation of the statistical parameters, since the number of observations is, in most cases, too limited. Some qualitative comparisons can be made, particularly for the Navajo and Mohave sources where a relatively large number of test results are available for certain characteristic properties. If the test values can be considered normal random variables, then the dimensionless coefficient of variation can be used to establish the probable total range of variation to be expected for the given variable. Substantially all test results would be expected to fall within a range defined by the average value plus and minus three times the coefficient of variation. It is realized that the preceding statement is subject to qualification based on a number of considerations, not the least of which is a determination of whether or not the data was obtained under controlled conditions. The purpose here is to simply establish a method of at least qualitative comparison of whatever data are available. It has been reasonably established elsewhere that plus and minus three times the standard deviation (or coefficient of variation in dimensionless terms) defines the range of variation about the average for substantially all expected data points (and for practical purpose "substantial" refers to greater than 95% compliance) for tests on materials and manufactured products.

With this explanation in mind, the specific gravities, for example, of the Navajo and Mohave sources can be compared. The Navajo test results appear to represent a material with a specific gravity of 2.25 $\pm$ 14.4%. The Mohave source tests indicate in the same manner a specific gravity of 2.37 $\pm$ 7.2%. Other characteristic properties can be similarly compared.

Fly ash in the present context of discussion is a by-product, or waste material, not manufactured to a set of standards. Much of the potential value, at present, lies in the fact that some benefit can be derived by using the material in the "as is" condition and thereby maintain costs at low levels (screening and other relatively inexpensive processes are occasionally being employed to improve desired characteristics). Some benefit can apparently be derived from the use of fly ash in portland cement concrete and soil stabilization irrespective of the character or quality of the ash. The potential usefulness may be proportional to, but not dependent on, compliance with some specification, such as the ASTM: C618. The process for manufacturing the end product must remain under

control, however, and to this end the variability (or uniformity) of the fly ash becomes a consideration at least as important as the absolute values of the characteristic properties. It follows that certain individual properties become more or less important depending on the end uses of the ash.
Finally if the end product, concrete or stabilized soil, or whatever, can be designed with the desired performance characteristics, then from a practical standpoint it is primarily the uniformity of the ash which is of concern rather than the individual values of the property characteristics.

The laboratory test procedures performed for these studies (both portland cement concrete and stabilized soil) utilized a single sample of fly ash with a fixed set of physical and chemical characteristics. There are no data, therefore, which may be used to assess the relationship between performance and individual fly ash characteristics. The four data points representing the four fly ash sources might be considered for this purpose. However, consideration of the variability indicated for each of the individual physical and chemical parameters quickly dispells any hope of gaining meaningful answers to this question from such limited data.

It can be readily observed from the test data that the fly ashes sampled during the course of the study did not generally comply with the requirements of ASTM Designation: C618 for Class F Pozzolans. The deviations were primarily in the area of fineness and Pozzolanic Activity Index.

The Cholla fly ash was found to be below the specified

6500 cm^2/cm^3 Blaine fineness for each of the four samples tested including the sample from the ash used in the concrete testing program. The single samples tested for the percent retained on the #325 sieve and the Pozzolanic Activity Index also failed to meet the specifications.

The Four Corners fly ash test results fall below the minimum specified Blaine fineness for each of the five samples tested, including the sample from ash used in the concrete test program. The average percent retained on the #325 sieve, for five samples, was outside the specified limit; the extreme values exceeded the limit by a considerable margin. The one test result obtained for the Pozzolanic Activity Index was also outside the specified range.

The Navajo source was sampled more extensively than the previous two sources. The 50 samples tested for percent passing the #325 sieve were substantially within the specified limit although the result corresponding to the ash used in the concrete batched for the test program was slightly out. The Pozzolanic Activity Indexes were outside specified limits for a large number of the test results.

The Mohave source was also sampled more extensively than the Cholla and Four Corners sources. The 61 samples tested for percent passing the #325 sieve indicated a broad range of variance with numerous samples outside the specified limit. The Pozzolanic Activity Indexes were also out of specification for a large number of the 30 samples tested.

A.2.2 Fly Ash Quality Variables

The fly ash characteristics defined by the test procedures of ASTM: C618 were compared to determine if any of the procedures might be redundant. A high degree of linear correlation between two of the fly ash properties might indicate that one of the properties, and therefore one of the tests, could be eliminated without sacrificing the reliability of the fly ash evaluation. The objective of any such approach would be to reduce the evaluation of fly ash to the least number of test procedures and to the most straightforward and repeatable test procedures.

The coefficient of linear correlation was computed for each combination of two variables, using the twenty principal variables of the ASTM: C618 test series. The correlation matrix is presented in Table A-5. The tabulated values are coefficients of determination (coefficient of correlation squared), written as percentages. A value of 100 would indicate precise linear correlation; zero would indicate no correlation. All of the data indicated in Tables A-4a and A-4b are included in the correlation matrix. The coefficients appear to indicate that the results of the various test procedures are in most cases relatively independent. Individual discussion of the 160 or so coefficients would be laborious and unrewarding; examination of Table A-5 will quickly reveal the variables which have any significant correlation. The coefficients are indicators of statistical correlation and no physical relationships are implied by the data.

TABLE A-5. Fly Ash Test Result Correlation Matrix (Coefficients of Determination)

	Blaine	G_s	+325	Sound.	Poz. Act. w/PC	Water Req.	LOI	SO_3	Moist.	Shrink.	AEA	Expan.	Mult. Factor	Poz. Act. w/lime	SiO_2	Al_2O_3	Fe_2O_3	Oxides	MgO	Alk. Na_2O
Blaine	100	71	8	8	48	70	20	53	25	20	0	0	3	1	38	31	15	49	10	57
G_s, Sp. Gravity		100	11	13	28	5	13	36	7	15	0	6	2	24	48	39	20	53	21	31
+325			100	8	23	17	2	6	7	0	9	13	29	21	2	6	4	3	7	3
Autoclave Soundness				100	0	2	3	2	1	3	15	43	0	11	6	0	0	2	0	4
Poz. Act. w/PC					100	41	1	31	5	11	0	7	2	7	8	10	20	7	3	16
Water Requirement						100	14	0	0	NSD	76	NSD	18	NSD	67	75	62	77	27	78
LOI, Loss on Ignition							100	8	0	NSD	NSD	NSD	88	NSD	19	6	8	15	1	19
SO_3								100	8	NSD	NSD	NSD	2	NSD	68	5	23	26	36	67
Moisture Content									100	33	1	NSD	9	NSD	6	1	8	0	9	3
Shrinkage (Drying)										100	14	6	NSD	0	1	23	9	10	2	23
AEA, Air Entraining Admixture											100	1	NSD	5	0	9	11	3	3	3
Mortar Expansion												100	NSD	1	25	0	0	15	0	0
Multiple Factor													100	NSD	22	13	14	17	1	24
Poz. Act. w/lime														100	1	0	6	0	20	21
SiO_2															100	18	7	69	10	28
Al_2O_3																100	11	67	3	15
Fe_2O_3																	100	3	0	19
Sum of Oxides																		100	7	22
MgO																			100	8
Alkalinity as Equivalent Na_2O																				100

*Not sufficient data, less than 4 results common to the two tests

APPENDIX B. TEST DATA

B.1 Concrete Mix Proportions

Batch weights, air content, slump, unit weight and temperature data representing concrete used in the preparation of test specimens are presented in this section. The tables which follow are arranged in the order listed below:

TABLE B-1 Control Mixes
TABLE B-2 Cholla Fly Ash
TABLE B-3 Four Corners Fly Ash
TABLE B-4 Mohave Fly Ash
TABLE B-5 Navajo Fly Ash
TABLE B-6 IP Cement
TABLE B-7 Freeze-Thaw Test Specimens Only

It should be noted that the concrete for freeze-thaw testing was batched separately from that used for strength testing. The batch weights and test data are, therefore, tabulated separately.

B.2 Compressive and Flexural Strength Results

Compressive and flexural strength test data are presented immediately after the mix proportion data in the following order:

TABLE B-8 Control Mixes (molded specimens)
TABLE B-9 Cholla Fly Ash (molded specimens)
TABLE B-10 Four Corners Fly Ash (molded specimens)
TABLE B-11 Mohave Fly Ash (molded specimens)
TABLE B-12 Navajo Fly Ash (molded specimens)
TABLE B-13 IP Cement (molded specimens)
TABLE B-14 Control Mixes and IP (drilled cores)
TABLE B-15 Cholla and Four Corners Fly Ash (drilled cores)
TABLE B-16 Mohave and Navajo Fly Ash (drilled cores)

TABLE B-1. Concrete Mix Proportions

Control Mixes

Series & Mix	Fly Ash (lb./cy)	Cement (lb./cy)	Water (lb./cy)	Fine Agg. (lb./cy)	Coarse Agg. (lb./cy)	Air Agent (cc/cy)	Air Content Test (%)	Air Content Calc. (%)	Slump (in.)	Unit Wt. (lb./ft^3)	Conc. Temp. (°F)
Control A1	-	577	273	1143	1989	172*	4.1	3.3	3.5	147.5	62
A2	-	572	276	1145	1989	173	4.0	3.1	3.5	147.5	65
Control B1	-	570	273	1144	1990	172*	3.8	3.4	2.5	147.3	63
B2	-	571	273	1144	1992	172	4.0	3.3	2.5	147.4	66
Control C1	-	570	270	1142	1989	272	4.5	3.6	3.5	147.1	60
C2	-	567	271	1137	1978	271	4.5	4.0	3.25	146.4	-
0-0-A	-	568	275	1130	1978	271	4.6	3.8	3.25	146.4	58
0-0-B	-	570	265	1146	1992	272	3.9	3.7	2.75	147.2	64
0-1-A	-	506	255	1175	1960	250	5.0	5.6	2.75	144.3	58
0-1-B	-	513	261	1190	1986	230	4.2	4.2	3.0	146.3	69
0-2-A	-	457	249	1240	1979	215	4.6	5.0	3.25	145.4	64
0-2-B	-	456	248	1237	1985	214	4.5	5.0	2.75	145.4	70
0-3-A	-	397	260	1277	1975	200	4.5	4.8	3.0	144.8	61
0-3-B	-	402	256	1243	2003	202	4.6	5.1	3.0	144.6	61

*Air Agent: Darex

TABLE B-2. Concrete Mix Proportions

Cholla Fly Ash

Series & Mix	Fly Ash (lb./cy)	Cement (lb./cy)	Water (lb./cy)	Fine Agg. (lb./cy)	Coarse Agg. (lb./cy)	Air Agent (cc/cy)	Air Content Test (%)	Air Content Calc. (%)	Slump (in.)	Unit Wt. (lb./ft^3)	Conc. Temp. (^oF)
C-1-1-A	38	513	266	1142	1986	287	4.8	3.9	3.0	146.1	64
C-1-1-B	38	511	265	1138	1979	286	-	4.2	2.75	145.6	63
C-1-1A-A	39	518	264	1161	2006	260	4.3	3.0	3.0	147.7	59
C-1-1A-B	38	511	235	1150	1991	257	4.5	5.5	3.0	145.4	60
C-1-2-A	77	458	270	1147	1995	288	4.8	3.3	3.75	146.2	64
C-1-2-B	77	457	269	1145	1993	287	4.5	3.4	3.75	146.0	68
C-1-3-A	115	397	263	1137	1978	285	4.9	4.3	3.5	144.1	62
C-1-3-B	115	399	265	1143	1988	287	5.0	3.9	3.75	144.8	70
C-2-2-A	94	483	245	1097	1994	345	4.7	4.9	3.25	144.9	67
C-2-2-B	94	484	262	1090	1993	345	4.3	4.1	2.5	145.3	68
C-2-3-A	130	422	264	1121	1980	285	4.5	3.7	3.25	145.1	55
C-2-3-B	130	421	253	1129	1978	284	4.5	4.2	3.25	144.9	61
C-3-1-A	97	544	275	1052	1998	317	4.0	2.8	3.25	146.9	68
C-3-1-B	98	548	276	998	2012	319	4.0	3.6	3.0	145.6	66
C-3-2-A	131	483	270	1050	1994	345	4.2	3.4	3.0	145.5	60
C-3-2-B	130	477	267	1036	1968	340	4.3	4.7	3.0	143.6	65
C-3-3-A	169	425	265	1049	1992	344	4.5	3.8	3.5	144.5	68
C-3-3-B	168	424	265	1045	1986	343	4.4	4.1	3.25	144.0	68
C-5-1-A	188	513	276	956	2000	401	4.7	2.9	3.25	145.7	60
C-5-1-B	185	504	274	939	1965	382	4.6	4.4	3.5	143.2	61
C-5-2-A	224	452	280	947	1981	386	4.5	3.4	3.0	143.9	55
C-5-2-B	224	452	269	948	1984	386	4.6	3.9	3.25	143.6	60
C-5-3-A	261	396	273	949	1984	386	4.1	3.7	3.5	143.1	55
C-5-3-B	261	395	279	944	1977	385	4.6	3.6	3.75	142.8	60

TABLE B-3. Concrete Mix Proportions

Four Corners Fly Ash

Series & Mix	Fly Ash (lb./cy)	Cement (lb./cy)	Water (lb./cy)	Fine Agg. (lb./cy)	Coarse Agg. (lb./cy)	Air Agent (cc/cy)	Air Content Test (%)	Air Content Calc. (%)	Slump (in.)	Unit Wt. (lb./ft^3)	Conc. Temp. (°F)
F-1-1-A	34	510	274	1146	1975	285	4.4	3.7	3.5	145.9	63
F-1-1-B	34	512	269	1141	1987	286	3.8	3.7	3.25	146.1	76
F-1-2-A	70	457	281	1144	1990	287	4.7	2.9	3.5	146.0	63
F-1-2-B	70	457	281	1146	1998	287	4.2	2.6	3.5	146.4	74
F-1-3-A	105	402	266	1150	2002	289	4.2	3.3	3.25	145.4	64
F-1-3-B	105	402	267	1153	2006	298	3.2	3.1	3.5	145.7	74
F-2-2-A	88	489	267	1105	1973	376	3.8	3.8	3.25	145.3	76
F-2-2-B	88	489	267	1105	1973	376	4.2	3.8	3.0	145.3	75
F-2-3-A	123	432	268	1106	1974	395	4.4	3.7	3.5	144.6	69
F-2-3-B	123	433	263	1109	1980	396	4.1	3.7	3.5	144.8	72
F-3-1-A	86	540	269	1049	1984	357	4.0	3.8	3.0	145.5	70
F-3-1-B	86	540	269	1050	1987	384	3.8	3.6	3.0	145.7	70
F-3-2-A	122	486	265	1051	1992	402	4.7	3.7	3.5	145.1	50
F-3-2-B	123	488	263	1054	2001	404	4.4	3.5	3.5	145.5	53
F-3-3-A	158	432	249	1057	2009	434	4.3	4.0	3.5	144.7	60
F-3-3-B	158	434	254	1060	2014	436	4.4	3.5	3.5	145.2	64

TABLE B-4. Concrete Mix Proportions

Mohave Fly Ash

Series & Mix	Fly Ash (lb./cy)	Cement (lb./cy)	Water (lb./cy)	Fine Agg. (lb./cy)	Coarse Agg. (lb./cy)	Air Agent (cc/cy)	Air Content Test (%)	Air Content Calc. (%)	Slump (in.)	Unit Wt. ($lb./ft^3$)	Conc. Temp. (^oF)
M-1-1-A	44	512	271	1148	1948	286	4.4	4.4	3.0	145.3	81
M-1-1-B	44	514	261	1148	1956	287	4.4	4.8	3.25	145.3	78
M-1-2-A	90	460	271	1152	2003	375	4.5	2.9	2.5	147.3	89
M-1-2-B	88	453	278	1134	1974	370	5.0	3.7	2.75	145.5	90
M-2-2-A	112	485	265	1096	1991	387	5.0	3.8	4.0	146.3	86
M-2-2-B	111	483	264	1090	1980	386	4.5	4.3	3.5	145.5	90
M-2-3-A	153	421	261	1077	1957	409	5.0	5.5	4.0	143.3	89
M-2-3-B	154	423	257	1083	1967	397	5.0	5.2	3.25	143.9	89
M-3-2-A	156	484	262	1045	1986	415	4.5	4.2	3.5	145.7	85
M-3-2-B	154	479	256	1043	1966	411	4.5	5.3	3.5	144.1	87
M-3-3-A	200	427	262	1044	1984	415	5.0	4.3	3.5	145.1	85
M-3-3-B	201	429	263	1050	1995	417	5.0	3.7	3.75	145.9	87

TABLE B-5. Concrete Mix Proportions

Navajo Fly Ash

Series & Mix	Fly Ash (lb./cy)	Cement (lb./cy)	Water (lb./cy)	Fine Agg. (lb./cy)	Coarse Agg. (lb./cy)	Air Agent (cc/cy)	Air Content Test (%)	Air Content Calc. (%)	Slump (in.)	Unit Wt. (lb./ft^3)	Conc. Temp. (°F)
N-1-1-A	39	520	267	1157	1978	377	4.0	3.6	3.0	146.7	69
N-1-1-B	39	521	266	1150	1984	378	4.0	3.6	3.25	146.7	71
N-1-2-A	77	458	257	1148	1961	504	4.5	4.8	3.0	144.5	71
N-1-2-B	77	459	256	1152	1972	505	4.2	4.5	3.0	145.1	76
N-1-3-A	117	406	247	1165	1992	613	4.3	4.2	3.5	145.5	69
N-1-3-B	116	404	244	1159	1982	609	4.9	4.8	2.75	144.7	70
N-2-2-A	97	489	267	1107	1973	644	4.7	3.8	3.0	145.6	64
N-2-2-B	96	487	266	1100	1963	641	4.9	4.2	3.0	144.9	65
N-2-3-A	136	434	266	1103	1974	695	4.3	3.9	3.25	144.9	67
N-2-3-B	136	435	263	1102	1975	697	4.3	3.9	3.5	144.9	72
N-3-1-A	96	540	275	1053	1946	685	4.4	4.1	3.0	144.9	90
N-3-1-B	95	536	278	1042	1933	709	5.1	4.6	3.75	143.9	84
N-3-2-A	136	491	263	1055	1978	785	4.2	3.9	3.5	145.3	81
N-3-2-B	136	491	262	1054	1979	785	4.2	3.9	3.5	145.3	80
N-3-3-A	174	432	265	1058	1977	956	4.4	3.8	3.5	144.6	77
N-3-3-B	174	431	265	1054	1971	985	4.5	4.0	3.5	144.3	86

TABLE B-6. Concrete Mix Proportions

IP Cement

Series & Mix	Fly Ash (lb./cy)	Cement (lb./cy)	Water (lb./cy)	Fine Agg. (lb./cy)	Coarse Agg. (lb./cy)	Air Agent (cc/cy)	Air Content Test (%)	Air Content Calc. (%)	Slump (in.)	Unit Wt. (lb./ft^3)	Conc. Temp. (°F)
IP-0-0-A	-	499	271	1158	2015	320	4.5	2.4	3.5	146.1	85
IP-0-0-B	-	493	268	1144	1990	316	5.0	3.6	3.8	144.3	86
IP-0-1-A	-	443	262	1189	1986	287	4.2	4.2	3.5	143.7	84
IP-0-1-B	-	448	263	1203	2009	290	5.0	3.2	3.5	145.3	86
IP-0-2-A	-	397	243	1249	2006	260	5.0	4.3	3.0	144.3	86
IP-0-2-B	-	400	246	1257	2019	239	5.0	3.8	3.0	145.3	90
IP-0-3-A	-	351	242	1310	2025	204	4.5	3.8	3.0	145.3	84
IP-0-3-B	-	349	251	1301	2011	188	4.5	3.8	3.0	144.9	86
IP-1-0-A	-	548	256	1109	2015	348	4.5	3.4	3.5	145.5	84
IP-1-0-B	-	548	266	1108	2012	333	4.5	2.9	3.0	145.7	88
IP-2-0-A	-	597	281	1057	2009	376	4.5	2.1	3.5	146.1	82
IP-2-0-B	-	592	277	1049	1993	359	4.3	3.0	3.5	144.9	84
IP-3-0-A	-	647	282	999	2010	405	4.0	2.2	3.5	145.9	84
IP-3-0-B	-	652	282	1018	2025	409	4.0	1.4	3.3	147.3	86

TABLE B-7. Concrete Mix Proportions

Freeze-Thaw Test Specimens Only

Series & Mix	Fly Ash (lb./cy)	Cement (lb./cy)	Water (lb./cy)	Fine Agg. (lb./cy)	Coarse Agg. (lb./cy)	Air Agent (cc/cy)	Air Content Test (%)	Air Content Calc. (%)	Slump (in.)	Unit Wt. (lb./ft^3)	Conc. Temp. (°F)
0-3	0	401	220	1294	2001	151	4.8	6.1	3.0	145.0	61
IP-0-0	-	503	249	1161	2020	320	4.7	5.0	3.5	145.7	65
C-1-2	77	449	249	1122	1960	296	5.0	6.1	4.0	142.8	70
M-2-2	109	479	276	1082	1956	270	4.5	4.4	3.0	144.5	69
0-2	0	461	225	1252	2015	152	4.4	5.3	3.5	146.4	72
N-1-3	115	402	283	1148	1963	686	4.5	3.2	2.5	144.8	65
F-1-3	105	404	242	1157	2013	180	4.6	4.3	3.0	145.2	-
C-3-2	131	481	288	1046	1987	204	4.0	2.4	3.25	145.6	66
C-5-3	259	396	292	950	1988	259	4.1	1.9	3.0	143.9	66

TABLE B 8. Strength Characteristics

Control Mixes

Series & Mix	Water*/Cement	Fly Ash*/Cement	Compressive**				Flexural**			
			7	28	60	90	7	28	60	90
Control 1A	0.473	–	2630	4260	–	–	470	487	–	–
2A	0.483	–	–	–	5220	6060	–	–	645	678
Control 1B	0.479	–	3070	4390	–	–	447	588	–	–
2B	0.478	–	–	–	5460	6040	–	–	645	634
Control 1C	0.474	–	2780	4190	–	–	485	692	–	–
2C	0.478	–	–	–	5170	5560	–	–	664	678
0-0-A	0.48	–	3140	4700	–	–	373	573	–	–
0-0-B	0.465	–	–	–	5800	6350	–	–	756	727
0-1-A	0.504	–	2850	4290	–	–	420	570	–	–
0-1-B	0.509	–	–	–	5460	5920	–	–	650	774
0-2-A	0.545	–	2040	3450	–	–	380	563	–	–
0-2-B	0.544	–	–	–	4200	4690	–	–	663	716
0-3-A	0.655	–	1790	2710	–	–	387	569	–	–
0-3-B	0.637	–	–	–	3660	3910	–	–	614	634

*By weight
**psi

TABLE B-9. Strength Characteristics

Cholla Fly Ash

Series & Mix	Water*/Cement	Fly Ash*/Cement	Compressive** 7	28	60	90	Flexural** 7	28	60	90
C-1-1-A	0.52	0.075	3120	4400	–	–	436	593	–	–
C-1-1-B	0.52	0.075	–	–	5580	5990	–	–	680	740
C-1-1A-A	0.51	0.075	2780	3820	–	–	457	557	–	–
C-1-1A-B	0.49	0.075	–	–	4870	5750	–	–	670	766
C-1-2-A	0.59	0.168	2020	3190	–	–	400	513	–	–
C-1-2-B	0.58	0.168	–	–	4420	4750	–	–	590	625
C-1-3-A	0.66	0.290	1910	3010	–	–	310	493	–	–
C-1-3-B	0.66	0.290	–	–	3470	4170	–	–	593	730
C-2-2-A	0.51	0.195	2570	3870	–	–	363	507	–	–
C-2-2-B	0.54	0.195	–	–	5220	5410	–	–	667	830
C-2-3-A	0.62	0.308	1980	3130	–	–	270	450	–	–
C-2-3-B	0.60	0.308	–	–	4500	5100	–	–	643	758
C-3-1-A	0.53	0.178	2920	4530	–	–	447	600	–	–
C-3-1-B	0.50	0.178	–	–	5630	6060	–	–	727	732
C-3-2-A	0.56	0.272	2430	3770	–	–	405	552	–	–
C-3-2-B	0.56	0.272	–	–	4990	5650	–	–	720	765
C-3-3-A	0.62	0.396	2010	3100	–	–	345	448	–	–
C-3-3-B	0.62	0.396	–	–	4250	5130	–	–	703	770
C-5-1-A	0.54	0.368	2410	4020	–	–	347	557	–	–
C-5-1-B	0.54	0.368	–	–	4930	5520	–	–	660	808
C-5-2-A	0.62	0.496	2140	3630	–	–	350	550	–	–
C-5-2-B	0.60	0.495	–	–	4520	5340	–	–	653	737
C-5-3-A	0.69	0.661	1850	3180	–	–	303	488	–	–
C-5-3-B	0.71	0.661	–	–	4070	4990	–	–	630	714

*By weight
**psi

TABLE B-10. Strength Characteristics

Four Corners Fly Ash

Series & Mix	Water*/Cement	Fly Ash*/Cement	Compressive** 7	28	60	90	Flexural** 7	28	60	90
F-1-1-A	0.54	0.067	–	–	4830	5000	–	–	740	778
F-1-1-B	0.54	0.067	2610	4160	–	–	445	695	–	–
F-1-2-A	0.62	0.153	2620	3930	–	–	435	626	–	–
F-1-2-B	0.62	0.153	–	–	4600	5180	–	–	689	759
F-1-3-A	0.66	0.261	2180	3370	–	–	370	580	–	–
F-1-3-B	0.66	0.261	–	–	4510	4790	–	–	715	761
F-2-2-A	0.55	0.179	–	–	4990	5740	–	–	668	730
F-2-2-B	0.55	0.179	2670	4010	–	–	381	550	–	–
F-2-3-A	0.62	0.285	2420	3700	–	–	372	518	–	–
F-2-3-B	0.61	0.285	–	–	4700	5550	–	–	682	716
F-3-1-A	0.50	0.160	3270	4610	–	–	500	710	–	–
F-3-1-B	0.50	0.161	–	–	5240	5510	–	–	757	742
F-3-2-A	0.55	0.251	2970	4420	–	–	455	670	–	–
F-3-2-B	0.54	0.251	–	–	5220	5920	–	–	744	790
F-3-3-A	0.58	0.366	2320	3660	–	–	388	572	–	–
F-3-3-B	0.59	0.366	–	–	4950	5540	–	–	742	810

*By weight
**psi

TABLE B-11. Strength Characteristics

Mohave Fly Ash

Series & Mix	Water*/Cement	Fly Ash*/Cement	Compressive**				Flexural**			
			7	28	60	90	7	28	60	90
M-1-1-A	.51	.086	3050	4290	–	–	483	612	–	–
M-1-1-B	.53	.086	–	–	5030	5260	–	–	718	747
M-1-2-A	.59	.196	2910	4140	–	–	482	662	–	–
M-1-2-B	.61	.194	–	–	4260	4710	–	–	694	567
M-2-2-A	.55	.230	2610	3710	–	–	493	654	–	–
M-2-2-B	.55	.230	–	–	4340	4640	–	–	775	617
M-2-3-A	.62	.364	2520	3640	–	–	421	600	–	–
M-2-3-B	.61	.364	–	–	3900	4260	–	–	589	528
M-3-2-A	.54	.322	3130	4500	–	–	532	685	–	–
M-3-2-B	.53	.324	–	–	4860	5200	–	–	729	800
M-3-3-A	.61	.469	2610	4110	–	–	439	642	–	–
M-3-3-B	.61	.471	–	–	4940	5130	–	–	781	808

*By weight
**psi

TABLE B-12. Strength Characteristics

Navajo Fly Ash

Series & Mix	Water*/Cement	Fly Ash*/Cement	Compressive**				Flexural**			
			7	28	60	90	7	28	60	90
N-1-1-A	0.51	0.075	2820	4330	–	–	437	626	–	–
N-1-1-B	0.51	0.075	–	–	5350	5390	–	–	736	717
N-1-2-A	0.56	0.169	2980	4340	–	–	518	633	–	–
N-1-2-B	0.56	0.169	–	–	4850	5390	–	–	681	679
N-1-3-A	0.61	0.288	2410	3750	–	–	469	620	–	–
N-1-3-B	0.60	0.288	–	–	5100	5900	–	–	754	795
N-2-2-A	0.55	0.198	3140	4410	–	–	496	646	–	–
N-2-2-B	0.55	0.198	–	–	4990	5280	–	–	720	765
N-2-3-A	0.61	0.313	2790	4400	–	–	553	660	–	–
N-2-3-B	0.60	0.313	–	–	5230	5510	–	–	789	801
N-3-1-A	0.51	0.177	3350	4700	–	–	557	688	–	–
N-3-1-B	0.52	0.177	–	–	5300	5130	–	–	662	703
N-3-2-A	0.54	0.277	3140	4720	–	–	511	635	–	–
N-3-2-B	0.54	0.277	–	–	5990	5710	–	–	769	805
N-3-3-A	0.61	0.403	3050	4520	–	–	493	613	–	–
N-3-3-B	0.61	0.403	–	–	5880	5840	–	–	775	825

*By weight
**psi

TABLE B-13. Strength Characteristics

IP Cement

Series & Mix	Water*/CM	Fly Ash*/Cement	Compressive** 7	Compressive** 28	Compressive** 60	Compressive** 90	Flexural** 7	Flexural** 28	Flexural** 60	Flexural** 90
IP-0-0-A	.54	–	2120	3290	–	–	411	564	–	–
IP-0-0-B	.54	–	–	–	4050	4590	–	–	642	575
IP-0-1-A	.59	–	1770	2880	–	–	362	499	–	–
IP-0-1-B	.59	–	–	–	3590	4000	–	–	569	567
IP-0-2-A	.61	–	1650	2720	–	–	361	510	–	–
IP-0-2-B	.62	–	–	–	3470	3990	–	–	631	644
IP-0-3-A	.69	–	1300	2200	–	–	297	451	–	–
IP-0-3-B	.72	–	–	–	2700	3140	–	–	477	556
IP-1-0-A	.47	–	2410	3630	–	–	462	583	–	–
IP-1-0-B	.49	–	–	–	4280	4770	–	–	689	661
IP-2-0-A	.47	–	2770	3990	–	–	518	600	–	–
IP-2-0-B	.47	–	–	–	4970	5390	–	–	736	628
IP-3-0-A	.42	–	3000	4350	–	–	532	647	–	–
IP-3-0-B	.43	–	–	–	5070	5550	–	–	700	785

*By weight
**psi

TABLE B-14. Drilled Core Strength Characteristics

Control Mixes

Series & Mix	Water** / Cement	Fly Ash** / Cement	Compressive, psi 60	90	180	360
Control 2A	0.483	-	5120	5600*	6080	7040
Control 2B	0.478	-	5250	5260	6350	6700
Control 2C	0.478	-	4720	5650*	5840	6370*
0-0-B	0.465	-	5430*	5510	5680	8090
0-1-B	0.509	-	5400	6010*	5920	7610*
0-2-B	0.544	-	4970	5290	5470	5330
0-3-B	0.637	-	3890*	3940	3970	4380

IP Cement

Series & Mix	Water** / CM	Fly Ash** / Cement	Compressive, psi 60	90	180	360
IP-0-0-B	.54	-	3840	4600	4600	5160
IP-0-1-B	.59	-	3100	3630	3890	4810
IP-0-2-B	.62	-	3310	4340	3960	5110
IP-0-3-B	.72	-	2600	3320	3300	3650
IP-1-0-B	.49	-	4210	4970	5400	5590
IP-2-0-B	.47	-	4110	5230	5540	5840
IP-3-0-B	.43	-	4650	6060	6700	8280

*Average of 2 samples
**By weight

TABLE B-15. Drilled Core Strength Characteristics

Cholla Fly Ash

Series & Mix	Water** / Cement	Fly Ash** / Cement	Compressive, psi 60	90	180	360
C-1-1-B	.52	.075	5110	5820*	7010	6580*
C-1-1A-B	.49	.075	4670	6140*	6880	6510*
C-1-2-B	.58	.168	4260	4780*	5660	6470*
C-1-3-B	.66	.290	3680	4310	5290	6410
C-2-2-B	.54	.195	4770	5910	5490*	6460
C-2-3-B	.60	.308	4020	5320	6200	6670
C-3-1-B	.50	.178	4830	4840	7010	6860
C-3-2-B	.56	.272	4310	5540*	6970	7530*
C-3-3-B	.62	.396	4360	5120	6250	6680*
C-5-1-B	.54	.368	5010	6260	7270	6600
C-5-2-B	.60	.495	4360	5780	6350	6880
C-5-3-B	.71	.661	3990	5080	6040	6670

Four Corners Fly Ash

Series & Mix	Water** / Cement	Fly Ash** / Cement	Compressive, psi 60	90	180	360
F-1-1-A	.54	.067	5020	5330	5260	6920
F-1-2-B	.62	.153	4660	5270	4930	6520
F-1-3-B	.66	.261	4290	5110	5590	5860
F-2-2-A	.55	.179	5030	5820	6640	7130
F-2-3-B	.61	.285	4780	5210	5500	5810
F-3-1-B	.50	.161	4780	6060	5700	7980*
F-3-2-B	.54	.251	5290	5870***	6040	6420***
F-3-3-B	.59	.366	5080	5300	5950	6070

*Average of 2 samples
**By weight
***Value from 1 sample only

TABLE B-16. Drilled Core Strength Characteristics

Mohave Fly Ash

Series & Mix	Water** / Cement	Fly Ash** / Cement	Compressive, psi 60	90	180	360
M-1-1-B	.53	.086	4720	4990	6930	6250
M-1-2-B	.61	.194	4040	4340	5640	5210
M-2-2-B	.55	.230	4550	4850	6370	5750
M-2-3-B	.61	.364	3640	4350	5640	4830
M-3-2-B	.53	.324	4230	5160	5070	5910
M-3-3-B	.61	.471	4430	5120	5070	6220

Navajo Fly Ash

Series & Mix	Water** / Cement	Fly Ash** / Cement	Compressive, psi 60	90	180	360
N-1-1-B	.51	.075	5590	5740*	6630	6420
N-1-2-B	.56	.169	4340	5060*	5800	6800
N-1-3-B	.60	.288	-	5560	6160	7200
N-2-2-B	.55	.198	4750	5640	6600	6780
N-2-3-B	.60	.313	5050	5860	6790	7060
N-3-1-B	.52	.177	-	4610	4710	5990
N-3-2-B	.54	.277	-	5750	7400	6080
N-3-3-B	.61	.403	-	5420	6410	6880

*Average of 2 samples
**By weight